THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

# Options for improving the yield and nutritive value of maize and grain legume residues for ruminants in East African farming systems

Mesfin Dejene Ejigu

MSc degree (Animal nutrition)

BSc degree (Animal production and rangeland management)

*A thesis submitted for the degree of Doctor of Philosophy at*

*The University of Queensland in 2018*

Queensland Alliance for Agriculture and Food Innovation

**Abstract**

The role and importance of livestock in smallholder crop-livestock systems and the importance of crop residues (CR) as ruminant feedstuffs in such systems are well established. The effects of genotype (G), environment (E) and crop management (M) factors on yields of grain and CR and the nutritive value of the CR of maize (*Zea mays*) and common bean (*Phaseolus vulgaris*) were investigated in an East African context. Genotype effects were examined in early and medium maturing (EM and MM, respectively) maize hybrids and popular varieties of common bean. Environment was examined at three sites for maize in the 2013 and 2014 cropping seasons and at four sites for common bean in 2013. Management effects examined were plant density (D) (5 and 7 plants/$m^2$), height of cutting at harvest in maize, and harvest at early and final seed maturity in common bean. Quality attributes (nitrogen (N), neutral detergent fibre (NDF) and acid detergent fibre (ADF) contents and dry matter digestibility (DMD)) were analysed using near infrared spectroscopy (NIRS) and calibrations expanded and validated with reference samples of CR representing the experimental sample set.

There was substantial variation ($P<0.05$ to $P<0.0001$) among maize genotypes in yields of grain and stover and quality of stover as a feedstuff. Dual purpose genotypes were identified but G x E interactions for some yield and quality attributes showed that the variation among genotypes can depend on environment. In general the higher D increased yields of grain by 9-15% and stover by 21-31%, but had only minor effects on stover quality attributes. Year (Y) x density (D), G x E and G x D interactions were observed for some of the yield and stover attributes.

High cutting height of maize (two internodes below the lowest ear) allowed harvest of most of the stover (on average 63-72% in EM and MM genotypes, respectively) as feedstuff while leaving stubble in the field available for other uses. This is established practice by farmers in some regions. The amount and quality as a feedstuff of the upper and lower stover components varied ($P<0.01$) among genotypes. N and DMD were 0.05-0.09% and 1.7-3.6%, respectively higher ($P<0.0001$) in the upper fraction of the stover than in whole stover. Thus evaluation and estimation of the amount and quality of maize stover available as a feedstuff should consider harvest at high cutting height to increase quality. G x E interactions were observed in yield and in some stover attributes in the upper and lower fractions, but these were not consistent.

Common bean varieties varied (P<0.05 to P<0.0001) in yields of seed and haulm and in the nutritive value of haulm fractions (leaf, stem and pod wall) when harvested at seed maturity. There was extensive leaf loss at seed maturity which decreased haulm quality. Seed and haulm yields were correlated (r=0.87). Seed yield was generally not related to haulm quality as N% or DMD%. The variation in yield and haulm feedstuff quality was also examined in common bean varieties harvested at early seed maturity. Leaf proportion (23.1 vs. 6.9%), haulm N (1.53 vs.0.85%) and DMD (62.2 vs. 48.8%) were much higher at early harvest. G x E (site) interactions (P<0.05 to P<0.0001) were observed for yields of seed and haulm, and the N content and DMD of pod wall. Harvest at seed maturity increased (P< 0.0001) seed yield but reduced haulm yield.

To relate the research findings to farming systems a survey was conducted in three weredas/districts (Akaki, Shalla ad Misrak-Badawacho) in 2014 to examine the practices, perceptions and rationale of farmers in relation to their management of cereal and grain legume crops and their crop-livestock integration. The survey used participatory rural appraisal tools (semi-structured interviews and group discussions) followed by a household level survey (n=600). There was wide variation in agronomic practices (e.g. crop variety, seed rate, harvest procedure) affecting CR yield and quality and also in farmers perceptions compared to the recommended practices. On average 77%, 58% and 29% of farmers adopted improved varieties of maize, common bean and chickpea, respectively, but this varied widely among districts. Seeding rates (and hence D) often differed substantially from recommendations. Regression models showed that the probability of increasing maize CR yield was associated with education level of the HH head in years, livestock wealth, proportion of adopters of improved maize varieties, mean distance to output market and total maize seed used in tonnes/HH.

In conclusion, these studies demonstrated that improved maize and common bean genotypes which combine high yield of grain or seed and CR and improved CR quality as feedstuffs can be identified for use as dual purpose crops. In maize higher D and modification of harvest procedure should provide options to increase the amount and value of CR as ruminant feedstuffs without reducing grain yield. Improved understanding of farmers practices and perceptions relevant to CR yield, quality and use and crop-livestock integration should hasten adoption of improved technologies and practices for enhanced output from the whole farm.

**Declaration by author**

This thesis *is composed of my original work, and contains* no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted *to qualify for the award of any* other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the policy and procedures of The University of Queensland, the thesis be made available for research and study in accordance with the Copyright Act 1968 unless a period of embargo has been approved by the Dean of the Graduate School.

I acknowledge that copyright of all material contained in my thesis resides with the copyright holder(s) of that material. Where appropriate I have obtained copyright permission from the copyright holder to reproduce material in this thesis.

Mesfin Dejene Ejigu

## Publications during candidature

### Conference abstracts

1. Ejigu, M. D., Dixon, R. M., Duncan, A. J., McNeill, D. M., Walsh, K. and Woldemeskel, E. (2015). Variability of food fodder traits in grain legume genotypes in Ethiopia: 1. Seed and residue yields, morphological characteristics and straw quality in common bean. *In*: "Meeting the Productivity Challenge in the Tropics", Tropical Agriculture Conference, 16-18 November 2015, Brisbane, Australia. p 90-91.

2. Ejigu, M. D., Dixon, R. M., Duncan, A. J., McNeill, D. M., Walsh, K. and Woldemeskel, E. (2016). Effect of variety and location on seed and straw yields and nutritive value of Common Bean (*Phaseolus vulgaris* L.) straw in crop-livestock systems of Ethiopia. *In*: "Sustainable Grain Legume Systems for Food, Income and Nutritional Security in a Rapidly Changing Climate", Pan-African Grain Legume and World Cowpea Conference, 28 February to 4 March 2016, Livingstone, Zambia. p133.

## Publications included in this thesis

"No publications included".

**Contributions by others to the thesis**

"No contributions by others."

**Statement of parts of the thesis submitted to qualify for the award of another degree**

"None".

**Acknowledgements**

First of all, my gratefully expressed thanks to God, for his blessing and abundance of mercy. Many people and institutions were involved and supported me directly or indirectly in the accomplishment of this thesis. I would like to thank all for their support and contribution in different ways.

This PhD research was made possible by the program entitled "*Sustainable Intensification of Maize-Legume cropping systems for food security in Eastern and Southern Africa*" funded by Australian Centre for International Agricultural Research (ACIAR). I am grateful to the project leader Dr Mulugetta Mekuria. Also this PhD programme would not have been possible without the support from ACIAR through the John Allwright Fellowship Program, the Ethiopian Institute of Agricultural Research (EIAR) for granting me a study leave in order to pursue this programme, the financial support from International Livestock Research Institute (ILRI) through the N2Africa Project, Ethiopia, and complete access to N2 Africa experimental plots for my field data collection and crop residue sampling during 2013 in Ethiopia. I am indebted to Dr Daniel Rodriguez and Dr Girma Tesfahun for their kind support from the very beginning of this PhD program.

I am sincerely grateful to my supervisors Dr Robert M. Dixon, Dr Alan J. Duncan, Professor Kerry B. Walsh and Dr David McNeill. Rob, your being my principal supervisor played a very significant role towards the accomplishment of this thesis. When I was faced with technical or personal challenges you were a solution to them, always timely with your advice and assistance and never out of reach. I cannot forget how you and your family (Mrs Dora Dixon) helped me when I faced personal challenges during the study period. I thank you very much for your persistent guidance, critical follow-ups at each and every step of the thesis, encouraging words and advices in every communication with a very polite and friendly approach. Alan, thank you very much for your motivational support, critical follow-ups and guidance throughout the process of this study. When I moved to Ethiopia for the field research work, you hosted me at ILRI-Addis Ababa with significant financial support for the first year field and laboratory research work. Heartfelt thanks for your kind help and your overall critical views during the development of this thesis. I am highly indebted to your valuable ideas, kind support and guidance. I extend my profound sincere thanks to Prof. Kerry, for your great supervision and hosting me at Central

Queensland University with necessary office supplies and laboratory facilities for the first two years during my study period. David, my deep thanks also goes to you for enthusiastic support and advice in my study period especially when I was at Gatton Campus during the last year of my study period.

I would like to thank the N2Africa research team members at ILRI-Addis Ababa, federal and regional research centres who helped me during field data collection. Dr Endalkachew Wolde-meskel, country coordinator for the N2Africa Project, Ethiopia, deserves my special thanks for his help during the process of field data collection. My thanks are due to the ILRI-Addis Ababa analytical laboratory staff (Yonas Asmare, Degusew and Alemeshet) for their help during sample processing and shipment to Australia. I express my profound gratitude to the farmers who accepted and cooperated in the process of the survey work, to the local extension staff and also to the survey team without whom it would have been impossible to accomplish this task. I would like to extend my special thanks to Dr Getnet Assefa, Dr Fekede Feyissa, and Dr Temesgen Desalegn for their smooth facilitations and help.

I would like to extend my thanks to many individuals who directly or indirectly played a role for the successful accomplishment of this thesis. It comes with a long list of friends and colleagues. I benefited from the scientific expertise of many colleagues and I need to officially mention and thank: Dr Girma Tesfahun for his inputs in Chapter 8, and Dr Getaw Tadesse, Asheber Tegegn, and my late friend Samuel Menbere for their technical support during the course of my candidature. Menbere passed away during the final preparation of this thesis and rests in peace! Besufekad Tadesse deserves special thanks for his continuous encouragement and help in many ways. I am grateful to my colleagues Solomon Seyoum, Solomon Hassen and Nascimento Nhantumbo for their inspirational scientific discussions and helpful advice during our stay in Gatton. I would like to thank Getu Shewarega for his helpful encouragements. Life would have been difficult without the light moments I shared with my friends and their families at Gatton. Special thanks goes to Solomon Seyoum for allowing me full access of his experimental plots for my data collection, access to yield and yield related data and crop residue sampling during my field work in Ethiopia. Derbew Kefyalew and Dr Aweke Mulualem; for their continuous encouragement and the joy I shared with you at Addis Ababa will not be forgotten. Thanks to Gebremariam, Mamaru, Behailu, Cherinet, Tibebu and Hailu for their encouragements

and help. Many other people deserve special thanks for helping me in one way or another; it is impossible to mention all of them but I should say thank you all.

I would like to express deepest gratitude to my mother Bogalech Habte-Georgies and my father Dejene Ejigu, who both passed away during the final year of my study period. Your love and encouragement were the basis of my achievements in my educational career. My beloved parents rest in peace! My brothers and sisters, I thank you very much for taking care of all family matters during our difficult time.

Finally, my dearest gratitude is for my wife Zenebech Alemu for her understanding, support and continuous encouragement that inspired me to accomplish the PhD program.

**Keywords**

maize, common bean, grain legumes, crop residues, stover, farming systems, eastern and southern Africa, livestock, NIRS

**Australian and New Zealand Standard Research Classifications (ANZSRC)**

070204, Animal Nutrition, 50%
070107, Farming Systems Research, 30%
070108, Sustainable Agricultural Development, 20%

**Fields of Research (FoR) Classification**

0702, Animal Production, 60
0701, Agriculture, Land and Farm Management, 40%

**Table of contents**

**ABSTRACT** ..... **I**

**DECLARATION BY AUTHOR** ..... **III**

**PUBLICATIONS DURING CANDIDATURE** ..... **IV**

**ACKNOWLEDGEMENTS** ..... **VI**

**TABLE OF CONTENTS** ..... **X**

**LIST OF FIGURES** ..... **XVII**

**LIST OF TABLES** ..... **XVIII**

**LIST OF ABBREVIATIONS USED IN THE THESIS** ..... **XXIII**

**CHAPTER 1 INTRODUCTION** ..... **1**

1.1. IMPORTANCE AND ROLE OF LIVESTOCK PRODUCTION IN DEVELOPING COUNTRIES ..... 1

1.2. NUTRITIONAL CONSTRAINTS TO LIVESTOCK PRODUCTION IN DEVELOPING COUNTRIES ..... 2

1.3. OPTIONS FOR IMPROVING YIELD AND QUALITY OF CR ..... 4

*1.3.1. Genotype choice* ..... *5*

*1.3.2. Crop management and farmer perceptions* ..... *6*

1.4. OBJECTIVES ..... 8

**CHAPTER 2 LITERATURE REVIEW** ..... **9**

2.1. CHARACTERISTICS OF MIXED CROP-LIVESTOCK SYSTEMS AND CR IN SSA ..... 9

2.2. TYPES OF CR AND BY-PRODUCTS AVAILABLE FOR RUMINANTS ..... 9

*2.2.1. Maize and legume crop residues* ..... *10*

2.3. VARIATION IN YIELD AND NUTRITIVE VALUE OF CEREAL AND LEGUME CR ..... 11

*2.3.1. Variation in composition and digestibility* ..... *12*

2.3.1.1. Effect of genotypes on variation in composition and digestibility ..... 16

2.3.1.2. Anatomy of plants and cell wall characteristics in relation to digestibility ..... 17

2.4. VARIATION IN VI AND FACTORS AFFECTING THE UTILIZATION OF POOR- QUALITY FORAGES BY RUMINANTS ..... 19

*2.4.1. Effect of plant genotype on variation in VI, digestibility, N balance and live weight change* ..... *23*

2.5 VARIATION IN GRAIN AND CR ATTRIBUTES AMONG CEREAL GENOTYPES ..... 24

*2.5.1. Variation in grain and CR attributes and their relationships in cereal genotypes* ..... *24*
2.6. VARIATION IN SEED AND CR ATTRIBUTES AND THEIR RELATIONSHIPS AMONG LEGUME GENOTYPES ..... 25
2.7. CROP MANAGEMENT FACTORS AFFECTING THE YIELD AND NUTRITIVE VALUE OF CR ..... 26
*2.7.1. Effect of plant density on maize grain and total biomass yields and stover quality* ..... *27*
*2.7.2. Effect of cutting height at harvest on the yield and quality of maize stover* ..... *28*
*2.7.3. Effect of maturity at harvest on legume CR yield and feeding value* ..... *29*
2.8. CONCLUDING COMMENTS ..... 30

**CHAPTER 3 DEVELOPING ROBUST NIRS CALIBRATION EQUATIONS TO PREDICT COMPOSITION AND DRY MATTER DIGESTIBILITY OF CROP RESIDUES FROM EAST AFRICAN FARMING SYSTEMS ..... 33**

3.1. INTRODUCTION ..... 33
3.2. MATERIALS AND METHODS ..... 35
*3.2.1. Crop residue sampling and processing* ..... *35*
*3.2.2. Measurement of NIRS spectra* ..... *35*
*3.2.3. Wet chemistry analysis of reference samples* ..... *37*
*3.2.4. Calibration procedure* ..... *38*
*3.2.5. Validation procedure* ..... *38*
3.3. RESULTS ..... 39
*3.3.1. Instrument stability* ..... *39*
*3.3.2. Calibration equations calculated from the reference values of the constituents and calibration statistics* ..... *39*
*3.3.3. Validation of calibration for maize and grain legumes residue quality attributes* *41*
3.4. DISCUSSION ..... 46
*3.4.1. Instrument stability and standardization* ..... *46*
*3.4.2. Reference values and equation development* ..... *47*
*3.4.3. Equation performance* ..... *50*
3.5. CONCLUSION ..... 52

**CHAPTER 4 MAIZE GRAIN AND STOVER YIELD AND STOVER QUALITY AS AFFECTED BY GENOTYPE, ENVIRONMENT AND PLANT DENSITY ..... 55**

4.1. INTRODUCTION ..... 55
4.2. MATERIALS AND METHODS ..... 56

*4.2.1. Site descriptions and experimental design* ..... *56*
*4.2.2. Measurements* ..... *57*
*4.2.3. Laboratory analyses* ..... *57*
*4.2.4. Statistical analyses* ..... *59*
4.3. RESULTS ..... 59
*4.3.1. Total biomass, grain and stover yields and HI across years by site* ..... *59*
*4.3.2. Total biomass, grain and stover yields and HI across years and sites* ..... *62*
*4.3.3. Relationships between stover and grain yields* ..... *64*
*4.3.4. Stover quality across years by site* ..... *64*
*4.3.5. Stover quality across years and sites* ..... *66*
*4.3.6. Relationships between grain yield and stover DMD and total N content* ..... *68*
*4.3.7. DDM yield, nitrogen yield (NY) and PUI by site* ..... *68*
*4.3.8. Stover quality and DDM yield, NY and PUI across sites* ..... *70*
4.4. DISCUSSION ..... 71
*4.4.1. Sources of variation for yield attributes* ..... *71*
4.4.1.1. Environment ..... 71
4.4.1.2. Management as effects of plant density ..... 72
4.4.1.3. Genotype ..... 74
*4.4.2. Sources of variation for stover quality attributes* ..... *75*
4.4.2.1. Environment and management as plant density ..... 75
4.4.2.2. Genotype ..... 76
*4.4.3. Factors affecting stover nutrient yields and PUI* ..... *78*
4.4.3.1. Environment and plant density ..... 78
4.4.3.2. Genotype ..... 78
4.5. CONCLUSION ..... 79

**CHAPTER 5 VARIATION IN YIELD AND NUTRITIVE VALUE OF THE MORPHOLOGICAL FRACTIONS IN THE UPPER AND LOWER COMPONENTS OF MAIZE STOVER AS AFFECTED BY GENOTYPE AND ENVIRONMENT ..... 81**

5.1. INTRODUCTION ..... 81
5.2. MATERIALS AND METHODS ..... 82
*5.2.1. Site descriptions and experimental design* ..... *82*
*5.2.2. Measurements and sampling method* ..... *82*
*5.2.3. Statistical analyses* ..... *83*
5.3. RESULTS ..... 84

*5.3.1. Plant height at harvest and proportions of the HCT and HCB of the stover .....84*
*5.3.2. Proportion of morphological fractions within HCT and HCB parts of the stover.84*
*5.3.3. Grain and crop residue (CR) yields .....86*
*5.3.4. Composition and digestibility of stover components.....90*
*5.3.5. Nutrient composition and digestibility of stover morphological fractions.....93*
5.4. DISCUSSION .....96
*5.4.1. Plant dimensions and the proportions of morphological fractions at harvest.....96*
*5.4.2. Grain and CR yields of EM and MM genotypes.....96*
*5.4.3. Nutrient content and digestibility of stover components .....97*
*5.4.4. Nutrient composition and digestibility of morphological fractions within the stover components.....99*
5.5. CONCLUSION .....100

**CHAPTER 6 VARIABILITY IN YIELD AND THE NUTRITIVE VALUE FOR RUMINANTS OF THE POST-HARVEST RESIDUES OF COMMON BEAN: EFFECTS OF VARIETY AND ENVIRONMENT.....101**

6.1. INTRODUCTION.....101
6.2. MATERIALS AND METHODS.....102
*6.2.1. Site and trials descriptions.....102*
*6.2.2. Experimental design and measurements .....104*
*6.2.3. Statistical analyses.....105*
6.3. RESULTS.....105
*6.3.1. Variation in yields of seed, post-harvest residues and total biomass .....105*
*6.3.2. Variation in morphological characteristics .....108*
*6.3.3. Variation in post-harvest residue composition and DMD.....110*
*6.3.4. Variation in yields of total N and digestible DM and PUI .....115*
*6.3.5. Relationships between seed and yield related attributes.....115*
*6.3.6. Relationships between seed and HPW quality related attributes .....116*
6.4. DISCUSSION .....117
*6.4.1. Variation amongst varieties for yield and yield related attributes.....117*
*6.4.2. Variation amongst varieties for morphological fractions and residue quality attributes at harvest.....119*
6.5. CONCLUSION .....121

**CHAPTER 7 VARIABILITY IN YIELD AND THE NUTRITIVE VALUE FOR RUMINANTS OF COMMON BEAN RESIDUES: EFFECTS OF VARIETY AND HARVESTING STAGES ..... 123**

7.1. INTRODUCTION ..... 123
7.2. MATERIALS AND METHODS ..... 123
7.3. RESULTS ..... 124
*7.3.1. Yields and characteristics of crop fractions at 'early harvest' ..... 124*
*7.3.2. Haulm quality characteristics of crop fractions at 'early harvest' ..... 126*
*7.3.3. Haulm nutrient yields at 'early harvest' ..... 128*
*7.3.4. Effect of crop growth stage at harvest on seed and haulm DM yields ..... 129*
*7.3.5. Effect of crop growth stage at harvest on haulm quality and nutrient yields ..... 130*
*7.3.6. Relationships between yield and yield related attributes and haulm quality parameters ..... 131*
7.4. DISCUSSION ..... 134
*7.4.1. Variation in yield and haulm morphological characteristics and quality attributes among varieties ..... 134*
*7.4.2. Variation in haulm nutrient yields ..... 135*
*7.4.3. Effect of crop growth stage at harvest on seed and haulm yields, morphological proportions and haulm quality ..... 135*
*7.4.4. Relationships between yield, yield related attributes and haulm quality parameters ..... 136*
7.5. CONCLUSION ..... 137

**CHAPTER 8 AGRONOMIC PRACTICES AND PRODUCTION OF CROP RESIDUES FOR RUMINANTS: FARMERS' PERCEPTIONS AND RATIONALE FOR CURRENT PRACTICE IN CROP–LIVESTOCK SYSTEMS IN ETHIOPIA ..... 139**

8.1. INTRODUCTION ..... 139
8.2. METHODOLOGY ..... 140
*8.2.1. Site descriptions ..... 140*
*8.2.2. Survey approach and sampling techniques ..... 141*
8.2.2.1. Village level survey data collection ..... 141
8.2.2.2. Household (HH) level survey data collection ..... 142
*8.2.3. Data analysis ..... 143*
8.3. RESULTS ..... 143
*8.3.1. Household socio-demographic characteristics ..... 143*

*8.3.2. Cropping seasons and type of crops grown in the study areas* ..... *147*
*8.3.3. Adoption of improved varieties, and farmers' perceptions and rationale* ..... *148*
*8.3.4. Seed rate used, and farmers' perceptions and rationale* ..... *149*
8.3.4.1. The relationship between seed rate used and grain and residue yields ..... 150
8.3.4.2. The relationship between seed rate used and residue quality as feedstuffs ..... 152
*8.3.5. Maize pre-harvest practices and farmers' perceptions/rationale* ..... *153*
*8.3.6. Early-harvest practices, and farmers' perceptions and rationale in relation to residue availability and use* ..... *154*
*8.3.7. Maize and grain legumes maturity stage at harvest and farmers' perceptions* *156*
*8.3.8. Crop cutting height at harvest and CR management practices* ..... *158*
*8.3.9. Farmers' perceptions on CR management and use* ..... *159*
*8.3.10. Farmers' perceptions on livestock and crop-livestock integration* ..... *159*
*8.3.11. Regressions of maize CR yield with possible explanatory variables.* ..... *162*
8.4. DISCUSSION ..... 162
*8.4.1. Types of crops grown and adoption of improved varieties, and farmers perceptions* ..... *163*
*8.4.2. Maize seed rate used, and farmers perceptions for current practice* ..... *164*
*8.4.3. Maize pre-harvest practices versus seed rate used and perceptions* ..... *166*
*8.4.4. Early-harvest practices, and farmers perceptions in relation to residue availability and use* ..... *166*
*8.4.5. Farmers perceptions on maturity stage at harvest in relation to grain and residue yields and quality* ..... *167*
*8.4.6. Crop cutting height at harvest and farmers perceptions* ..... *168*
*8.4.7. Farmers' perceptions on CR use and crop-livestock integration* ..... *168*
*8.4.8. Socio-economic factors and crop management practices in relation to maize and CR yields* ..... *169*
8.5. CONCLUSION ..... 171

**CHAPTER 9 GENERAL DISCUSSION AND CONCLUSION ..... 173**

9.1. GENERAL DISCUSSION ..... 173
*9.1.1. Introduction* ..... *173*
*9.1.2. Study approach* ..... *175*
9.1.2.1. Site selection and CR sampling, processing and measurements ..... 175
9.1.2.2. Crop residue quality attributes and methods used ..... 175

9.1.2.3. Application of NIRS and development of robust calibration equations ..... 177
9.1.2.4. Survey approaches in avoiding survey biases ..... 179
*9.1.3. Options to increase the quantity and quality of maize stover available as a ruminant feedstuffs ..... 179*
9.1.3.1. Maize genotype choice ..... 179
9.1.3.2. Plant density ..... 181
9.1.3.3. Higher cutting height in maize: Yield and quality of stover components ..... 183
*9.1.4. Options to increase the quantity and quality of common bean residues available as a ruminant feedstuffs ..... 186*
9.1.4.1. Varietal choice at seed maturity ..... 186
9.1.4.2. The potential of early harvest CR in common bean varieties ..... 187
*9.1.5. Effects of harvesting stage on yields of seed and haulm and haulm quality ..... 188*
*9.1.6. Farmers practices and perceptions ..... 189*
9.2. CONCLUSION ..... 191
**BIBLIOGRAPHY ..... 193**
**APPENDIX ..... 240**

**List of Figures**

Figure 2.1 Crop type and the relative contribution of the total CR produced in 2003 and 2011 cropping season in Ethiopia (CSA, 2004, 2012b).....10

Figure 3.1 Scatter plot of predicted verses reference data for total N% concentration (A), dry matter digestibility (DMD) (B), NDF (C) and ADF (D) calculated from the NA+A+B calibration data set. .....41

Figure 6.1 Relationship between the haulm + pod wall (HPW) yield (t/ha) (Y) and seed yield (t/ha) (X) in common bean varieties across four trials in 2013. .....115

Figure 6.2 Relationship between the haulm + pod wall (HPW) N (%) concentration (Y) and seed yield (t/ha) (X) in common bean varieties across four trials in 2013. .....116

Figure 6.3 Relationship between the haulm + pod wall (HPW) DMD (%) (Y) and seed yield (t/ha) (X) in common bean varieties across four trials in 2013. .....117

Figure 7.1 Scheme for biomass sampling and seed yield measurement in field plots with common bean varieties. .....124

Figure A4.1 Map showing the study sites of Chapter 4 in Oromia and SNNP regional states, Ethiopia.....240

Figure A5.1 Map showing the study sites of Chapter 5 in Oromia regional state, Ethiopia. .....241

Figure A6.1 Map showing the study sites of Chapter 6 in Benshangul Gumuz, Oromia and SNNP regional states, Ethiopia. .....242

Figure A7.1 showing the study sites of Chapter 7 in Benshangul Gumuz and SNNP regional states, Ethiopia. .....243

Figure A8.1 Map showing the survey study sites of Chapter 8 in Oromia and SNNP regional states, Ethiopia. .....244

**List of Tables**

Table 1.1 Projected demands for livestock products in the developed and developing world .....2

Table 2.1 The total area and production of grain and CR for private land holdings, 2003 and 2011 main cropping seasons in Ethiopia .....10
Table 2.2 Composition and digestibility of common cereal crop residues and natural pasture hay*, % DM .....15
Table 2.3 Composition and in-vitro digestibility of common legume crop residues .....15
Table 2.4 Composition and in-vitro digestibility of maize and legume genotypes CR .....16
Table 2.5 Nutrient intake, N retention and LW change of ruminants fed exclusively CR diets .....22
Table 2.6 Effect of genotypes on VI, digestibility, N-balance and LW change of ruminants .....23

Table 3.1 Type and number of samples collected during 2013 and 2014 cropping seasons from different crop species and environments in Ethiopia .....36
Table 3.2 The variation in measurement of the attributes (%) of a laboratory standard comprising *Cenchrus ciliaris* in a sealed cell scanned on 58 occasions over 27days in 2014 and 33 occasions over 14 days in 2015 .....39
Table 3.3 Attributes of North Australian (NA) and the NA plus Ethiopian (NA+A+B) forage NIRS calibration statistics for contents of total N, DMD, NDF and ADF .....40
Table 3.4 NIRS calibration statistics using North Australia (NA) plus ½ maize + ½ grain legume CR samples from Ethiopia for prediction of estimated DMD and N, NDF and ADF .....42
Table 3.5 Performance of NIR equations for predicting DMD (%) of maize and legume CR samples (A+B, A or B) with North Australia (NA), NA+B, NA+A and NA+A+B calibration equations .....43
Table 3.6 Performance of NIR equations for predicting total N content (%) of maize and legume CR samples (A+B, A or B) with North Australia (NA), NA+B, NA+A and NA+A+B calibration equations .....44
Table 3.7 Performance of NIR equations for predicting NDF content (%) of maize and legume CR samples (A+B, A or B) with North Australia (NA), NA+B, NA+A and NA+A+B calibration equations .....45

Table 3.8 Performance of NIR equations for predicting ADF content (%) of maize and legume CR samples (A+B, A or B) with North Australia (NA), NA+B, NA+A and NA+A+B calibration equations .....46
Table 3.9 Calibration statistics for prediction of chemical and digestibility of maize stover by NIRS in the ILRI laboratories, India .....49
Table 3.10 Calibration statistics for prediction of chemical and digestibility of sorghum and pearl millet stover and groundnut haulms by NIRS in the ILRI laboratories in India....51

Table 4.1 Planting and harvesting date, monthly and long term (1982-2014) total rainfall and average minimum-maximum temperature in 2013 and 2014 cropping seasons by site.....58
Table 4.2 Early (EM) and Medium (MM) maturing maize genotypes mean square for yield attributes across 2 years by site and pooled across years and sites by maturity group .....60
Table 4.3 Effects of year, plant density or genotype on maize yield attributes across 2 years by site and maturity group .....61
Table 4.4 Effects of year, site, plant density or genotype on maize yield attributes by maturity group .....63
Table 4.5 Early (EM) and medium (MM) maturing maize genotypes mean square for stover quality attributes across 2 years by site and pooled across sites and years.....65
Table 4.6 Effects of year, plant density or genotype on maize stover quality attributes (%) by site and maturity group .....66
Table 4.7 Effects of year, site, plant density or genotype on maize stover quality attributes (%) by maturity group .....67
Table 4.8 Effects of year, plant density or genotype on maize stover NDFD (%), DDMY (t/ha), NY (kg/ha) and PUI (%) by site and maturity group .....69
Table 4.9 Effects of year, site, plant density or genotype NDFD (%), DDMY (t/ha), NY (kg/ha) and PUI (%) by maturity group .....71

Table 5.1 Plant height and proportion (% w/w in LCS) of the HCT and HCB parts of three EM and MM maize genotypes grown at Bako and Melkassa, Ethiopia in 2013 and 2014 .....85
Table 5.2 Proportion of morphological fractions (% w/w of HCT and HCB stover components) of the three EM and MM maize genotypes grown at Bako and Melkassa, Ethiopia in 2014.....86

Table 5.3 Mean square for yield attributes of the EM and MM maize genotypes across 2 years by site and pooled across 2 sites and years .....87
Table 5.4 Yield attributes of three EM maize genotypes grown at Bako and Melkassa, Ethiopia in 2013 and 2014 .....88
Table 5.5 Yield attributes of three MM maize genotypes grown at Bako and Melkassa, Ethiopia in 2013 and 2014 .....89
Table 5.6 Mean square for DMD and total N, NDF and ADF contents of HCT, HCB and LCS of EM and MM maize genotypes across 2 years by site and pooled across 2 sites .....91
Table 5.7 Stover quality attributes (%) of HCT, HCB and LCS of three EM and MM maize genotypes grown at Bako and Melkassa , Ethiopia in 2013 and 2014 .....92
Table 5.8 Stover quality attributes (%) of HCT, HCB and LCS averaged across two years and three EM and MM maize genotypes grown at Bako and Melkassa .....94
Table 5.9 Stover quality attributes (%) of HCT, HCB and LCS averaged across three EM and MM maize genotypes grown at Bako and Melkassa in 2014 .....95

Table 6.1 Trial sites, agro-ecologies and major soil types and crops grown in each site in 2013 .....103
Table 6.2 Yield, HPW morphological fractions and HI of common bean varieties harvested at seed maturity stage at *Shalla* (Trial 1) and *Bako-Tibe* (Trial 2) in 2013 (n=3) .....106
Table 6.3 Effects of variety and site on yield, HPW morphological fractions and HI of common bean varieties harvested at seed maturity stage at *Boricha* (Trial 3)*, Mandura* (Trial 4) (n=3) and across both sites (n=6) in 2013 .....107
Table 6.4 Morphological characteristics and nutrient yields of HPW and PUI of common bean varieties harvested at seed maturity stage at *Shalla* (Trial 1) and *Bako-Tibe* (Trial 2) in 2013 (n=3) .....108
Table 6.5 Effects of variety and site on morphological characteristics and nutrient yields of HPW and PUI of common bean varieties harvested at seed maturity stage at *Boricha* (Trial 3)*, Mandura* (Trial 4) (n=3) and across both sites (n=6) in 2013 .....109
Table 6.6 Composition and DMD of pod wall, haulm (stem+ little leaf) and HPW of common bean varieties harvested at seed maturity stage at Shalla (Trial 1) and Bako-Tibe (Trial 2) in 2013 (n=3) .....112
Table 6.7 Composition and DMD of pod wall, haulm (leaf +stem) and HPW of common bean varieties harvested at seed maturity stage at *Boricha* (Trial 3)*, Mandura* (Trial 4) (n=3) and across both sites (n=6) in 2013 .....113

Table 6.8 Composition and DMD of common bean morphological fractions harvested at seed maturity stage at *Shalla* (Trial 1) *Bako-Tibe* (Trial 2), *Boricha* (Trial 3) and *Mandura* (Trial 4) in 2013 ..... 114

Table 7.1 Yield and whole haulm morphological fractions (% w/w) of common bean varieties harvested at the “early maturity” in 2013 (n=3). The results for the corresponding “final maturity” harvest are given in Chapter 6 Table 6.3 ..... 125
Table 7.2 Composition and DMD of pod wall, leaf, stem and whole plant residue of common bean varieties harvested at “early maturity” in 2013 (n=3). The corresponding results for the “final maturity” harvest are given in Chapter 6 Table 6.7 ..... 127
Table 7.3 Composition and DMD of common bean morphological fractions harvested at “early maturity” in 2013 (n=27) ..... 128
Table 7.4 Yields of haulm N and DDM of common bean varieties harvested at “early maturity” in 2013 (n=3). The corresponding results for the “final maturity” harvest are given in Chapter 6 Table 6.5 ..... 129
Table 7.5 Seed and residue yields and morphological proportions (%) of common bean residue harvested at early and final (seed) maturity crop growth stages in 2013 (n = 27) ..... 130
Table 7.6 Composition, DMD, and nutrient yields of common bean residue harvested at early and final (seed) maturity crop growth stages in 2013 (n = 27) ..... 131
Table 7.7 Pearson correlation matrix among variates between yield and quality attributes measured in common bean varieties harvested at early crop growth stage in 2013 (n=27) ..... 133

Table 8.1 Descriptions and number of HH that participated in the village level survey in 2014 ..... 142
Table 8.2 Variables and their descriptions used for the linear regression model ..... 144
Table 8.3 Socio-economic characteristics of sample households (%) in 2014 ..... 145
Table 8.4 Land holding of sample households (hectare) in the three districts in 2014 ..... 145
Table 8.5 Livestock owned (TLU[#]) by the sample households in 2014 ..... 146
Table 8.6 Farming experiences (in years) of sample households in 2014 ..... 147
Table 8.7 Proportion (%) of farmers growing cereal and grain legume crops in 2014 ..... 147
Table 8.8 Proportion (%) of farmers that have adopted improved varieties of main cereal and legume crops in 2014 ..... 148
Table 8.9 Proportion (%) of farmers that perceived CR quantity/quality is essential to accept or reject new crop varieties in 2014 ..... 149

Table 8.10 Mean and standard deviation (SD) of seed rate (kg/ha) of maize and major grain legume crops in 2014 ..... 149
Table 8.11 Sample farmers (%) opinion on factors affecting seed rate of maize and/or grain legumes in 2014 ..... 150
Table 8.12 The proportion (%) of farmers' who perceived that there are relationships between seed rate used and yield of maize and grain legumes in 2014 ..... 151
Table 8.13 Proportion (%) of sample farmers' who perceived that there are relationships between seed rate used and the yields of maize and grain legume residue produced in 2014 ..... 152
Table 8.14 The proportion (%) of farmers' who perceived that there are relationships between the seed rate used and maize and grain legume residue quality in 2014 ... 153
Table 8.15 Proportion (%) of sample farmers' practicing various pre-harvest practices in maize for fodder at early crop growth stage in 2014..... 154
Table 8.16 The proportion (%) of farmers' practiced early harvest practices in various crops for *Eshet* in 2014 ..... 155
Table 8.17 The proportion (%) of farmers' who harvested the crop timely at grain maturity in maize and grain legume crops in 2014..... 156
Table 8.18 Proportion (%) of sample farmers practicing delayed harvest after grain maturity in maize crop in 2014 ..... 156
Table 8.19 Farmers' perceptions (%) on the influence of crop maturity at harvest on CR yield and quality in 2014..... 157
Table 8.20 Farmers' perceptions (%) on the relationships between maize and grain legume maturity stage at harvest and grain yield and quality in 2014 ..... 157
Table 8.21 Farmers' perceptions (%) on the relationships between maize and grain legume maturity stage at harvest and residue yield and quality in 2014 ..... 158
Table 8.22 Proportion (%) of sample farmers' practicing cutting at different height at harvest in 2014..... 159
Table 8.23 Proportion (%) of farmers' perceived on crop residue management and use in 2014 ..... 160
Table 8.24 Farmers' perceptions (%) on various livestock issues in 2014..... 161
Table 8.25 Determinants of level of maize CR yield (tonnes/HH) - linear regression model ..... 162

**List of Abbreviations used in the thesis**

| Terms | Description |
|---|---|
| ADF | Acid detergent fibre |
| AEH | Above ear height |
| AEZ | Agro- ecological zones |
| BL | Bottom-leaf blade of the lower part of the stover |
| BS | Bottom-stem of the lower part of the stover including leaf sheath |
| CP | Crude protein |
| CPS | Centre for Plant Science |
| CQU | Central Queensland University |
| CR | Crop residue (s) |
| CSA | Central Statistical Agency |
| DDMI | Digestible DM intake |
| DDMY | Digestible DM yield |
| DE | Digestible energy |
| DM | Dry matter |
| DMD | Dry matter digestibility |
| DMI | DM intake |
| EA | East Africa |
| EH | Ear height |
| EIAR | Ethiopian Institute of Agricultural Research |
| EM | Early maturing |
| ESA | Eastern and southern Africa |
| FGD | Focus group discussions |
| GDP | Gross domestic product |
| GY | Grain yield |
| HCB | High-cut bottom part of maize stover |
| HCT | High-cut top part of maize stover |
| HH | Households |
| HI | Harvest index |
| HPW | Haulm plus pod wall |
| IVOMD | In-vitro organic matter digestibility |
| LAI | Leaf area index |
| LCS | Low-cut whole stover |
| LSR | Leaf to stem ratio |

| | |
|---|---|
| LW | Live weight |
| masl | Meters above sea level |
| ME | Metabolisable energy |
| MM | Medium maturing |
| MPLS | Modified partial least squares |
| N | Nitrogen |
| NA | North Australia |
| NDF | Neutral detergent fibre |
| NDFD | Neutral detergent fibre digestibility |
| NEL | Net energy for lactation |
| OM | Organic matter |
| OMD | Organic matter digestibility |
| OMI | Organic matter intake |
| PH | Plant height |
| PUI | Potential utility index |
| QAAFI | Queensland Alliance for Agriculture and Food Innovation |
| RDP | Rumen degradable protein |
| RUP | Rumen undegradable protein |
| SAFS | School of Agriculture and Food Science |
| SEC | Standard error of calibration |
| SECV | Standard error of cross validation |
| SIMLESA | Sustainable Intensification of Maize-Legume cropping systems for food security in Eastern and Southern Africa |
| SNNP | Southern Nations, Nationalities and Peoples |
| SNV | Standard normal variate |
| SSA | Sub-Saharan Africa |
| TBY | Total biomass yield |
| TDN | Total digestible nutrient |
| TL | Top-leaf blade of the HCT |
| TLU | Tropical livestock unit |
| TS | Top-stem of the HCT including leaf sheath and tassel |
| UIP | Undegradable intake protein |
| UQ | University of Queensland |
| VI | Voluntary intake |

# Chapter 1 Introduction

## 1.1. Importance and role of livestock production in developing countries

The majority of the world's estimated 1.3 billion poor people live in rural areas of developing countries and are at least partly dependent on livestock for their livelihoods (FAO, 2009; Thornton et al., 2003). Livestock contribute about 40 percent of the agricultural gross domestic product (GDP) globally, and about 30 percent of the agricultural GDP in the developing world (World-Bank, 2009). The contribution of livestock in developing countries is diverse (Ellis and Freeman, 2004; Herrero et al., 2010; Randolph et al., 2007). The major reasons for people to keep livestock include income, increased food crop production through livestock providing traction and manure for fertiliser, for transport, for animal products especially as high-quality food, and to store wealth (Herrero et al., 2013; Schiere et al., 2004). Livestock contribute to the livelihoods of 70% of the world's rural poor, contribute about 20% of the global trade of agricultural products (Ali, 2007), provide almost 30 percent of human food protein (Steinfeld et al., 2006), liquid assets (and thus a safety net for the poor), and a strategy of diversification of food production (Herrero et al., 2013). Hence, the livestock sector has a key role to play in both sustainability and intensification of agricultural productivity, in reducing poverty, and in contributing to economic growth (World-Bank, 2009).

The role of livestock in Ethiopia is comparable with many other developing countries. Agriculture is the mainstay of the national economy providing employment for ca. 80-85% of the rural population and who mainly depend on subsistence crop and livestock production (Farm-Africa, 2017; Tegegne et al., 2010). Livestock are estimated to contribute to the livelihoods of 60-70% of the population (Halderman, 2004). Ethiopia has an estimated (in millions) 60 cattle, 31 sheep, 30 goats, 2.2 horses, 8.4 donkeys, 0.4 million mules, 1.2 million camels and 57 poultry (CSA, 2017). Livestock account for 16-25% of the national and 40-44% of the agricultural GDP (African Business Council, 2010; Diao et al., 2007; Stapleton, 2016), and 61% of total export earnings (African Business Council, 2010).

Globally, livestock systems in developing communities are changing rapidly due to factors such as population growth and urbanisation, general economic development and consumption patterns, environment and climate change, and available technologies and

knowledge (Reddy et al., 2003; Steinfeld et al., 2006; World-Bank, 2009). Delgado et al. (1999) estimated that between 1993 and 2020, the demand for livestock products would double and meat and milk production in developing countries would grow at annual rates of 2.7 and 3.2%, respectively, much higher rates than in developed countries. Even higher rates of increase in the sector have been estimated by FAO (2012).

Table 1.1 Projected demands for livestock products in the developed and developing world

| | | Annual per capita Consumption (kg) | | Total consumption (tonnes) | |
|---|---|---|---|---|---|
| | Year | Meat | Milk | Meat | Milk |
| Developing | 2002 | 28 | 44 | 137 | 222 |
| | 2050 | 44 | 78 | 326 | 585 |
| Developed | 2002 | 78 | 202 | 102 | 265 |
| | 2050 | 94 | 216 | 126 | 295 |

*Source: (Tarawali et al., 2011).*

This growing demand for animal protein in developing countries provides opportunities for the poor in rural areas to improve economic growth, reduce poverty, and improve their livelihoods (McDermott et al., 2010; World-Bank, 2009). Furthermore, pressures of increasing population on a fixed land base are likely to promote severe competition for resources and drive agriculture progressively towards intensification (Smith et al., 1997).

### 1.2. Nutritional constraints to livestock production in developing countries

There are many constraints to increases in livestock production in smallholder mixed farming systems, including in Sub-Saharan Africa (SSA) and Ethiopia. One of the most important is in the nutrition of livestock. Concentrate feedstuffs are generally scarce and too costly to use widely in ruminant production. Ruminants are generally dependent on forages and in mixed crop-livestock farming systems the only forages available for much of the year, and particularly during the dry season, are the fibrous crop residues (CR) from food crops and a little natural pasture. The overriding constraint to ruminant livestock production is nutrition associated with shortages of feedstuffs, and generally low nutritive value and fluctuating quality and quantity of those available (Gebremedhin et al., 2009; Kaitho et al., 1998a; Murphy and Colucci, 1999). As a result livestock productivity in Ethiopia is very low (Negassa et al., 2011) and is characterised by low lactation yields, poor growth rates, extended reproduction intervals and a late onset of puberty (Assefa and Ledin, 2000; Sileshi and Bediye, 1989). For instance, the overall mean age at first service

were 48.9 and 33.3 months for local Horro breed and Horro-Jersey F1 crosses, respectively in smallholders farm in Western Ethiopia (Hundie et al., 2013) and 25.2 months for Holstein-Friesian crossbred cows in urban and peri-urban dairy farms in Northern Ethiopia (Kumar and Tkui, 2014). Age at first calving ranged from 39.8-57.1 months and 32.2-36.4 months for local and cross-bred cows, respectively (Ayenew et al., 2009; Duncan et al., 2013; Kumar and Tkui, 2014). The calving intervals ranged from 14.6-23.1 months for local cows (Ayenew et al., 2009; Desalegn, 2015; Duncan et al., 2013) and 13.9-17.2 months for cross-bred cows (Ayenew et al., 2009; Duncan et al., 2013; Kumar and Tkui, 2014; Lobago et al., 2007). The average milk yield of local and cross-bred cows in Ethiopia was 276 and 1556 litres/year, respectively (Duncan et al., 2013). Average lactation length of local cows was 11.5 months (Ayenew et al., 2009) while that of cross-bred cows ranged from 10.5-13.6 months (Ayenew et al., 2009; Lobago et al., 2007). Improving the feed supply, both in yield and quality is an effective means to increase livestock productivity (Reddy et al., 2003).

Due to increasing population pressure in many of the crop-livestock regions much of the grazing land has been, or is being, converted to crop production thus reducing the availability of forage from pasture lands (Mekasha et al., 2014). These trends are likely to increase in smallholder crop–livestock systems so that the use of CR to feed livestock will increase, particularly during the dry season (Duncan et al., 2016; Koralagama et al., 2008; Reddy et al., 2003; Suttie, 2000). Such scenarios suggest that the general shortage of feedstuffs for ruminant livestock is likely to be exacerbated (Ertiro et al., 2013a). Increased productivity of both food and livestock will generally have to come from increasing productivity per unit area (Lenné et al., 2003). This is a compelling reason for greater effective integration of crop and livestock production systems to produce more food from smaller land units (Mohamed-Saleem and Tedla, 1995). Livestock intensification strategies need to focus on improving CR production and utilization (Mohamed-Saleem, 1995; Renard, 1997).

The adoption of improved and cultivated forages has been general low particularly in smallholder systems where it is usually difficult to reallocate land from grain for forage production (Koralagama et al., 2008; Williams et al., 1997). There are also limitations such as seed availability and a lack of evidence of economic profitability (Reddy et al., 2003). One exception has been the development of Napier grass (*Pennisetum purpureum*) in smallholder dairy production systems in Kenya (Nyambati et al., 2010; Orodho, 2006). Cultivated forages contribute <1% of the total livestock feed resources in Ethiopia (CSA,

2012a, 2017). Consequently, CR will continue to contribute substantially to the feedstuff supply for livestock in smallholder farms in Ethiopia and in most tropical developing countries (Reddy et al., 2003). Between 40 and 60% of livestock diets are made up of CR in rain-fed agriculture in SSA and South Asia (Duncan et al., 2011) and provide a similar proportion in the Ethiopian highlands (Schulthess et al., 1995).

There are further considerations in the use of CR as ruminant feedstuffs. First, as by-products CR comprise one of the few feed resources that do not need additional water or land (Sharma et al., 2010). Second, because there are other potential uses for CR (e.g. as biomass for soil health and fertility for conservation agriculture, for construction and household fuel) (Duncan et al., 2011; Suttie, 2000; Tittonell et al., 2015; Valbuena et al., 2012), there often have to be trade-offs among the uses of CR. These trade-offs are likely to increase as the demands for biomass for food, feed and energy increase (Dixon et al., 2010).

CR are generally of poor nutritive value (Zerbini and Thomas, 2003). They are characterised by high fibre content (>700 g/kg of cell wall), low DM digestibility (< 50%), low metabolizable energy (ME) content (<7.5 MJ ME/kg DM), low concentrations of crude protein (CP) (<60 g CP/kg DM), low voluntary intake (VI) (e.g. 10-20 g/kg live weight (LW)) and low concentrations of essential minerals (Kabaija and Little, 1988; Tolera and Sundstøl, 2000). As sole feeds they are often too low in quality to even maintain adult ruminants, far less provide for lactation or rapid growth. Nevertheless, in many situations CR make a valuable contribution to the annual feed requirements of ruminants. Often feeding CR to animals during the dry season will provide sufficient nutrients to avoid mortality so that meat or milk can be produced when feed supply is more adequate during the wet season. In general, the availability and quality of CR for feedstuffs must be increased to sustain the such increased availability in livestock production (Delgado et al., 1999; Joshi et al., 1995), and this also offers a simple way to reduce competition for the use of CR (Blümmel et al., 2013b).

### 1.3. Options for improving yield and quality of CR

The major challenge with CR is to develop ways for increasing feeding value, particularly N content, digestibility and intake potential, in order to increase animal production in CR-based feeding systems and to increase the proportion of CR in the diet (Ertiro et al., 2013a; Wilkins, 2000). Extensive research, development and extension have been done, particularly in the tropics, to improve the nutritive value of CR as ruminant feedstuffs and

there has been a strong focus on post-harvest interventions and treatment of CR to increase their contents of ME and N and therefore intake (Jackson, 1978; Schiere and Ibrahim, 1989; Sundstol, 1985). Physical treatments have included chopping, chaffing, crushing and grinding, (McDonald et al., 2002), chemical treatments have included treatment with steam, alkali or ammonia, and biological treatments with fungi or enzymes (Jackson, 1978; McDonald et al., 2002; Sundstol, 1985). However, treatments for improvement of CR have not been widely adopted due to the constraints related to the involvement of substantial input costs and labour because the treated CR material is usually equivalent to forage of only moderate quality (Gebremedhin et al., 2007; Schiere and Nell, 1993).

### 1.3.1. Genotype choice

An alternative practical strategy for improving the quantity, and sometimes the nutritive value of CR for ruminants is through exploiting plant genetic variability and selection of more appropriate crop genotypes (Blümmel et al., 2013a; Lenné et al., 2003; Sharma et al., 2010; Wilkins, 2000) and use of dual-purpose crops for both food and livestock feedstuffs. Such dual purpose crop varieties are usually cereals or legumes that combine good food grain yields with high yield and quality of the CR as feedstuffs (De Groote et al., 2013) and are likely to be particularly appropriate for smallholder farmers. Wilkins (2000) considered that the incorporation within breeding programmes of criteria in relation to straw quality has high potential for success and should be vigorously pursued. Moreover, improved integration of food legumes into cereal-based cropping systems is a promising option for system sustainability to address the general lack of N in cereal cropping systems and in and in CR as feedstuffs. This provides opportunities to increase productivity (Lenné and Thomas, 2006) and the efficiency of utilization of CR as ruminant feed (FAO, 2012). There are obvious reasons for plant breeders, agronomists, economists and animal nutritionists to give more attention to the value of the entire crop (Schiere et al., 2004).

Maize is the most important and preferred staple cereal food of most Eastern and Southern Africa (ESA). Maize stover represents the largest share of CR biomass in this region and is widely used as a ruminant feedstuff during the dry season. However, maize CR like that of most cereals is of low nutritional quality for ruminants (Ertiro et al., 2013a); it is deficient in N and other essential nutrients, has a low ME content, and is often associated with low VI and animal performance. Despite its importance the quality of maize CR as a feedstuff has not been considered as a criterion during development of

improved genotypes or in evaluating new varieties for release (Ertiro et al., 2013a). Maize breeding programs in ESA are designed mainly to improve the yield and quality of food grain (Ertiro et al., 2013a; Tolera et al., 1999). Reasons include a lack of recognition of the importance or opportunity to improve CR as feedstuffs, and poor research linkages between crop breeders and animal nutritionists (Gebremedhin et al., 2007). De Groote et al. (2013) concluded that there is a demand for maize varieties with increased CR quantity and quality providing that grain yield and consumer qualities are not compromised. Thus the research focus in improving crop genotypes has begun to shift towards improving the productivity, including for the feedstuff quality of CR, and the genetic potential of maize as a more productive dual-purpose crop is beginning to be exploited (Blümmel et al., 2013a; Lenné and Thomas, 2006).

Common bean is the most important food legume crop in ESA and the haulm is often used as a feedstuff in smallholder crop (maize and sorghum)-livestock systems. The CR of common bean comprising stems and leaves (collectively the haulm), pod wall and sometimes roots, are often used as a feedstuff (Capper, 1990; Heuzé et al., 2013). Common bean is often grown in association with maize, sorghum and bananas (Broughton et al., 2003). During the last decade in Ethiopia production has doubled in conjunction with a 76% increase in area (CSA, 2004, 2012b). The increasing availability, as well as the higher N content and nutritive value of common bean CR makes it an important feed resource. Clearly simultaneous increases in the yield and quality of both grain and CR are highly desirable (Blümmel et al., 2013a; Erenstein et al., 2013) and large variability among genotypes indicates this should be possible. In addition to maize and common bean there also appears to be considerable potential for selecting improved genotypes of the CR of sorghum and pearl millet (Blümmel et al., 2003; Sharma et al., 2010) and legumes (Kafilzadeh and Maleki, 2012; Nigam and Blummel, 2010; Prasad et al., 2010; Singh et al., 2003) without sacrificing grain yield.

### 1.3.2. Crop management and farmer perceptions

Reddy et al. (2003) reviewed crop management interventions such as plant population on the yield and quality of various CR as feedstuffs. These authors concluded that low density planting improved fodder quality but fodder yield declined and plant density recommendations should be followed to maximise productivity. Workayehu et al. (1993) concluded that independent of agro-ecology, a population of between 4-7 plants/$m^2$ has been found to be optimum for grain yield across early, medium and late maturing maize

varieties. Since then new genotypes/hybrids have been developed and released but the recommended seed rate (25-30 kg/ha) (Negasa et al., 1993) providing maize plant populations of 4.4-5.3 plants/$m^2$ has not been revised. The greater stress tolerance of modern hybrids, especially stress from interplant competition (crowding stress) (Raymond et al., 2009; Tokatlidis and Koutroubas, 2004) suggests that further investigation is needed with modern hybrids to examine the potential of improving maize stover yield without reducing grain yield and stover quality.

The yield and quality of maize stover varies between the upper and lower portions of the plant (Hoskinson et al., 2007; Johnson et al., 2010; Lewis et al., 2004). Thus the cutting height at harvest affects both the amount and quality of stover available for livestock and stubble left in the field for other uses (Baudron et al., 2014; Dong et al., 2013; Rodriguez et al., 2017; Suttie, 2000). There have been few investigations on the differences in stover yield and feeding quality of maize genotypes cut low (ground level) or higher at harvest and the effects of early harvest on seed and haulm yields, and nutritive value of haulm morphological fractions of common bean varieties. Field observations indicate that smallholder farmers usually harvest some of the maize and common bean crop at green pod fill (immature) growth stages (i.e. Eshet or early harvest) and use this green bean for home consumption when other food sources are not ready for harvest. The green common bean fodder left after early harvest is available as a good quality feedstuff for livestock potentially to be used in conjunction with a cereal/maize stover based diet. Moreover, farmers' choice of varieties, crop-management practices, harvest procedures and their perceptions relevant to CR yield and quality usually have not been related to the recommendations and intervention strategies.

In summary, livestock are integral and important components of subsistence smallholder crop-livestock systems and greatly influence the ability of farmers to produce crops, particularly by providing draught power, cash and manure. CR will play an increasingly crucial role in livestock nutrition as crop cultivation encroaches on grazing lands due to increasing population pressure. Nutrition is one of the major constraints on improved livestock productivity. The investigation of options to improve CR yield and quality through genotype (G) of crops and management (M) (e.g. plant density and harvesting strategies) and as these interact with environment (E) (G x E x M) in maize and common bean production in smallholder farming systems is therefore important.

### 1.4. Objectives

The objectives of the present studies were: (1) to investigate the effects of maize genotypes differing in relative maturity [early maturing (EM*)* versus medium maturing (MM) groups] (G), environment (site and years) (E) and management (M) as plant density (G x E x M) on maize grain and stover yield, and stover quality attributes under a range of tropical environments; (2) to determine the effects of G and E on the yield and value as a ruminant feedstuff of the upper and lower parts of maize stover; (3) to assess the extent of genetic variation in seed and haulm yields, and haulm quality among existing popular common bean varieties harvested at seed maturity or at immature (R6-mid seed fill) crop growth stages; (4) to develop improved and robust NIRS calibration equations for analysis of CR forages in Ethiopia based on an established calibration dataset from north Australia (NA); and (5) to examine smallholder farmers' practices, perceptions and rationale on crop agronomic practices for maize and grain legume based farming in relation to CR yield and quality, the crop-livestock system, and investigate the relationships among socio-economic and crop management factors with maize grain and residue yield in smallholder maize-legume-livestock systems.

# Chapter 2 Literature review

## 2.1. Characteristics of mixed crop-livestock systems and CR in SSA

Crop-livestock systems, in which crops and livestock husbandry are integrated within the same farm management unit and resources flow between crops and livestock (Blümmel et al., 2013b; Mohamed-Saleem and Tedla, 1995) are widespread in rain-fed agriculture in Sub-Saharan Africa. These integrated systems usually make efficient use of resources such as the animal manure to fertilise crops and the CR as livestock feedstuffs (Williams et al., 2000). This latter use of CR is one of the major interactions between crop and livestock production (Erenstein and Thorpe, 2010; Moritz, 2010). A key advantage of ruminants in developing countries and in Sub-Saharan Africa crop-livestock farming systems is their ability to convert fibrous vegetation, especially grass and CR, into useful products including food and thereby utilizing resources which would otherwise be wasted (Gryseels, 1988).

## 2.2. Types of CR and by-products available for ruminants

In the present context CR are defined as the roughage that becomes available after food crops have been harvested and which is potentially available as livestock feedstuffs. Other by-products become available from processing grains and other food crops and these (e.g. brans, broken grains, oil cakes) are generally known as agro-industrial by-products. These may have a high nutritive value but often other limitations as feedstuffs. The crops whose residues and by-products are commonly used as livestock feedstuffs in smallholder systems in Ethiopia are the cereal, pulse and occasionally oilseeds presented in Table 2.1 and Figure 2.1. Cereals obviously produce large quantities of CR which usually comprise over half the crop biomass DM (Suttie, 2000).

The term stover is generally used for the residue of cereal crops with thick-stemmed residue (e.g. maize, sorghum and millet) (Schiere et al., 2004; Suttie, 2000). Maize stover comprises the stem, leaf blade, leaf sheath, husk, cobs and tassel (Schiere et al., 2004) while maize stubble describes the stumps of the reaped crop (Suttie, 2000). The term haulm (leaf, stem and pod wall) describes the residues of legume or pulse crops. The term straw is generally used for the residue from the slender-stemmed small cereals grain crops [e.g. wheat, barley, teff (*Eragrostis tef*) and rice]. The proportion of various CR produced

in Ethiopia is shown in Figure 2.1. The cereal CR contributed 87% and pulses 6% of total CR produced (CSA, 2004, 2012b). Maize is the most important CR (Table 2.1).

Table 2.1 The total area and production of grain and CR for private land holdings, 2003 and 2011 main cropping seasons in Ethiopia

| Crop category | Area coverage % | | Contribution to grain production, % | | Contribution to total CR availability,% | |
|---|---|---|---|---|---|---|
| Grain crops | 2003 | 2011 | 2003 | 2011 | 2003 | 2011 |
| Cereals | 81.0 | 79.0 | 87.0 | 86.0 | 87.0 | 87.0 |
| Pulses | 12.0 | 14.0 | 10.0 | 11.0 | 6.0 | 6.0 |
| Oil seeds | 7.0 | 7.0 | 3.0 | 3.0 | 7.0 | 7.0 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 |
| Maize contributions from cereal crops | 16.0 | 17.0 | 24.6 | 27.8 | 28.4 | 31.5 |

*Source: Calculation using CSA agricultural Sample Survey data (CSA, 2004, 2012b).*

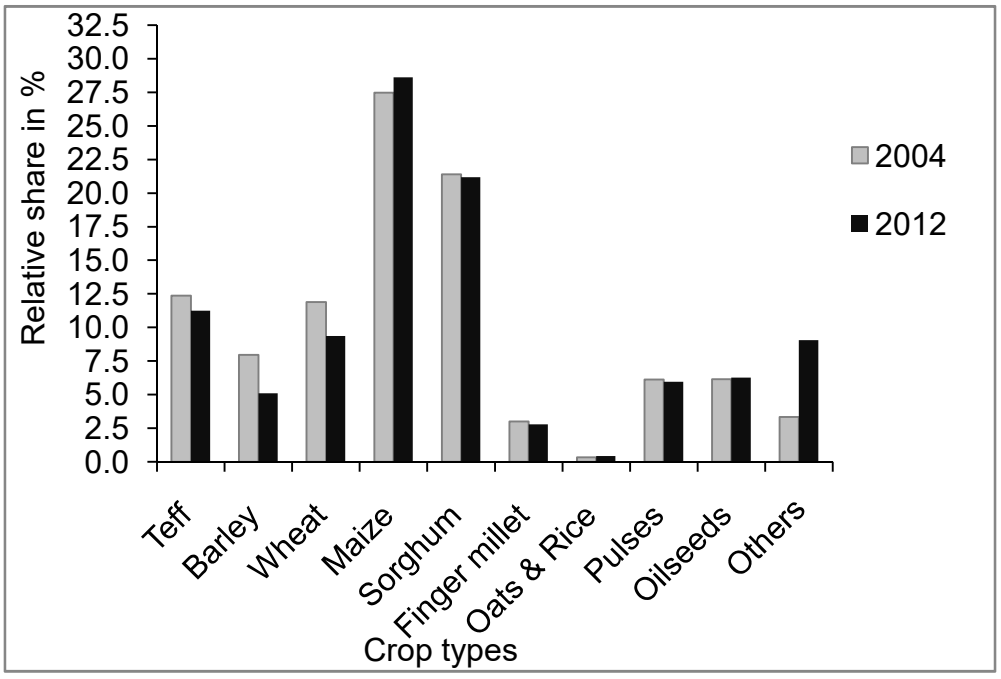


Figure 2.1 Crop type and the relative contribution of the total CR produced in 2003 and 2011 cropping season in Ethiopia (CSA, 2004, 2012b).

### 2.2.1. Maize and legume crop residues

Maize (*Zea mays* L.) is the most important global cereal crop reflecting its capacity to be grown and to provide high grain yields across a wide range of cereal cropping environments in the sub-tropics and tropics, and also its versatility as human food, animal feed and fodder, industrial products and bio-fuel (Blümmel et al., 2013a). It is

the most important food crop in ESA (23% and 34% of cropland, respectively) (FAOSTAT, 2012). In Ethiopia, maize ranks second to teff in area but first in production. Maize is increasingly grown in the Highlands of Ethiopia (Abakemal et al., 2013) and its CR as a ruminant feedstuff is the most available (Figure 2.1).

Grain legumes have long been an important food crop in ESA as an important source of protein and often have a high market price. Grain legume CR (leaves, stems and empty pods/pod wall are collectively described as haulms or vines) are often good quality forage sources that are locally available. At similar stages of plant growth legume forages usually contain more N and are more digestible and higher in ME content than grasses (Norton, 1982). This is also true for the CR from legume (haulm) or cereal crops (stover or straw) harvested as is most usual following seed maturity (Devendra and Sevilla, 2002). When legume CR are fed as a supplement for cereal CR it is expected that intake of ME will be increased due simply to the generally higher N and ME contents of the legume CR, but there is also some evidence that legume forage has an additional effect to stimulate fibre digestion in the rumen and thus increase ME intake (McMeniman et al., 1988). Since the production of grain legumes crops is minor compared with the cereal crops, the amount of legume CR available will usually be much less than of cereal CR (Figure 2.1). Nevertheless, legume CR may represent an important ruminant feedstuff resource by providing N for N-deficient cereal straw, and due to any positive effects on utilization of the fibrous components of cereal CR like maize stover (Koralagama et al., 2008), rice straw (McMeniman et al., 1988) and poor quality natural pasture hay (Manyuchi et al., 1997). Hence legume CR represent feed resources in crop-livestock mixed systems which are potentially more important than indicated solely by their relatively low importance as cropped area.

### 2.3. Variation in yield and nutritive value of cereal and legume CR

The proportion of grain to total biomass at harvest (harvest index (HI)) is an important criterion in plant selection where the principal objective is usually to achieve high grain production. Breeding and agronomic advances, including higher fertilizer and water inputs in many crops (e.g. wheat, barley and rice) have generally increased grain yield, total above ground biomass and HI (ILCA, 1987; Joshi et al., 1995). However, there are some improved varieties of crops with higher total biomass but a decrease in straw yield per hectare (e.g. dwarf, bird-resistant varieties of sorghum in Ethiopia and some finger millet

varieties in India). It is to be expected that G x E x M interactions will modify the yields of grain and CR and the characteristics of the CR for any specific circumstance.

### 2.3.1. Variation in composition and digestibility

Many studies have reported the nutritive value of the straws of cereal (Table 2.2) and legume crops (Table 2.3) and examined differences among and within species. A useful categorization is to divide cereal crop species into the coarse-stemmed and fine-stemmed cereals, and to consider legume crops separately. The coarse-stemmed CR (finger millet, sorghum, pearl millet and maize) generally differ from fine-stemmed CR from the 'small' cereals (wheat, barley, rice and oats straws) in having a higher leaf-stem ratio (LSR), higher contents of N and cell solubles, and higher DM intake and nutrient digestibility (Reddy et al., 2003). Thus, the coarse-stemmed CR should be generally of higher nutritive for ruminants. However the thick stems remaining after ruminants have selectively ingested the leaf may be unpalatable when dry, particularly to small ruminants. As a consequence the overall nutritive value of the coarse-stemmed CR may be very low in some circumstances. Among the small cereals, oat straw is generally considered to have the highest nutritive value, followed by barley, wheat, and rye straw, and with rice straw having the lowest value (Dias-da-Silva and Guedes, 1990; Mosi and Butterworth, 1985). Teff straw is considered as a nutritious fodder comparable to good natural pasture in Ethiopia and much preferred by farmers to the straw of other cereals, particularly during the dry season (Gebrehiwot and Mohammed, 1989). The nutritive value of CR can vary widely among cereal and legume species (Tables 2.2 and 2.3) and is influenced by factors such as genotype and environment (Erickson et al., 1982; Karlen and Camp, 1985; López et al., 2005; White et al., 1981) crop management and agronomic practices. The variation in nutritive value among batches of CR of a specific crop species is sometimes higher than among species or genotypes (Dias-da-Silva and Guedes, 1990). López et al. (2005) reported large variability among cereal and legume species and that legume straw had better nutritional quality than cereal straws.

As digestibility of DM or organic matter (OM) is closely related to the ME content it provides an estimate of the energy in the forage available to the animal. Digestibility is often correlated with VI of the diet and digestibility is often used in feeding standards as a proxy to estimate intake of ME (ARC, 1980; CSIRO, 2007). However, and especially with CR, VI may be constrained by other factors such as the palatability or acceptability of the forage to the animal and VI may be low due to forage characteristics other than digestibility

(Romney and Gill, 2000). A further consideration is that the efficiency with which ME is used by the ruminant for production as growth may vary although feeding standards simply assume that it is in general proportional to diet digestibility and thus usually low for many CR diets.

An important factor influencing the value of CR as ruminant feedstuffs is the proportion of the various botanical fractions, and most importantly the LSR. Animals tend to select the more nutritious parts of plants and usually reject more mature, coarser and more fibrous material (Van Soest, 1994). In both grasses and legumes the leaf blade is usually higher in N and other essential nutrients, much more digestible, and lower in fibre (Minson, 1990; Norton, 1982). Thus, an important determinant of composition and digestibility of straw in many crop species is the LSR not only because of the generally higher nutritive value in leaves, but because leaves are usually more acceptable to ruminants and eaten in larger quantity because they are easier to chew as well as being more digestible (Powell, 1984). Furthermore the importance of physical breakdown by chewing and rumination in constraining the VI of low quality forages is well known (Allen, 1996; Minson, 1990; Weston, 2002). The importance of LSR of the forage available has been shown in numerous pen-feeding experiments where offering cereal straw diets in excess of daily intake (e.g. up to 3 times the previous VI) has led to large increases in VI (Heaney, 1973; Osafo, 1993; Zemmelink and ’t Mannetje, 2002) due to the animals being able to select a diet high in leaf blade. There are, however, interactions between the proportion of leaf in the diet and the responses to supply of nutrients. Rafiq et al. (2002) demonstrated that in sheep fed diets of leaf-rich or stem-rich barley straw the voluntary intakes were similar when rumen degradable N was deficient, but intake of the leaf-rich straw was much higher than of stem-rich straw when the supply of rumen degradable N was adequate. VI was also influenced by interactions associated with supplements containing fermentable ME as cereal grain or additional metabolisable protein in a protein meal.

The LSR, and the digestibility of leaf and stem fractions, have been reported to vary both between and within cereal species. Leaf blade content in CR can be expected to vary markedly depending on the agronomic circumstances affecting the leaf proportion of the plant at harvest, the part of the plant harvested, and the loss of leaf during handling. Genotype within plant species is also important. For instance (Capper, 1988) reported that there were higher proportions of leaf blade in straws of dwarf varieties of barley and wheat than in taller varieties. In barley and wheat leaf blade is more digestible than leaf sheath

and stem and thus straw from shorter varieties is more digestible. In this instance selection for high grain yield may have improved straw quality. However the converse occurs in rice straw with the highest digestibility in stem followed by leaf blade and leaf sheath (Capper, 1988; Dong et al., 2013). This inverse relationship in rice may be because the leaf of rice may contain high concentrations of silica which reduces digestibility (Doyle et al., 1986). Preston and Leng (1987) have also summarized reports that straws from various species of grain crops appear to be highly variable in digestibility. For instance, Dolstra et al. (1992) reported that forage maize is a highly heterogeneous product when all above ground parts of the plants are harvested. Its quality is closely related to the composition and physiological status of plants at harvest, which in turn depend on the growing conditions, i.e. weather, soil and cultural practices, age, developmental stage and hybrid choice. The effect of differences between hybrids on the nutritive value of the crop could be large. Seasonal, cultural and environmental variations greatly influence the digestibility of forage maize (Dolstra et al., 1992).

Table 2.2 Composition and digestibility of common cereal crop residues and natural pasture hay*, % DM

| Cereal CR/Hay | DM | OM | CP | NDF | ADF | ADL | IVDMD | IVOMD | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Maize stover | 89.8-94.5 | 90.7-93.3 | 1.6-6.1 | 65.5-86.7 | 32.3-52.3 | 3.0-9.4 | 39.9-53.1 | 41.3-66.9 | 1,2,3,4,5,6,7,8,9,34,35,36,37 |
| Sorghum stover | 90.7-92.6 | 84.2-93.2 | 2.4-5.3 | 57.0-76.0 | 31.6-53.0 | 4.3-8.4 | 53.0-64.0 | 39.2-66.6 | 10, 11,12,13, 39 |
| Wheat straw | 92.2-95.0 | 73.7-94.6 | 1.1-5.2 | 71.0-80.2 | 44.3-59.0 | 5.2-10.2 | 44.0 | 42.2-77.0 | 2,13,14,15,16,17,35,39 |
| Barley Straw | 94.0 | 91.8-93.8 | 2.6-8.0 | 71.6-75.1 | 42.3-49.5 | 9.8 | 57.5 | 40.2-58.1 | 2,16,18,35,39 |
| Teff straw | 90.2-95.1 | 78.4-92.1 | 2.6-7.5 | 64.8-81.7 | 24.4-47.8 | 3.9-8.8 | | 40.9-61.3 | 2,14,19,20,21,22,39 23,24,25,26,27,28, 34 |
| Oat straw | 91.4-93.0 | 90.9 | 4.4-8.3 | 67.0-73.7 | 40.8-53.1 | 5.9-10.5 | 58.2 | 43-62 | 2,29,30,31, 41, 42 |
| Native Hay | 89.5 – 95.2 | 89.1-93.8 | 2.0 – 10.0 | 52.1 – 79.4 | 28.4 – 50.4 | 8.3 | | 42.8-78.5 | 2, 40 |

1. *Geleti (2005b); 2. Bediye and Sileshi (1989); 3. Hindrichsen et al. (2002); 4. Osuji et al. (1993); 5. Tolera et al. (1999); 6. Koralagama (2004); 7. Geleti (2005a); 8. Geleti (2005c); 9. Tolera and Sundstøl (1999); 10. Osafo (1993); 11. Mohammed (2005); 12. Walelign (1995); 13. Sileshi et al. (1996); 14. Menbere (2005); 15. Mengistu (2001); 16. Bogale et al. (2008); 17. Schulthess et al. (1995); 18. Bediye et al. (1998); 19. Tolla et al. (2002); 20. Bonsi and Osuji (1997); 21. Ebro et al. (1995); 22. Kaitho et al. (1998b); 23. Sisay et al. (2006); 24. Melaku et al. (2003); 25. Bediye et al. (1996); 26. Crosse et al. (1998); 27. Bonsi et al. (1995); 28. Kebede (2006); 29. Bekele and Yilma (2004); 30. Umunna et al. (1995); 31. Butterworth and Mosi (1986); 32. Eshete (2002); 33. Ebro et al. (2005); 34. Aredo and Musimba (2003b); 35. López et al. (2005); 36. Ertiro et al. (2013a); 37. Ravi et al. (2013); 38. Gebremeskel et al. (2011); 39. Fekadu et al. (2010b); 40. Fekadu et al. (2010a); 41. Feyissa et al. (2007); 42. Negash et al. (2017) *Natural (native) pasture hay composed of mainly grasses species (Chloris, Cenchrus, Hyparrhenia, Setaria, Paspalum, Cynodon, Pennisetum, Panicum, Eleusine, Eragrostis, Cymbopogon, Andropogon and Festuca) and legume species (Neonotonia wightii, Indigofera spp., Crotolaria sp., Desmodium sp., Rhynchosia sp., Vigna sp. and Trifolium sp.) (Mengistu, 1985).*

Table 2.3 Composition and in-vitro digestibility of common legume crop residues

| Legume Residues | DM | OM | CP | NDF | ADF | ADL | IVD/OMD | Reference* |
|---|---|---|---|---|---|---|---|---|
| Faba bean straw | 92.3-94.4 | 89.7 | 5.4-8.8 | 35.7-79.3 | 32.2-68.1 | 5.9-18.6 | 58.8 | 2,16, 38 |
| Chick Pea straw | 91.5-94.0 | 76.3-92.0 | 4.1-5.2 | 44.8-66.9 | 31.2-47.7 | 8.2-13.9 | 50.1-62.7 | 2,14,32,35 |
| Soybean straw | 90.9-93.4 | | 4.3-6.2 | 62.1-68.5 | 50.2-55.5 | 10.9-13.2 | | 2 |
| Haricot bean straw | 92.0-94.4 | 91.5-92.7 | 4.4-5.4 | 69.2 | 56.5 | 8.3 | | 33,34 |
| Field pea straw | 91.9-94.4 | 89.7-93.2 | 6.0-7.9 | 54.8-73.0 | 38.4-57.3 | 16.4 | 54.4 | 2,16,35 |
| Cow pea straw | 88.5 – 95.9 | 80.6-90.5 | 7.5 – 28.3 | 32.0 – 52.5 | 17.8 – 23.5 | Lignin (3.0 – 4.0) | 60.6 – 60.7 | 39 |
| Lentil straw | 86.2 – 98.5 | 86.4-97.1 | 5.1 – 11.0 | 35.5 – 79.6 | 12.5 – 68.6 | Lignin (4.4 – 12.6) | 39.2 – 70.2 | 39 |

**The references are the same as Table 2.2.*

*Source: Ethiopian feed composition Database. http://192.156.137.110/ethfeedlit/Feedtwo.asp?FTID=4 Accessed on Feb 20, 2014*

### 2.3.1.1. Effect of genotypes on variation in composition and digestibility

There is extensive evidence that maize, chickpea and faba bean CR composition and digestibility vary among genotypes within species (Table 2.4). In addition sorghum genotypes varied in CR quality attributes (Blümmel et al., 2013b; ILCA, 1987; Osafo, 1993; Reed et al., 1988a).

Table 2.4 Composition and in-vitro digestibility of maize and legume genotypes CR

| Crop residues | Number of Genotype | Attribute (%) | Mean (%) | Range (%) | P | Reference |
|---|---|---|---|---|---|---|
| Maize stover | 8 | CP | 4.8 | 2.8-6.1 | P<0.05 | (Tolera et al., 1999) |
| | | NDF | 77.0 | 73.1-83.7 | P<0.05 | |
| | | ADF | 49.5 | 45.4-52.3 | P<0.05 | |
| | | DMD | 48.9 | 42.8-51.2 | P<0.05 | |
| Maize stover | 15 | CP | 4.8 | 3.8-5.7 | NS | (Mengistu, 2010) |
| | | NDF | 79.5 | 69.2-83.1 | NS | |
| | | ADF | 47.2 | 38.2-52.8 | P<0.05 | |
| | | IVOMD | 58.7 | 53.3-67.2 | P<0.05 | |
| Maize stover | 3 | CP | 2.8 | 2.7-2.8 | NS | (Geleti et al., 2011) |
| | | NDF | 79.3 | 74.1-86.7 | P<0.01 | |
| | | ADF | 45.5 | 44.2-46.4 | P<0.05 | |
| | | DMD | 46.3 | 40.2-53.9 | P<0.01 | |
| Maize stover | 12-36 | CP | - | 1.6-5.5 | P<0.01 | (Ertiro et al., 2013a) |
| | | ADF | - | 44.1-48.7 | P<0.01 | |
| | | TIVOMD | - | 62.8-66.9 | P<0.05 | |
| Maize stover | 60 | CP | 7.5 | 4.9-10.3 | - | (Zaidi et al., 2013) |
| | | NDF | 73.1 | 65.3-80.3 | - | |
| | | ADF | 35.4 | 31.3-39.2 | - | |
| | | IVOMD | 52.3 | 44.4-58.2 | - | |
| Maize stover | 6 | CP | 5.6 | 5.3-6.0 | P<0.01 | (Anandan et al., 2013) |
| | | NDF | 76.7 | 73.4-81.5 | P<0.0001 | |
| | | ADF | 40.3 | 38.0-43.7 | P<0.0001 | |
| | | IVOMD | 54.8 | 53.4-56.9 | P<0.0001 | |
| Chickpea haulm | 4 Kabuli | CP | 3.2 | 2.8-3.6 | NS | (Kafilzadeh and Maleki, 2012) |
| | | NDF | 61.6 | 59.9-64.5 | P<0.001 | |
| | | ADF | 46.7 | 45.9-47.3 | NS | |
| | | IVDMD | 51.1 | 48.9-53.4 | P=0.07 | |
| | | IVOMD | 49.7 | 47.1-53.6 | P<0.01 | |
| Chickpea haulm | 17 kabuli | CP | 6.5 | 4.7-8.4 | P<0.05 | (Alemu, 2016) |
| | | NDF | 52.1 | 45.3-56.2 | P<0.05 | |
| | | ADF | 38.9 | 33.7-41.8 | P<0.05 | |
| | | TIVOMD | 54.5 | 52.1-58.7 | P<0.05 | |
| Chickpea haulm | 17 Desi | CP | 4.2 | 3.3-5.2 | P<0.05 | (Alemu, 2016) |
| | | NDF | 58.3 | 56.4-60.3 | P<0.05 | |
| | | ADF | 42.7 | 41.1-44.7 | P<0.05 | |
| | | TIVOMD | 51.5 | 49.5-53.1 | P<0.05 | |
| Faba bean haulm | 5 | NDF | 35.6 | 33.1-40.9 | P<0.001 | (Gebremeskel et al., 2011) |
| | | ADF | 32.2 | 30.4-36.6 | P<0.001 | |
| | | DMD | 60.5 | 53.9-65.6 | P<0.001 | |

*P: Probability for genotype differences; CP: Crude protein; N: Nitrogen; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; DMD; Dry matter digestibility: IVOMD: In-vitro organic matter digestibility; TIVOMD: True in-vitro OMD; NS: Not significant (P>0.05).*

In high grain yielding (>6 t/ha) rainy-season sorghum genotypes, the stover CP content has been reported to vary from 3.5 to 9.0% and IVOMD from 40 to 50% (Blümmel et al., 2013b). A number of authors have also observed substantial differences in the chemical composition and digestibility among varieties of fine-stemmed cereals. These include among cultivars and varieties of wheat straw (Dias-da-Silva and Guedes, 1990; Habib et al., 1995; Schulthess et al., 1995; Tolera et al., 2008), barley straw (Erickson et al., 1982; Herbert et al., 1994; White et al., 1981) and rice straw (Capper, 1988; Flachowsky et al., 1991; Pearce et al., 1988).

In legumes, the variation in chemical composition and digestibility of haulms among various groundnut, lentil and cowpea genotypes has also been reported (Erskine et al., 1990; Grings et al., 2012; Larbi et al., 1999; Omokanye et al., 2001). As observed by Nigam and Blummel (2010), who investigated a wide range of groundnut cultivars (*Arachis hypogaea*) and breeding lines (n=860), haulm N content varied almost two-fold (mean=1.7, range 1.2-2.3%), and IVOMD varied ($P<0.0001$) by almost 10% units (mean 56.3%; range 51.7-61.1%). Lentil haulm DMD varied from 40-49% and CP content from 5.8-6.9% between cultivars (Erskine et al., 1990).

In summary, there is large variation among CR of cereal and legume genotypes in chemical composition and digestibility. This has a great potential for exploitation. These wide variations can be attributed to the inherent variation among the species, cultivars and varieties within the species, the location and climatic condition of the growing area, crop management/agronomic practices, harvesting stages, cutting height at harvest, and post-harvest management and storage practices. In the majority of the reports the descriptions of the origin and history of CR samples are inadequate to identify the reasons for this variability. It is generally not known how much of the variation is due to inherent characteristics of the plant material and how much is due to differences in the proportions of morphological fractions (leaves, stems, husks) arising from different growing conditions, harvesting procedures (such as the height of cutting, threshing) and storage methods and duration. Considerable caution needs to be exercised therefore when using mean values from literature to formulate diets or predict animal performance.

#### 2.3.1.2. Anatomy of plants and cell wall characteristics in relation to digestibility

As discussed above, the nutritive value of leaf, particularly leaf blade, is generally much higher than of stem. The digestibility and concentrations of nutrients (N and essential

minerals), and ME contents (Rattunde et al., 2001) and VI are usually higher, and resistance to physical breakdown during chewing and rumination is much lower than for stem (Osafo et al., 1997; Wilson and Kennedy, 1996). The higher VI of the leaf fraction of Pangola grass (*Digitaria decunzbens*) and Rhodes grass (*Chloris gayana*) in sheep and cattle was associated with a shorter retention time of DM and NDF in the rumen (Poppi et al., 1981). Lundvall et al. (1994) also observed the occurrence of substantial variation among maize inbred lines for IVDDM and cell-wall components and the variation was greatest in late-harvest stems and least in leaf blades. Hansey et al. (2010) reported that stem was the largest fraction of whole maize plant DM (46%) and had the lowest neutral detergent fibre digestibility (NDFD) (375 g/kg) at physiological maturity.

There are also differences within stems of forage grasses as the digestibility of the stem tissue decreases from the top to the bottom of the stems of the plant. During plant growth the internode located at the base of the stem completes its development first (the 'oldest' internode), followed by progressively younger internodes from the bottom to the top of the plant. As a consequence there is a gradient of physiological cell wall age from the base to the top of the stem. However, a further complexity is that within an internode of maize the younger portion is at the bottom of the internode while the older portion is at the top (Lam et al., 2013). Grass stems have a meristematic zone at the base of each internode, and cell development is basipetal with the oldest cells at the top of an internode (Lam et al., 2013; Scobbie et al., 1993; Wilson and Hatfield, 1997). This is in contrast to legume stems. In maize, several investigations (Boon et al., 2005; Boon et al., 2012; Boon et al., 2008; Méchin et al., 2005) of internode quality have reported that differences in the percentage of lignified area in the internodes between the plants was associated with differences in the extent of in-vitro DMD.

Among the histological attributes the bottom of the stem plant shows more genetic variation than the top of the stem, probably because the tops of stems of plant have a common structure of young tissues with elongation and little lignification (Julier et al., 2001). Maize stem is made up of vascular bundles, sclerenchyma, epidermis, chlorenchyma and parenchyma (Boon et al., 2005). The differences in digestibility of various fractions of maize stover are caused by differences in the proportions and digestibility of these various tissues (Cone and Engels, 1990; Deinum and Struik, 1989). These tissues are digested to varying extents in the rumen. Degradation of chlorenchyma and parenchyma is almost complete after 24 hours of fermentation, whereas breakdown of

vascular bundles, sclerenchyma and epidermis is far from complete even after 96 hours (Engels and Schuurmans, 1992). Resistance to digestion increases in the following order: mesophyll and phloem < epidermis and parenchyma sheath < sclerenchyma < lignified vascular tissue and the proportion of these tissues varies among species, plant parts, and stage of growth and is affected by management factors (Minson, 1990). Cell types with thickened secondary walls, such as in the vascular bundles, sclerenchyma strands, epidermis and parenchyma bundle sheath of $C_4$ tropical grass leaves are the main contributors to poor quality (Wilson, 1994). A major difference between grasses and legumes is that whilst legumes often contain a higher content of lignin than grasses, only the xylem vascular tissues are lignified. In grasses, lignin is distributed throughout the plant tissue, and located in the walls of many different cell types (Wilson, 1993). Wilson and Kennedy (1996) suggested that the lower digestibility of tropical grasses compared with temperate grasses and legumes reflect an interlocking and therefore more rigid cell structure. These authors also suggested that the greater digestibility of legumes compared with grasses may reflect leaf length. As vascular bundles and sclerenchyma make up about 80% of the weight of the maize stem (Engels and Schuurmans, 1992), whole plant digestibility can be considerably improved by improving the digestibility of these tissues. Most of the large vascular bundles and sclerenchyma can be found in the rind, i.e. the outer layer of the stem. The inner part, commonly referred to as pith, consists mainly of parenchyma with small vascular bundles (Boon et al., 2005).

### 2.4. Variation in VI and factors affecting the utilization of poor- quality forages by ruminants

Variation in VI of forages is the major dietary factor determining level and efficiency of ruminant production and performance (Allison, 1985) As discussed in many reviews (CSIRO, 2007; Norton, 1982; Pearce et al., 1988) the VI and digestibility of CR by ruminants are influenced by many factors including straw characteristics (including chemical composition, morphological and anatomical features, physical nature and palatability), by feeding practices (including the amount offered, frequency of feeding. and the interactions between feeds or between one or more feeds), and by animal characteristics (including species/genotype, LW, age, body condition, type and level of production, physiological state such as lactation, compensatory growth effects and disease). Also, extremes of temperature and humidity, and social interactions between animals, may affect intake.

Conrad et al. (1964) suggested that intake was restricted by gut fill up to a breakpoint in digestibility, beyond which the relationship between intake and digestibility became negative and controlled by the animal's requirements. The concept that animals try to meet their energy requirement by eating an appropriate amount of food is central to theories of the control of food intake (Forbes, 2007). However, where low-quality forages (e.g. stovers or straws tend to have a high fibre and low N content, which may limit the rate of fibre digestion) form the major proportion of the diet particularly during the dry season in the tropics, intake is constrained by the rate at which the fibre is digested and passes through the gastrointestinal tract (Romney and Gill, 2000). Physical fill limitations (physical factors limit reduction in particle size) and physical characteristics of the cell wall or fibre particles themselves affect the rate at which particles are broken down and the ease of passage (Wilson and Kennedy, 1996). With unchopped forages it is likely that intake is constrained by the capacity of the digestive tract and the dynamics of breakdown and passage of food particles (Forbes, 2007).

As discussed above, forage digestibility is largely determined by features of the plant, but potential digestibility, and hence potential intake, may not be achieved, due to interactions between feeds or between one or more feeds and the animal itself (Romney and Gill, 2000). Supplementation tends to have a positive effect on overall DMI, but may have positive or negative (substitution) effects on intake of the basal forage. Minson (1990) suggested that, for feeds with a crude protein (CP) content of less than 62 g CP/kg DM, fibre digestion is inhibited by deficiency of N substrates for rumen microorganisms and in many trials intake of forages have increased by 14–77% following provision of supplementary non-protein N or protein or protein. Leng (1990) noted that farmers in developing countries recognize the benefit of adding small amounts of green forage to poor-quality roughage diets and supplementation of a CR-based diet with forage of high digestibility boosts digestibility of the basal feed, even when levels of supplementation are low. He suggested that this may be through provision of a highly colonized fibre source to seed bacteria on to the less digestible fibre or through increasing rumen ammonia concentrations above a critical level.

One simple physical method to increase VI is to increase the amount of forage on offer, to allow the animal to select the more palatable or nutritious parts, thereby increasing the quality of the diet consumed as well as intake (Fernandez-Rivera et al., 1994). Other physical methods are chopping or grinding (Minson, 1990). Chopping sorghum stover

resulted positive effects on VI in sheep, but not in cattle (Osafo et al., 1997). Chemical treatment with acid or alkali to break down fibres, with a view to increasing digestibility and therefore intake, has been reported (Schiere and Nell, 1993; Schiere and Ibrahim, 1989). However, as discussed above these chemical treatments are rarely practical and cost-effective in the context of developing countries.

Although there is a vast literature reporting experiments where ruminants have been fed diets which have included some CR material (Table 2.5), this information is of limited relevance to improving ruminant nutrition in smallholder farms in SSA where animals have to depend on diets containing little or no concentrate or protein meal feed. Although supplementary N can be supplied as rumen degradable nitrogen in the form of urea (Rafiq et al., 2002) there are serious difficulties to be able to do as without risk of animal mortality from excess ingestion of urea under smallholder farmers conditions. The present discussion will therefore focus on the information available where CR have comprised most or all of the diet. Furthermore in the absence of satisfactory animal production experiments conclusions will often have to be drawn from the indirect measurements such as forage digestibility and VI as a function of both the intake potential of the feed and the nutrient demand. Digestibility is often used as a proxy for nutritive value, but as discussed above may not be well correlated with VI in animals fed many CR diets. The combination of digestibility with intake [Digestible DM intake (DDMI)] is a reasonable determinant of ME intake and thus of feed quality, and is well accepted as an indicator of animal production (Coleman and Moore, 2003). DDMI of tropical grasses (Milford and Minson, 1965) is usually better correlated with animal gain than are digestibility or VI alone (Lippke, 1980). Variation in VI is likely to play a greater role than digestibility in influencing the feeding value of CR (Jewell and Campling, 1986). However, complex interactions of feed, animal, and the environment of the animal can cause great variation in intake, and this variation causes difficulty in understanding and predicting forage intake by ruminants fed CR diets.

In general, cereal CR are lower in total N, rumen degradable N and phosphorus, marginal in calcium and higher in fibre and lignin than legume CR (McMeniman et al., 1988) and the rates of rumen digestion, rate of passage and VI are all low (Wilson and Kennedy, 1996). Animals fed cereal CR alone usually lose LW (Ebro et al., 2004; Tolera and Sundstøl, 2000). A review of some published studies in which CR were fed as the sole diet (Table 2.5) supports this conclusion. Diets of maize stover alone are usually inadequate to support the maintenance requirements of ruminants with low VI and negative N balance.

Table 2.5 Nutrient intake, N retention and LW change of ruminants fed exclusively CR diets

| Crop residues | Variable | Mean | Species | Reference |
|---|---|---|---|---|
| Maize stover | DMI, %LW | 1.9 | Sheep for | (Tolera and Sundstøl, 2000) |
| | DOMI. g/h/d | 130 | 63 days | |
| | CPI, g/h/d | 12.1 | | |
| | MEI,MJ/h/d | 1.9 | | |
| | LWG, g/h/d | -42 | | |
| Maize stover | DMI, %LW | 1.9 | Sheep for | (Koralagama et al., 2008) |
| | NI, g/h/d | 2.3 | 92 days | |
| | NR, g/h/d | -0.3 | | |
| | CWC, g/h/d | -26.1 | | |
| Maize stover + | DMI, %LW | 2.8 | Sheep for | (Koralagama et al., 2008) |
| Cowpea haulm (150g/h/d) | NI, g/h/d | 6.8 | 92 days | |
| | N retention, g/d | 1.7 | | |
| | CWC, g/h/d | 4.2 | | |
| Teff straw[a] | DMI, kg/h/d | 3.19 | Cross-bred calves for 111days | (Ebro et al., 2004) |
| | OMI, kg/h/d | 2.89 | | |
| | NI, g/h/d | 14.2 | | |
| | LWG, g/h/d | -75.8 | | |
| Maize stover | DMI, %LW | 1.4 | Borana | (Aredo and Musimba, 2003b) |
| | CPI, g/h/d | 100 | Bulls | |
| Common bean haulm | DMI, %LW | 1.8 | | |
| | CPI, g/h/d | 193 | | |
| Common bean haulm | DMD, % | 55.0 | Arsi bulls and heifers | (Ebro et al., 2005) |
| | ND, % | 25.4 | | |
| | DMI, kg/day | 2.6 | | |
| | LWG, g/day | 47.0 | | |
| Chickpea haulm | DMI*&LWG* | 3.6 &18 | Sheep for | (Yeheyis et al., 2005) |
| Lentil haulm | DMI*&LWG* | 3.7& 63 | 116 days | |
| Grass pea haulm [b] | DMI*&LWG* | 3.5& 27 | | |

*DMI: Dry-matter intake (% of live weight or kg/head/day); DOMI: Digestible organic matter intake (g/head/day), CPI: Crude protein intake (g/head/day), MEI: Metabolizable energy intake (MJ/head/day) LWG: Live weight gain (g/head/day); NI: Nitrogen intake; ND: Nitrogen digestibility (g/head/day); NR: Nitrogen retention, CWC: Carcass weight change (g/head/day), [a]Eragrostis tef; [b]Lathyrus sativus; *DMI in % of live weight.*

However, supplementation of maize stover with a small amount of legume CR (150 g DM/head/d) of dual-purpose cowpea (*Vigna unguiculata*) haulms can substantially improve the VI, N balance and carcass weight of sheep (Koralagama et al., 2008) (Table 2.5). Several experiments have confirmed that legume haulm diets are generally of better

nutritive value than cereal CR (Table 2.5). No comprehensive databases exist for VI of forages and fodder crops fed as the sole source of the diet, and for which complete chemical characterization has also been conducted (Coleman and Moore, 2003).

### 2.4.1. Effect of plant genotype on variation in VI, digestibility, N balance and live weight change

Genotype within crop species is another source of variation in VI, digestibility, N-balance and LW change in ruminants (Table 2.6). Within experiments with barley straws DOMI (as g/kgLW$^{0.75}$/d) was often ca. 9% higher for the 'best' barley genotype than for the "worst' genotype, and LW change often ranged from LW loss to modest LW gain e.g. (Capper et al., 1989) (Table 2.6). Thus it has been shown that livestock productivity can be influenced substantially by variation among genotypes of the same species of cereal and grain legume CR.

Table 2.6 Effect of genotypes on VI, digestibility, N-balance and LW change of ruminants

| Crop residues | G | Variable | Mean | Range | Species | Reference |
|---|---|---|---|---|---|---|
| Maize stover + 50g/h/d CM | 6 | DOMI,g/kgLW$^{0.75}$/d<br>NR, g/head/d | 27.4*<br>0.86** | 24.9-29.9<br>0.47-1.2 | Sheep | (Anandan et al., 2013) |
| Sorghum stover | 5 | DMI, kg/d | 4.9* | 4.1-6.0 | Cattle | (ILCA, 1987) |
| Barley straw | 9 | DOMI,g/kgLW$^{0.75}$/d<br>LWG, g/h/d | 19.0*<br>-109* | 14.9-25.1<br>-18-(-232) | Sheep | (Herbert et al., 1994) |
| Barley straw | 8 | DOMI,g/kgLW$^{0.75}$/d<br>LWG, g/h/d | 18.0*<br>-80.4* | 14.7-23.7<br>-143-18 | Sheep | (Capper et al., 1989) |
| Soybean haulm, mechanically threshed | 4 | OMI, g/kgLW$^{0.75}$/d<br>CPI, g/kgLW$^{0.75}$/d<br>DMD, %<br>NR, g/kgLW$^{0.75}$/d | 33.9*<br>3.9*<br>49.7*<br>0.36* | 30.6-38.6<br>2.8-4.4<br>42.9-63.0<br>0.14-0.47 | Sheep | (Dada et al., 1999) |
| Groundnut haulm | 10 | OMI, g/d<br>OMD, %<br><br>NR, g/h/d<br>LWG, g/h/d | 936<br>69.4***<br><br>9.1**<br>94* | 811-1017<br>65.5 - 72.7<br><br>6.7-11.4<br>65-137 | Sheep | (Prasad et al., 2010) |
| Groundnut haulm | 6 | OMI, g/kgLW$^{0.75}$/d<br>CPI, g/kgLW$^{0.75}$/d<br>DMD, %<br>NR, g/head/d<br>LWG, g/head/d | 60.9*<br>6.2<br>55.6*<br>3.0*<br>26.0* | 58-72<br>5.8-7.0<br>50.8-62.3<br>1.2-4.3<br>-6.0-46.0 | Sheep | (Etela and Dung, 2011) |

*G: genotype; CM: Concentrate mixture; DOMI: Digestible organic matter intake; OMI: organic matter intake; OMD: OM digestibility; CPI: Crude protein intake (g/head/day), NR: Nitrogen retention; DMI: Dry-matter intake; DMD: DM digestibility; LWG: Live weight gain (g/head/day); *P<0.05; **P<0.01;***P<0.001; genotype means with no * were not-significant (P>0.05).*

## 2.5 Variation in grain and CR attributes among cereal genotypes

It is well established that the nutritive value of mature and senesced cereal CR is usually poor for ruminants (see Tables 2.2 and 2.5). Past research has often focused on post-harvest interventions such as physical, biological or chemical treatment of straw to improve its feeding value, but the economic feasibility of adopting this approach in developing countries is doubtful (Chapter 1). An alternative approach is increasing CR value through genotype selection and genetic enhancement of dual purpose varieties whilst retaining the grain yield advantages of modern varieties (Kristjanson and Zerbini, 1999; Reed et al., 1988b).

### 2.5.1. Variation in grain and CR attributes and their relationships in cereal genotypes

Many research reports have indicated that large variation can occur in many attributes among and between different types or varieties of cereal CR. For example, genetic variation for maize grain-stover attributes was reported among released and popular varieties (Tolera et al., 1999), hybrids (Anandan et al., 2013) and experimental hybrids (Ertiro et al., 2013a). Further genetic enhancement towards dual purpose attributes has also confirmed the variation among maize parental lines (Ertiro et al., 2013b; Zaidi et al., 2013).

Substantial differences in grain-stover or straw attributes of sorghum (Blümmel et al., 2013b), pearl millet (Ravi et al., 2010), wheat (Dias-da-Silva and Guedes, 1990; Habib et al., 1995; Schulthess et al., 1995; Tolera et al., 2008), barley (Erickson et al., 1982; Herbert et al., 1994; White et al., 1981) and rice (Capper, 1988; Flachowsky et al., 1991; Pearce et al., 1988) cultivars have been observed and *in-vitro* digestibility has ranged by as much as 10–15% units. In many studies straw digestibility was not related to grain yield and it can therefore be concluded that higher grain yield is not necessarily associated with lower straw digestibility (Reddy et al., 2003). The results suggest that it should be possible to select varieties combining high production of grain and CR and higher quality of CR as a ruminant feedstuff.

Studies with barley, maize and sorghum (Akin et al., 1986; Ørskov et al., 1988b; Ørskov et al., 1988a) suggest that genetic variation in digestibility of straws and stover mainly originates from inherent variation in cell wall digestibility. Most studies in temperate environments have indicated that variation in OMD was mainly caused by variation in cell-

wall digestibility e.g. of maize stover (Deinum and Struik, 1989). Moreover, G × E interactions for cell wall digestibility were very often small compared to main effects (Barrière et al., 2003) and large genetic variation for cell wall digestibility has been established from both in vivo and in vitro experiments in numerous crop species. For a given starch content, NDF digestibility was found to be the major determinant factor of OMD. For improvement in residue quality, efforts will have to be made to increase both the soluble nutrient content (cell content) and the digestibility of the cell wall fraction (Reddy et al., 2003).

In summary, the literature indicates that in maize there is generally (1) a positive association between grain and stover yield, and (2) no association between the quality of stover (e.g. DMD) as a feedstuff for ruminants and yields of stover and grain (Anandan et al., 2013; Ertiro et al., 2013a; Geleti et al., 2011; Tolera et al., 1999; Zaidi et al., 2013). This is similar to reports for sorghum and millet (Sharma et al., 2010). Hence it should be possible to exploit genetic differences in feedstuff quality of maize CR without compromising on grain yield.

## 2.6. Variation in seed and CR attributes and their relationships among legume genotypes

There is little information available reporting the variation in legume crop genotypes compared with that for cereals (Capper, 1990). A number of studies have reported differences among genotypes in the quantity and quality attributes of the CR in a number of grain legume crops, and in some studies these differences have been related to botanical fractions, digestibility and other quality attributes. The most extensive evidence is for groundnut (*Arachis hypogaea*) (Larbi et al., 1999; Nigam and Blummel, 2010; Omokanye et al., 2001). In faba bean (*Vicia faba*) Gebremeskel et al. (2011) evaluated five varieties during one season at two locations in Ethiopia, and observed varietal differences in seed yield, haulm yield and haulm quality characteristics. Also large variation among chickpea varieties has been observed in seed and haulm yield, and haulm quality attributes, and positive correlations between seed and biomass yields in different varieties (r=0.86) (Kafilzadeh and Maleki, 2012). In lentils Erskine (1983) concluded that continued selection for increased seed yield would not adversely affect haulm yield.

In conclusion, it should be possible to select varieties combining high seed and haulm production and favourable CR quality characteristics for use as ruminant feedstuffs. However, although new cultivars of grain legume crops are continually being released plant improvement programmes focus almost entirely on higher seed or pod yields, pest and disease resistance, and rate of maturation. CR yield and quality as a feedstuff are rarely considered (Gebremeskel et al., 2011).

### 2.7. Crop management factors affecting the yield and nutritive value of CR

The yield and quality characteristics of CR are determined by many G x E x M factors. The most important E and M are the growing, harvesting, threshing and storage methods for the crop. There are different rates of change in composition and digestibility associated with the conditions of growth and which affect fodder nutritive value. The role of various crop management factors in affecting the productivity and quality of CR have been reviewed by Reddy et al. (2003) while Rotz and Muck (1994) extensively reviewed changes in forage quality during harvest and storage.

Fodder yield potential and quality attributes of cultivars vary depending on environmental conditions (Roth, 1994). Dias-da-Silva and Guedes (1990) evaluated 24 fine-stemmed cereal straws comprising six cultivars of wheat, rye and triticale grown at four locations and reported that genotype and location can greatly affect the nutritive value of cereal straws. Cultivar x environment interactions can obviously change the ranking of a cultivar with location and year so that CR were inconsistent in terms of nutritive value. Also, environmental conditions such as temperature and water stress significantly influence the content and digestibility of cell walls in forage (Wilson, 1994).

In the following discussion emphasis is given to maize as the most important cereal in the context of the present studies. Crop management factors such as effects of E, plant density and cutting height at harvest on maize stover yield and quality, and the effect of harvesting stages on legume CR yield and quality are discussed. The discussion focussed on those crop management aspects which presently vary, or could likely be easily modified, in smallholder systems in EA.

### 2.7.1. Effect of plant density on maize grain and total biomass yields and stover quality

Maize stover yield and its nutritive value are influenced by numerous interactions including environment (location and year) and agronomic management (row spacing/plant density, sowing date, fertilizer and harvest procedure) (Deinum and Struik, 1989; Graybill et al., 1991). Environmental factors tend to be larger than the genetic effects on quality and quantity of CR (Ertiro et al., 2013a). Moreover, it is important to identify and understand the optimum crop management factors that can contribute to the improvement of yield and quality of CR (Reddy et al., 2003). Hybrid selection is also a key to improving forage quality for optimum animal output (Widdicombe and Thelen, 2002a).

Modern maize hybrids which tolerate more environmental stress than older hybrids have higher optimum plant densities for grain yield, mainly due to lower lodging frequencies (Nafziger, 1994; Tollenaar, 1989). Increasing plant density (e.g., 4 to 10 plants/$m^2$) in maize is used to increase grain and whole plant yield (Cox, 1996; Tollenaar and Bruulsema, 1988). There is a large literature on the effects of plant density on the production of grain and forage in maize (Aziz et al., 2007; Burken et al., 2013; Cox and Cherney, 2011; Lutz et al., 1971; Sarlangue et al., 2007; Widdicombe and Thelen, 2002b) but the present discussion will focus on studies most relevant to smallholder systems in EA and when harvest is at grain maturity. For early maturing varieties, an increase in population density increased yield and yield components per area, but decreased yield per plant (Amede, 1993). The yield increases ranged from 10-46%. However, late maturing varieties gave the highest yield with 3.3 to 4.4 plants/$m^2$, particularly in the high and mid-altitude areas. In general, there is no single recommendation for all conditions because the ideal plant number per area (optimum density) will depend on a number of factors including water availability, soil fertility, hybrid maturity group, time of planting and row spacing (Sangoi, 2001).

Numerous studies have focused on investigating the effect of row spacing and/or plant populations on maize grown for forage/silage and mostly in temperate areas. However, very little has been published on the effects of plant population/density and genotype on the yield and quality of maize stover grown for grain (as a dual purpose crop) production harvested at grain maturity under various environments in tropical regions.

In Ethiopia, the maize genotypes available were selected for grain yield. Recommended plant population have been in the range of 4.4-5.3 plants/$m^2$ (Admassu et al., 2008; Anley et al., 2013; Baudron et al., 2014) since the 1980s regardless of genotype differences (old vs. recently released) and specific environmental effects. It may be possible to improve stover production per unit area from commercial maize hybrids through increasing plant density without reducing grain yield and stover quality, but this option has never been addressed in tropical environments.

### 2.7.2. Effect of cutting height at harvest on the yield and quality of maize stover

Cutting height at harvest will obviously affect both the quantity and quality of the stover removed from the field for livestock, and that remaining in the field for other purposes, most importantly for grazing by livestock and for soil conservation (Kennington et al., 2005; Suttie, 2000; Wu and Roth, 2005). There is extensive evidence that various fractions of cereal CR have different digestibilities, nutrient concentrations and acceptability to ruminants. This is an obvious consequence of the distribution of plant morphological fractions at various heights of the plant. When given the opportunity, livestock selectively ingest the most palatable fractions of which the most important are usually leaf and husk (Lardy et al., 2015; Powell, 1984) before consuming lower-quality stem material. This is an important consideration when developing diets based on CR. Nutrient concentrations vary between upper and lower portions of the stalk of maize stover (Johnson et al., 2010; Lewis et al., 2004). The lower portion contains more fibre and lignin and thus is less digestible (Tolera and Sundstøl, 1999). Morrison et al. (1994) reported that the lower internodes are the most intensively lignified internodes in maize.

Plant cutting height at harvest affects the feeding value of maize silage (Bernard et al., 2004; Kennington et al., 2005; Neylon and Kung, 2003; Oliveira et al., 2013), wheat and barley silage (Walsh et al., 2008), sorghum silage (Hart, 1990) and rice straw (Dong et al., 2013). However, the responses have varied among crop species and genotypes, and plant maturity within species. Reports evaluating maize silage quality indicate that raising the cutting height may increase the quality of maize silage; however, these responses might be affected by differences in maturity at harvest (Neylon and Kung, 2003) and maize genotypes (Bernard et al., 2004; Kennington et al., 2005). However, the literature on silage feeding value may not be applicable to the feeding value of the stover harvested at grain maturity. Much less information is available on the effect of cutting height and genotype on the stover yield and quality of the maize plant at grain maturity harvest.

Based on field observations, the cutting height of maize at grain harvest by smallholder farmers varies with region in Ethiopia. Most farmers in the Bako and Ambo areas of Ethiopia practice high cutting at the 2nd node below the first ear attached from the bottom of the plant. However, most of the farmers in Rift Valley region use a lower cutting height just above the ground. With the higher cutting height the lower part of the stover is left in the field and used for soil incorporation, fuel and/or stubble grazing while the upper part of the stover is stored and used as ruminant feed during the dry season. This has implications for how CR are allocated to various purposes, conserved and fed, and the measurement of the nutritive value of those parts of the maize stover actually used as a ruminant feedstuff. In most reports the maize stover yield and quality refer to the whole stover harvested just above the ground. Emphasis is usually placed on the value of the total yield and quality of the above-ground stover biomass and the amount of grain produced from maize genotypes without simulating the practices of farmers. Clearly such measurements may be poor indicators of nutritive value of the stover used for ruminant feeding (Cox and Cherney, 2001; Reed and Goe, 1989).

### 2.7.3. Effect of maturity at harvest on legume CR yield and feeding value

It is well recognised that the decline in forage quality with advancing plant maturity is the most important factor determining the quality of forage for ruminants (Wilson and Kennedy, 1996). The proportion of leaves in forage declines and this is usually more pronounced in food legumes than cereals (Batterham and Egan, 1987). Hence the stage of maturity at harvest can have a very large effect on the value of the CR as a ruminant feedstuff. Obviously most cereal and grain legume crops are harvested at, or soon after, the maturity of the seed, and thus the CR will represent the mature senesced plant. However, this is not always the situation. Smallholder farmers in Ethiopia often early harvest a proportion of common bean, chick pea, faba beans, field peas and cowpeas plot while the crop is at an immature green stage of growth. This is known as the Eshet stage of growth at harvest and is consumed in many forms (e.g. the green seeds are used as a vegetable). However, there is little information on the effects of early versus late harvest on the morphological fractions and nutritive value of the CR of food legume crops.

Many of the grain legume CR have a higher feeding value than cereal straws, and especially if harvested immature. Legumes generally have a greater protein concentration and a lower fibre concentration than grasses and are more rapidly fragmented and degraded in the rumen during rumination (Dewhurst et al., 2003; Jung and Allen, 1995).

Also leaf digestibility is high. However, the leaf content of most some legume CR harvested at maturity may be very low due to the loss of leaf by leaf drop before or during harvest, especially if the crop is threshed (Batterham and Egan, 1987). Hence, these CR are usually high in pod and stem with negligible leaf, and thus are not of high value as a feedstuff for ruminants.

Animal production during the dry season can be improved substantially by feeding legume residues in association with grasses, cereal CR or other locally available feed resources (Dada et al., 1999). For instance, green or dry pods may be hand harvested from dual purpose cowpeas, leaving green stem and leaf material comprising 50-70% of the biomass which contains sufficient crude protein and digestibility for growth in goats (Bhaid and Talapatra, 1965). However, at seed maturity protein content may fall to 10-11%, digestibility to 45-55%, and VI is likely to be low (Roxas et al., 1985). Foster et al. (2012) reported that the CP concentration of three annual peanut cultivars decreased and the NDF, ADF, and lignin concentrations increased, with maturity. Soybean CR harvested at seed maturity may have very low value; the stem material of hand-harvested soybean will typically have an OMD of 25-30%, whereas the leaf and pod material will be 50-60% digestible with high VI (Cheva-Isarakul and Saengdee, 1987; Gupta et al., 1978).

In conclusion, there is a paucity of information on the nutritive value for ruminants of the CR of most grain legume crops and of common bean in particular harvested either at immature stage or at seed maturity.

### 2.8. Concluding comments

Across sub-Saharan Africa, CR are an important and often scarce household resource and the major feedstuff available during the dry season. Maize is the most important food crop in ESA and the stover is the most available CR as a ruminant feedstuff but there are other competing uses (e.g. as construction, soil amendment and fuel) of CR to smallholder farmers. Moreover, the poor nutritive value of the stover as a feedstuff for ruminants is well known. The haulm of grain legumes such as common bean often grown in maize based production systems in ESA and are better feeding value than maize stover for ruminants (Table 2.5). Exploring options for improving the stover yield and quality on smallholder farms would be the preferred strategy as land is generally not available to grow fodder crops. The estimation of CR yield and nutritive value for ruminants is subject to interactions across genotype, environment, and crop management. Information is needed

about the quality and quantity of CR as affected by genotype, environment and crop management factors and options for improving the quantity and quality of this resource in smallholder farms to meet the increasing demands. Thus options for improving the stover yield and quality may include combinations of choice of genotype, plant density and harvest procedure for various situations (Chapters 4 and 5). In order to exploit the variability of CR yield and quality crop management and environmental variables need to be investigated. Management effects such as plant density (Chapter 4) and height of cutting at harvest in maize (Chapter 5), and harvest at early and final seed maturity in common bean (Chapters 6 and 7) need to be investigated.

In conclusion, there are a number of potential options to increase the amount and improve the values as feedstuff of maize and common bean CR. But to be effective these must be adopted by smallholder farmers. Thus, it is important that farmers' crop management practices and the perceptions in relation to CR yield and quality should be understood (Chapter 8) and should also be related with intervention trials (Chapters 4-7). There is a need for improved understanding of such factors to improve knowledge and in order to hasten the adoption pathways for improved management and use of CR in smallholder crop-livestock systems.

# Chapter 3 Developing robust NIRS calibration equations to predict composition and dry matter digestibility of crop residues from East African farming systems

## 3.1. Introduction

Forage quality for ruminant livestock is best defined in terms of its value for animal production of milk, meat and draught power, but the time and cost of large animal feeding trials limits the routine use of this approach to evaluate forages. The nutritional value of forage is usually evaluated by laboratory measurements of the composition and in vitro digestibility. Application of near infrared spectroscopy (NIRS) to make these laboratory measurements can reduce the costs compared with established 'wet chemistry' (Norris et al., 1976), particularly for the analyses required for large numbers of samples (Cozzolino et al., 2001).

NIRS for analysis including of feedstuffs (Givens and Deaville, 1999; Williams and Norris, 2001; Williams, 1975) is based on the measurement of the absorption of light in the near infrared range (700–3000 nanometres (nm) region) which is closely related to important chemical bonds (OH, NH and CH) (Deaville and Flinn, 2000; Dixon and Coates, 2010). Most NIRS of feedstuffs uses the range 1100 - 2500 nm. Once calibrations have been developed NIRS provides more rapid, reliable and economical feed analysis than using conventional laboratory procedures.

A wide range of forage quality attributes can be measured with NIRS and include crude protein, dry matter or organic matter digestibility, and fibre fractions (Norris et al., 1976; Shenk et al., 1979). NIRS has also been successfully used to estimate the voluntary intake of both tropical and temperate forages with moderate accuracy (r = 0.79, SEP = 7.8 g DM/kg $LW^{0.75}$ (Norris et al., 1976). Some studies (Eckman et al., 1983; Park et al., 1997; Steen et al., 1998; Ward et al., 1982) concluded that NIRS could be used to measure diet digestibility, voluntary DM intake and production responses in ruminants fed forage-based diets as accurately as can be done with conventional laboratory analyses. Many research groups and studies have successfully developed calibrations to measure a wide range of forage quality attributes (Ramana Reddy et al., 2013; Sharma et al., 2010; Smith and Flinn, 1991; Stimson et al., 1991), animal response (Abrams et al., 1987) and voluntary intake (Agnew et al., 2004; Deaville and Flinn, 2000; Givens and Deaville, 1999; Steen et al., 1998).

Use of NIRS requires the development of calibrations which require measurement of both the spectra and the actual composition or attributes of samples measured with established chemical, laboratory or animal procedures. These are known as the reference samples and their accurate determination is essential for successful development of calibrations and application of NIRS (Valdes et al., 1990). Furthermore calibration sets need to contain an adequate range of the property of interest and represent all the important sources of variability that may be present in the population of samples to be measured. Usually at least several hundred samples with reference values are required (Ramana Reddy et al., 2013; Sharma et al., 2010; Windham et al., 1989). An important characteristic of NIRS calibrations is that they are often specific for the class and ranges of samples used to build the calibrations, and usually have to be updated on an ongoing basis to accommodate even small changes in the sample populations such as associated with harvest season, cultivar and region (Stuth et al., 2003).

Calibration equations derived from tropical forages across northern Australia (the 'North Australia (NA) forage calibrations; D.B. Coates and R.M. Dixon, unpublished data) were available for the present study and were used as a basis to develop the calibrations required to measure Ethiopian crop residues for the present study. The NA calibrations had been developed to measure DM digestibility (DMD) and the concentrations of total N, neutral detergent fibre (NDF) and acid detergent fibre (ADF) in grasses and legumes commonly found in northern Australian rangelands. Most of the grasses were C4 tropical and included native and naturalized grasses such as the genera *Heteropogon, Chrysoponon, Urochloa, Astrebla, Bothriochloa, Dichanthium, Cynodon, Brachiaria, and Aristida spp*., and improved grasses such as *Cenchrus, Chloris,and Panicum spp*. Most of the legume samples comprised *Stylosanthes spp [S. scabra* (seca stylo) and *S. hamata* (verano stylo)], while other common introduced legumes were represented. Such calibrations based on pasture grasses and legumes cannot be expected to accurately and reliably predict the samples of crop residues (CR) such as the maize and food legumes, and especially from another continent, which were important in the present study (Windham et al., 1989). Hence the NA calibration sample set was expanded with reference samples of the CR of interest obtained from the field study sites in Ethiopia.

In general, NIRS calibrations for specific attributes can be developed and refined most easily for new circumstances and for a novel range of samples if a calibration is available for similar samples. Improved calibrations can be developed by enlarging and building onto existing calibrations for similar materials (Guthrie et al., 2005; Marten, 1989). For the

present study to develop reliable and robust calibrations for Ethiopian CR the existing NA calibrations were used as a core calibration data set. It was anticipated that tropical forages in the form of maize and legume CR from Ethiopia would not be reliably measured by the NA calibrations, but that addition of some representative reference samples would allow development of robust calibrations appropriate for these CR samples. For example, Guthrie et al. (2005) reported that model updating in fruit involving the addition of only few samples (~20) was successful in improving prediction of new population. Hence, more information was needed to use NIRS to reliably analyse the nutritionally important attributes and components of maize and grain legume CR. The objective of the present study was to develop robust forage NIRS calibration equation for analysis of CR in Ethiopia representing a range of crop species, varieties within species, environments, and harvest managements.

## 3.2. Materials and Methods

### 3.2.1. Crop residue sampling and processing

During the field studies reported in this thesis, samples of maize and various species of grain legumes were collected from sites encompassing a variety of agro-ecological environments and seasons, plant varieties, and crop management conditions. Also some of the CR were separated into morphological fractions. These samples are summarized in Table 3.1 and more detailed descriptions of their origins are given in Chapters 4-7. The dried and ground forage samples were air-freighted to Australia, gamma irradiated to meet Australian quarantine requirements (Quarantine Permit: IP14007043; 25k Gray or 2.5 Mrad) and then transported to laboratories for analysis.

### 3.2.2. Measurement of NIRS spectra

The near infrared spectra of the dried and ground forage samples was measured in reflectance using a scanning monochromator (Model Foss 6500; NIRSystem, Inc., Silver Springs, MD, USA) fitted with a spinning cup module. Sub-samples (~ 3 g air-dry) were carefully mixed and packed into the spinning cup cells. The NIRS scanning followed the procedures described by Coates and Dixon (2011). Samples were scanned in duplicate and absorbance spectra (log 1/R) were recorded at 2 nm intervals over the wavelength range of 400 – 2500nm. Spectral data was collected with ISI-Scan (Infrasoft International version 4.6.11) software and stored as the log 1/reflectance (*R*). Full diagnostic tests on the Foss 6500 NIRSystems instrument were performed daily before scanning. In addition,

the stability of the instrument was monitored by scanning 1-4 times daily a laboratory check sample Buffel grass (*Cenchrus ciliaris*) in a sealed standard spinning cup.

Table 3.1 Type and number of samples collected during 2013 and 2014 cropping seasons from different crop species and environments in Ethiopia

| Crop species | Type of samples | Crop growth stage | Year | | Total |
|---|---|---|---|---|---|
| | | | 2013 | 2014 | |
| Maize | Whole stover, upper part of plant, lower part of plant, leaf blade, stem, husk and tassel | At grain maturity | 694 | 612 | 1306 |
| Common bean | Haulm, leaf, stem, pod wall | At early and seed maturity | 652 | - | 652 |
| Chickpea | Haulm, leaf, stem, pod wall | At early and seed maturity | 194 | 288 | 482 |
| Faba bean | Haulm, leaf, stem, pod wall | At early and seed maturity | 255 | 96 | 351 |
| Soybean | Haulm and pod wall | Seed maturity | 60 | - | 60 |
| Total | | | 1855 | 996 | 2851 |

The scanning monochromator in Central Queensland University (CQU), Australia used to scan samples was the same manufacturer and model as that used to develop the NA calibration data set (Model Foss 6500; NIRSystem, Inc., Silver Springs, MD, USA). Also spectra from the CQU instrument were corrected to the CSIRO monochromator which had been used to develop the NA calibration data set and which was considered as the master instrument. A set of 10 sealed standards representing a range of sample quality had been scanned 18 times over several years on the CSIRO monochromator during development of the NA calibration data set. These 10 sealed standards were scanned 10 times in the CQU instrument. The instrument standardization procedure available in the WinISI software was used to correct the CQU instrument to the Master. Also, in order to match two other instruments in Ethiopia (at ILRI, Addis Ababa and EIAR, Holetta research centre) to the CQU instruments, 20 standard samples comprising a range of sample qualities and including CR, tropical grasses and legumes were used as lab standards and scanned repeatedly at intervals and with repacking of spinning cup cells. A total of 120 (6 spectra/sample), 200 (10 spectra/sample) and 200 (10 spectra/sample) spectra were collected in Holetta, ILRI and CQU instruments respectively. Spectra were averaged and standardized to the CQU instrument using the standardization procedures described above. Chemometrics was conducted with WinISI II (version 1.5) (Infrasoft International,

Port Matilda, PA, USA) and the spectral data were examined to relate infrared spectra to reference values (Shenk and Westerhaus, 1991a).

Calibrations were developed from the reference samples and the NIR spectra using the modified partial least squares (MPLS) procedure of Shenk and Westerhaus (1991b) and WinISI II (version 1.5) software (Infrasoft International, Port Matilda, PA, USA). Standard normal variate (SNV) followed by de-trending (DT) and two loading types (PCA and PL1) were examined with each of two maths treatments (1, 4, 4, 1 and 2, 4, 4, 1) over 1100-2500 nm wavelength band. Critical 'T' and 'H' outlier values were set at 4 and 10, respectively, and where the critical values were exceeded, the samples were eliminated from the calibration data set as outliers. Spectra with standardized GH [(Mahalanobis distance)$^2$/f ] (where f is number of factors in the model) >3.0 from the mean were also removed as spectral outliers. Two outlier elimination passes, a maximum of 16 terms and 4 cross-validation groups were used. The PCA and 2, 4, 4, 1 math treatment provided the best calibrations for DMD and was therefore in general used subsequently.

Calibrations to measure the concentrations in forage of total N, NDF and ADF, and the DMD of the forages, were developed and validated. A subset of the Ethiopian CR samples (15-43% of each subclass of crop species and morphological fraction) were selected on the basis of high GH values as recommended by Shenk and Westerhaus (1991b) with stratification so that each of the morphological fractions of maize and of each of the legume species was represented. These reference samples from Ethiopia were analysed for total N, NDF and ADF concentrations, and DMD, by conventional "wet chemistry" procedures, and were then used to improve and then to validate the calibrations.

### 3.2.3. Wet chemistry analysis of reference samples

The lab analyses were done in duplicate. Total N (0.15-0.18 g samples) was determined using a LECO combustion system (TruMac® CN analyser 2013 version1.3x) (LECO Corporation, St. Joseph, MI, USA) which complies with AOAC (2005) analysis #997.09.

NDF and ADF concentrations (Van Soest et al., 1991) were measured in 0.45-0.50 g samples with an ANKOM$^{200}$ Fibre Analyser (Model200, ANKOM Technology, Macedon, NY, USA) filter bag technique (Anonymous, 1995a; Vogel et al., 1999). Duplicate laboratory standard samples of tropical grass (*Astrebla spp)* and empty blank bags were included in each batch. Neutral detergent or acid detergent solutions, and for NDF also

ANKOM heat stable alpha-amylase (ANKOM Technology FAA, Macedon, NY, USA), were added to the analyser vessel and agitated for 75 min (NDF) or 60 min (ADF). Bags were then washed with tap water (90-95$^{o}$C) repeatedly, and for ADF until the washings were neutral pH. After the final rinse the bags were squeezed to remove excess water and then soaked in acetone for 5 min before drying.

In-vitro DMD (IVDMD) was determined with the filter bag method in DAISY$^{II}$ incubator (ANKOM Technology, Macedon, Fairport, NY, USA) (Anonymous, 1995b; Holden, 1999). Empty filter bags (57 micron pore size) were rinsed in acetone for 3-5 min and dried. Samples were prepared (~0.5g) in a pre-rinsed filter bags and heat sealed before being placed with buffer solution and rumen fluid (Anonymous, 1995b) in the fermentation chamber of the incubator.

Laboratory standard samples of tropical grass (*Astrebla spp)* and empty blank bags were included in each batch. Rumen fluid was obtained from two rumen fistulated steers fed a high quality forage diet, and was prepared as described by Holden (1999). Bags were incubated in rumen fluid and buffer for 48 h at 39.5$^{o}$C± 0.5 (Anonymous, 1995b), and then with acid-pepsin solution (Holden, 1999) before bags were dried and weighed.

### 3.2.4. Calibration procedure

As stated above (Section 3.2.2) calibrations to encompass the Ethiopian CR sample set were developed from an existing NA forage calibration data set (Table 3.3, D.B. Coates and R.M. Dixon, unpublished data) and with addition of reference data from the Ethiopian sample set. Calibration equations were developed for the four constituents DMD, Total N, NDF and ADF. The accuracy of the calibrations and selection of the best calibration equations was assessed based on the optimal combination of the regression standard error of calibration (SEC), the coefficient of determination in calibration ($R^2$), the standard error of cross validation (SECV), and the relative predictive determinant for cross validation (RPDc) (calculated as SD of population reference data/SECV) (Agnew et al., 2004; Marten et al., 1984; Patil et al., 2010).

### 3.2.5. Validation procedure

The protocols of Shenk et al. (1989) and Windham et al. (1989) were used to examine the performance of NIR equations. The Ethiopian reference crop residue samples (maize

n=203; common bean n=97, chickpea (n=80), faba bean (n=65) and soybean (n=25) samples were randomly divided within each crop species into 2 sub-sets (A and B). The NA data were combined with the A data (data set NA+A) and used to develop calibration equations. Validation then examined the errors associated with the prediction of the B data set from the NA+A calibrations in terms of the standard error of performance (SEP), the coefficient of determination in validation values ($R^2_v$),and bias of the prediction. Similarly the calibrations calculated from the NA+B data set to predict the A data set were examined. The validation of A and B samples were thus conducted independently. The SEP, $R^2_v$ and bias of the calibrations equation from NA to predict the A+B samples were also used to evaluate the performance of the NA calibrations to predict the Ethiopian crop residues samples. Relative predictive determinant (RPDv = SD of validation set data/ SEP(C)) were computed for all calibration models to determine the accuracy of prediction (Patil et al., 2010).

### 3.3. Results

#### 3.3.1. Instrument stability

The repeatability of the frequent measurements of the Buffel grass (*Cenchrus ciliaris*) laboratory standard on the CQU instrument was excellent with the CV ranging from 0.416 to 0.768% in 2014 and from 0.136 to 0.606% in 2015 scanning periods (Table 3.2).

Table 3.2 The variation in measurement of the attributes (%) of a laboratory standard comprising *Cenchrus ciliaris* in a sealed cell scanned on 58 occasions over 27days in 2014 and 33 occasions over 14 days in 2015

| | 2014 | | | | 2015 | | | |
|---|---|---|---|---|---|---|---|---|
| | Total N | DMD | NDF | ADF | Total N | DMD | NDF | ADF |
| Mean | 0.977 | 52.8 | 70.2 | 49.5 | 0.916 | 52.8 | 73.3 | 47.8 |
| Minimum | 0.954 | 52.4 | 69.6 | 48.9 | 0.908 | 52.6 | 73.1 | 47.5 |
| Maximum | 0.998 | 53.5 | 71.1 | 50.7 | 0.929 | 53.0 | 73.5 | 47.9 |
| SD | 0.0075 | 0.220 | 0.357 | 0.353 | 0.0055 | 0.087 | 0.100 | 0.088 |
| CV (%) | 0.768 | 0.416 | 0.509 | 0.713 | 0.606 | 0.164 | 0.136 | 0.184 |

*SD: standard deviation; CV: Coefficient of variation= (SD/mean) x100*

#### 3.3.2. Calibration equations calculated from the reference values of the constituents and calibration statistics

There was a wide range in the reference values for each of the constituents in both the NA and Ethiopian maize and grain legumes CR data sets (Table 3.3 D B Coates and R M Dixon). Total N content ranged from 0.22-5.45%, while the DMD and fibre fractions (NDF

and ADF) ranged by about 3 and 4 fold respectively. The coefficients of determination in calibration ($R^2$) of known forage quality values on NIRS values were ≥0.93 for the four constituents, with that for total N being highest at 0.98 (Table 3.3). The SEC of DMD, total N, NDF and ADF were 3.04, 0.145, 2.49 and 1.74 respectively.

Inclusion of maize and grain legume residue data set in NA forage data set resulted in improvement in calibration $R^2$ values for DMD (0.88 vs 0.93) but similar $R^2$ values for total N and fibre fractions (Table 3.3). The SECV was reduced with the development of new calibration for total N, DMD and fibre fractions compared to the NA calibration data set (Table 3.3). The RPDc value of the NA plus Ethiopian (NA+A+B) forage NIRS calibration statistics ranged from 3.4 for DMD to 6.1 for total N (Values can be calculated from the table).

Table 3.3 Attributes of North Australian (NA) and the NA plus Ethiopian (NA+A+B) forage NIRS calibration statistics for contents of total N, DMD, NDF and ADF

| Attribute | n | Mean | SD | Min | Max | SEC | $R^2$ | SECV |
|---|---|---|---|---|---|---|---|---|
| NA data set[#] | | | | | | | | |
| Total N | 1688 | 1.30 | 0.99 | 0.23 | 5.45 | 0.157 | 0.98 | 0.160 |
| DMD | 893 | 54.0 | 9.7 | 29.0 | 80.8 | 3.38 | 0.88 | 3.53 |
| NDF | 431 | 64.6 | 14.2 | 27.2 | 82.0 | 2.41 | 0.97 | 2.90 |
| ADF | 409 | 42.1 | 9.5 | 17.6 | 64.6 | 1.72 | 0.97 | 2.00 |
| NA+A+B data set | | | | | | | | |
| Total N | 2086 | 1.23 | 0.93 | 0.22 | 5.45 | 0.145 | 0.98 | 0.153 |
| DMD | 1320 | 54.9 | 11.1 | 25.3 | 89.1 | 3.04 | 0.93 | 3.23 |
| NDF | 877 | 65.1 | 15.2 | 22.2 | 88.6 | 2.49 | 0.97 | 2.73 |
| ADF | 855 | 43.2 | 10.1 | 18.1 | 70.4 | 1.74 | 0.97 | 1.87 |

[#]*(D.B. Coates and R.M. Dixon, unpublished results). All values expressed as % dry matter; n: Number of samples; SD: Standard deviation; Min: minimum and Max: maximum values in the calibration data set; SEC: Standard error of calibration; $R^2$: the coefficient of determination in calibration; SECV: Standard error of cross validation.*

The relationships between the reference and predicted values for total N, DMD, NDF and ADF for the NA+A+B samples i.e. comparison of predicted and reference values within the calibration sample set are shown in Figures 3.1A to 3.1D.

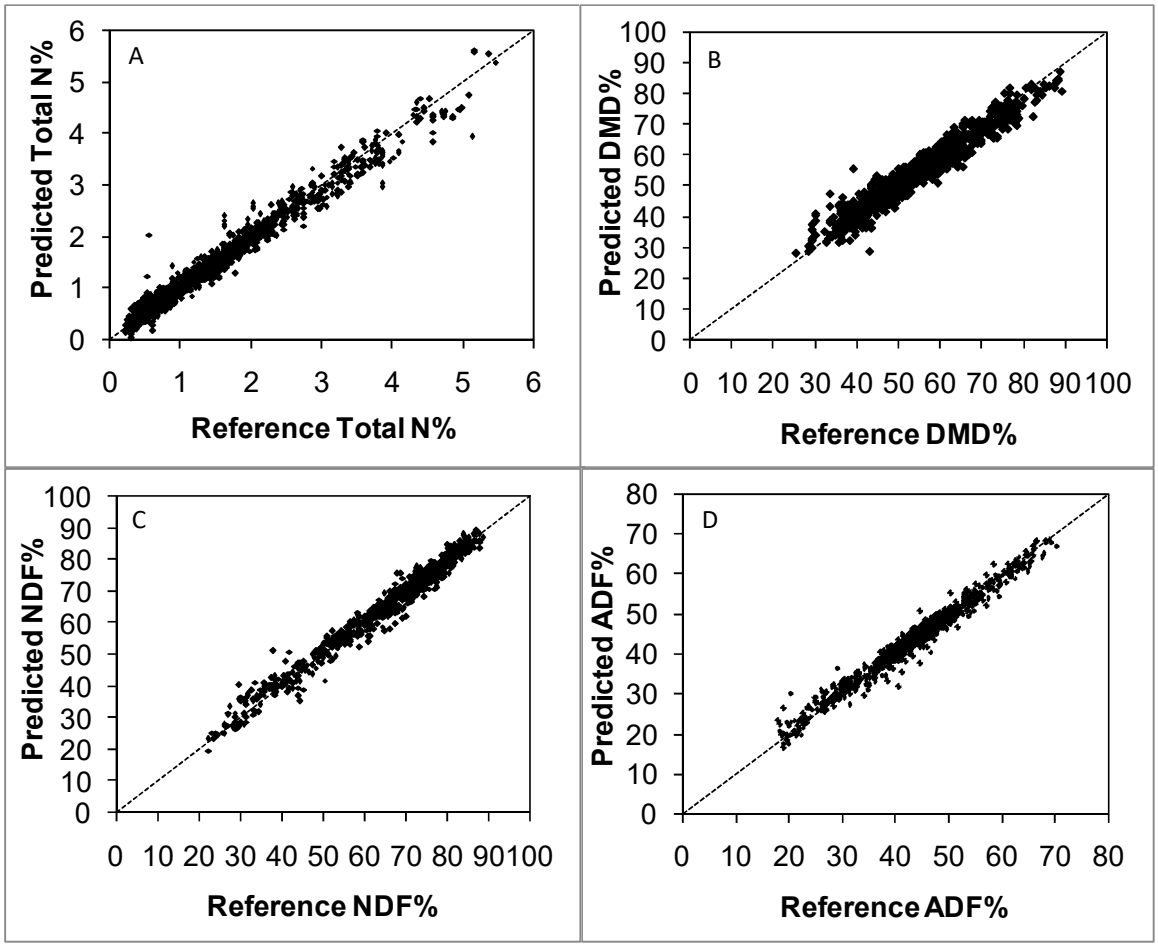


Figure 3.1 Scatter plot of predicted verses reference data for total N% concentration (A), dry matter digestibility (DMD) (B), NDF (C) and ADF (D) calculated from the NA+A+B calibration data set.

The equations were as follows:

$Y_{Total\ N}$ = 0.950x + 0.061, n= 2086, $R^2$ = 0.98;
$Y_{DMD}$ = 0.882x + 6.441, n= 1320, $R^2$ = 0.93;
$Y_{NDF}$ = 0.957x + 2.752, n=877, $R^2$ = 0.97
$Y_{ADF}$= 0.943x + 2.443, n= 855, $R^2$ = 0.97. The dotted line is the 1:1 relationship.

### 3.3.3. Validation of calibration for maize and grain legumes residue quality attributes

The calibration data sets for the two populations (NA+A and NA+B) showed a similar and wide range in the reference values for each of the constituents (Table 3.4). The calibration $R^2$ were ≥0.91for the four constituents, the highest being for total N at 0.98. The SECV and RPDc values were also satisfactory.

Table 3.4 NIRS calibration statistics using North Australia (NA) plus ½ maize + ½ grain legume CR samples from Ethiopia for prediction of estimated DMD and N, NDF and ADF

| Calibration | Attribute (%) | n | Mean | SD | Min | Max | SEC | $R^2$ | SECV | RPDc |
|---|---|---|---|---|---|---|---|---|---|---|
| NA + A | Total N | 1862 | 1.26 | 0.95 | 0.22 | 5.45 | 0.146 | 0.98 | 0.156 | 5.94 |
| | DMD | 1081 | 54.3 | 10.5 | 25.3 | 88.2 | 3.17 | 0.91 | 3.43 | 3.06 |
| | NDF | 656 | 64.3 | 15.0 | 22.2 | 88.6 | 2.54 | 0.97 | 2.84 | 5.28 |
| | ADF | 629 | 45.3 | 10.3 | 17.6 | 70.4 | 1.82 | 0.97 | 1.97 | 5.23 |
| NA + B | Total N | 1857 | 1.23 | 0.93 | 0.23 | 5.45 | 0.149 | 0.97 | 0.156 | 5.81 |
| | DMD | 1085 | 54.3 | 10.3 | 28.3 | 89.1 | 2.98 | 0.92 | 3.23 | 3.19 |
| | NDF | 651 | 65.6 | 14.8 | 22.3 | 87.7 | 2.65 | 0.97 | 2.95 | 5.02 |
| | ADF | 632 | 40.3 | 9.0 | 17.6 | 59.8 | 1.78 | 0.96 | 1.94 | 4.64 |

*All values expressed as % dry matter; n: Number of samples used in the calibration; NA: North Australia forage data set; A: Refers half of the Ethiopian maize and grain legumes crop residue (CR) samples; B: Refers another half of the Ethiopian maize and grain legumes crop residue samples; SD: Standard deviation; Min: minimum and Max: maximum values in the calibration data set; SEC: Standard error of calibration; $R^2$: the coefficient of determination in calibration; SECV: Standard error of cross validation; RPDc = SD/SECV – the ratio of SD (standard deviation of reference data) to SECV in the calibration set.*

The statistics describing the accuracy of the MPLS equations used to predict the DMD and total N, NDF and ADF contents of the maize and grain legumes residue samples are given in Tables 3.5-3.8. The $R^2$v of maize and grain legumes residue (population A+B) DMD predictions with NA+A+ B calibration equation ranged from ($R^2$v= 0.90–0.98) (Table 3.5). The SEP and bias were reduced while $R^2$v improved when the equation NA+A+B used to predict DMD compared to the predictions of NA equation. The RPDv values of NA+A+B calibration equation for predicting DMD of population A+B ranged from 2.93 in maize to 6.49 in soybean (Table 3.5).

The $R^2$v of maize and grain legumes (common bean, chickpea and faba bean) residue total N and DMD content predictions with the NA+A+B calibration equation ranged from 0.90-0.98 for total N and 0.97–0.99 for DMD% (Table 3.5 and 3.6). The SEP and bias were also satisfactory and were reduced, while $R^2_v$ improved, when the calibration equation NA+A+B rather than NA was used for prediction.

The $R^2$v of maize and grain legumes residue for NDF and ADF contents predicted with NA+A+ B calibration equations ranged from 0.95–1.00 (Tables 3.7 and 3.8). The RPDv values of NA+A+B calibration equation for predicting NDF of the population A+B ranged from 4.48 in common bean to 8.71 in faba bean (Table 3.7) while the RPDv values of

NA+A+B calibration equation for predicting ADF of population A+B ranged from 4.42 in common bean and 13.82 in soybean (Table 3.8).

Table 3.5 Performance of NIR equations for predicting DMD (%) of maize and legume CR samples (A+B, A or B) with North Australia (NA), NA+B, NA+A and NA+A+B calibration equations

| Cal | Val | n | Mean | SD | SEP | SEP(C) | $R^2$v | Bias | Slope | RPDv |
|---|---|---|---|---|---|---|---|---|---|---|
| Maize | | | | | | | | | | |
| NA | A+B | 203 | 40.4 | 8.34 | 12.86 | 5.74 | 0.53 | 11.51 | 1.04 | 1.45 |
| NA+B | A | 101 | 50.0 | 8.25 | 3.66 | 3.65 | 0.81 | 0.48 | 1.11 | 2.26 |
| NA+A | B | 102 | 52.3 | 8.24 | 3.20 | 3.07 | 0.87 | 0.93 | 1.14 | 2.68 |
| NA+A+B | A+B | 203 | 51.8 | 8.34 | 2.84 | 2.85 | 0.90 | 0.09 | 1.14 | 2.93 |
| Common bean | | | | | | | | | | |
| NA | A+B | 91 | 55.4 | 7.80 | 8.50 | 3.82 | 0.88 | 7.61 | 1.56 | 2.04 |
| NA+B | A | 45 | 65.0 | 4.67 | 4.52 | 3.92 | 0.44 | 2.33 | 0.64 | 1.19 |
| NA+A | B | 46 | 58.4 | 8.30 | 2.54 | 2.54 | 0.91 | 0.39 | 0.98 | 3.27 |
| NA+A+B | A+B | 91 | 62.6 | 7.80 | 2.51 | 2.49 | 0.90 | 0.44 | 1.02 | 3.13 |
| Chickpea | | | | | | | | | | |
| NA | A+B | 80 | 48.3 | 16.85 | 9.19 | 5.70 | 0.97 | 7.23 | 1.41 | 2.96 |
| NA+B | A | 40 | 52.2 | 16.49 | 5.42 | 4.31 | 0.97 | 3.36 | 1.23 | 3.83 |
| NA+A | B | 40 | 59.3 | 17.41 | 4.76 | 3.01 | 0.97 | -3.72 | 1.06 | 5.78 |
| NA+A+B | A+B | 80 | 55.6 | 16.85 | 3.20 | 3.22 | 0.97 | -0.03 | 1.08 | 5.23 |
| Faba bean | | | | | | | | | | |
| NA | A+B | 54 | 66.0 | 15.52 | 6.98 | 6.06 | 0.87 | 3.56 | 1.16 | 2.56 |
| NA+B | A | 27 | 73.0 | 13.22 | 3.24 | 3.14 | 0.99 | -1.01 | 1.26 | 4.21 |
| NA+A | B | 27 | 63.7 | 17.45 | 4.73 | 3.21 | 0.99 | 3.53 | 1.19 | 5.44 |
| NA+A+B | A+B | 54 | 68.9 | 15.52 | 2.82 | 2.75 | 0.98 | 0.73 | 1.11 | 5.64 |
| Soybean | | | | | | | | | | |
| NA | A+B | 25 | 46.7 | 14.80 | 5.71 | 4.65 | 0.98 | 3.44 | 1.40 | 3.18 |
| NA+B | A | 13 | 45.7 | 13.71 | 2.27 | 2.25 | 0.97 | -0.71 | 0.97 | 6.09 |
| NA+A | B | 12 | 54.6 | 14.64 | 2.54 | 2.44 | 0.99 | 1.00 | 1.14 | 6.00 |
| NA+A+B | A+B | 25 | 49.9 | 14.80 | 2.24 | 2.28 | 0.98 | 0.16 | 1.00 | 6.49 |

*All values expressed as % dry matter; Cal: calibration data set; Val: Validation data set; n:Number of samples used in the validation; NA: North Australia forage data set; A: refers half of the Ethiopian maize and grain legumes crop residue samples; B: Refers another half of the Ethiopian maize and grain legumes crop residue (CR) samples; SD: Standard deviation; SEP: Standard error of performance; SEP(C): Bias corrected standard error of performance; $R^2_v$: the coefficient of determination in validation; RPDv = SD/SEP – the ratio of SD (standard deviation of validation data) to SEP(C) in the validation set; Bias: mean difference between laboratory and NIR values; Slope: slope of regression between reference and NIR values.*

In general, the SEP and bias were consistently reduced while $R^2$v improved when the equation NA+A+B used to predict NDF and ADF of population A+B compared to the predictions of NA equation (Tables 3.7 and 3.8). The only exception to the generally good and satisfactory prediction of attributes was the total N content of soybean haulm which

was poorly predicted ($R^2v$ = 0.54; RPDv = 0.62) and with an SEP = 0.21 which was twice that for the other crops (Table 3.6).

Table 3.6 Performance of NIR equations for predicting total N content (%) of maize and legume CR samples (A+B, A or B) with North Australia (NA), NA+B, NA+A and NA+A+B calibration equations

| Cali | Vali | n | Mean | SD | SEP | SEP(C) | $R^2v$ | Bias | Slope | RPDv |
|---|---|---|---|---|---|---|---|---|---|---|
| Maize | | | | | | | | | | |
| NA | A+B | 201 | 0.87 | 0.51 | 0.15 | 0.11 | 0.97 | 0.10 | 1.13 | 4.64 |
| NA+B | A | 101 | 1.04 | 0.56 | 0.13 | 0.13 | 0.96 | 0.04 | 1.14 | 4.31 |
| NA+A | B | 100 | 0.84 | 0.43 | 0.09 | 0.09 | 0.96 | 0.02 | 1.01 | 4.78 |
| NA+A+B | A+B | 201 | 0.96 | 0.51 | 0.09 | 0.09 | 0.97 | 0.01 | 1.04 | 5.67 |
| Common bean | | | | | | | | | | |
| NA | A+B | 97 | 1.19 | 1.03 | 0.18 | 0.14 | 0.98 | 0.11 | 0.97 | 7.36 |
| NA+B | A | 49 | 1.43 | 1.20 | 0.14 | 0.14 | 0.99 | -0.00 | 1.01 | 8.57 |
| NA+A | B | 48 | 1.12 | 0.81 | 0.16 | 0.16 | 0.97 | 0.05 | 1.07 | 5.06 |
| NA+A+B | A+B | 97 | 1.27 | 1.03 | 0.14 | 0.14 | 0.98 | 0.03 | 1.03 | 7.36 |
| Chickpea | | | | | | | | | | |
| NA | A+B | 80 | 1.04 | 0.83 | 0.14 | 0.11 | 0.99 | -0.09 | 1.08 | 7.55 |
| NA+B | A | 40 | 1.02 | 0.86 | 0.14 | 0.14 | 0.98 | -0.02 | 1.08 | 6.14 |
| NA+A | B | 40 | 0.98 | 0.79 | 0.12 | 0.10 | 0.98 | -0.08 | 0.99 | 7.90 |
| NA+A+B | A+B | 80 | 0.95 | 0.83 | 0.10 | 0.11 | 0.99 | 0.00 | 1.03 | 7.55 |
| Faba bean | | | | | | | | | | |
| NA | A+B | 65 | 1.62 | 0.96 | 0.19 | 0.18 | 0.98 | 0.06 | 0.88 | 5.33 |
| NA+B | A | 32 | 0.97 | 0.48 | 0.34 | 0.15 | 0.92 | 0.30 | 1.16 | 3.20 |
| NA+A | B | 33 | 2.10 | 1.15 | 0.15 | 0.15 | 0.98 | -0.04 | 0.96 | 7.67 |
| NA+A+B | A+B | 65 | 1.70 | 0.96 | 0.11 | 0.10 | 0.99 | -0.03 | 1.00 | 9.60 |
| Soybean | | | | | | | | | | |
| NA | A+B | 23 | 0.73 | 0.08 | 0.31 | 0.16 | 0.45 | -0.26 | 0.28 | 0.50 |
| NA+B | A | 12 | 0.61 | 0.06 | 0.21 | 0.12 | 0.21 | -0.17 | 0.21 | 0.50 |
| NA+A | B | 11 | 0.74 | 0.09 | 0.26 | 0.11 | 0.72 | -0.24 | 0.45 | 0.82 |
| NA+A+B | A+B | 23 | 0.63 | 0.08 | 0.21 | 0.13 | 0.54 | -0.16 | 0.35 | 0.62 |

*All values expressed as % dry matter; Cal: calibration data set; Val: Validation data set; n: Number of samples used in the validation; NA: North Australia forage data set; A: refers half of the Ethiopian maize and grain legumes crop residue samples; B: Refers another half of the Ethiopian maize and grain legumes crop residue (CR) samples; SD: Standard deviation; SEP: Standard error of performance; SEP(C): Bias corrected standard error of performance; $R^2_v$: the coefficient of determination in validation; RPDv = SD/SEP – the ratio of SD (standard deviation of validation data) to SEP(C) in the validation set; Bias: mean difference between laboratory and NIR values; Slope: slope of regression between reference and NIR values.*

Table 3.7 Performance of NIR equations for predicting NDF content (%) of maize and legume CR samples (A+B, A or B) with North Australia (NA), NA+B, NA+A and NA+A+B calibration equations

| Cali | Vali | n | Mean | SD | SEP | SEP(C) | $R^2$v | Bias | Slope | RPDv |
|---|---|---|---|---|---|---|---|---|---|---|
| Maize | | | | | | | | | | |
| NA | A+B | 203 | 87.2 | 7.91 | 13.19 | 7.49 | 0.17 | -10.86 | 0.62 | 1.06 |
| NA+B | A | 102 | 74.7 | 9.04 | 2.45 | 2.46 | 0.95 | -0.17 | 1.17 | 3.67 |
| NA+A | B | 101 | 78.8 | 6.12 | 2.27 | 2.19 | 0.92 | -0.64 | 0.82 | 2.79 |
| NA+A+B | A+B | 203 | 76.4 | 7.91 | 1.57 | 1.57 | 0.96 | -0.11 | 1.00 | 5.04 |
| Common bean | | | | | | | | | | |
| NA | A+B | 97 | 61.8 | 10.98 | 6.04 | 4.68 | 0.88 | -3.86 | 1.35 | 2.35 |
| NA+B | A | 48 | 54.4 | 9.57 | 2.98 | 2.88 | 0.92 | -0.90 | 1.08 | 3.32 |
| NA+A | B | 49 | 60.0 | 10.54 | 4.16 | 3.43 | 0.91 | 2.41 | 1.13 | 3.07 |
| NA+A+B | A+B | 97 | 58.0 | 10.98 | 2.44 | 2.45 | 0.96 | -0.05 | 1.10 | 4.48 |
| Chickpea | | | | | | | | | | |
| NA | A+B | 80 | 53.5 | 18.96 | 6.26 | 5.46 | 0.96 | 3.13 | 0.82 | 3.47 |
| NA+B | A | 40 | 59.6 | 18.78 | 4.24 | 3.81 | 0.98 | -1.94 | 1.16 | 4.93 |
| NA+A | B | 40 | 53.3 | 19.32 | 4.03 | 3.29 | 0.99 | 2.38 | 0.89 | 5.87 |
| NA+A+B | A+B | 80 | 56.6 | 18.96 | 2.29 | 2.31 | 0.99 | 0.09 | 1.04 | 8.21 |
| Faba bean | | | | | | | | | | |
| NA | A+B | 54 | 50.2 | 14.89 | 6.99 | 6.19 | 0.85 | -3.35 | 0.85 | 2.41 |
| NA+B | A | 27 | 42.9 | 13.25 | 2.17 | 2.05 | 0.98 | 0.81 | 1.07 | 6.46 |
| NA+A | B | 27 | 50.8 | 15.99 | 2.92 | 2.88 | 0.97 | -0.76 | 1.05 | 5.55 |
| NA+A+B | A+B | 54 | 47.3 | 14.89 | 1.75 | 1.71 | 0.99 | -0.44 | 0.99 | 8.71 |
| Soybean | | | | | | | | | | |
| NA | A+B | 25 | 65.0 | 12.61 | 2.26 | 1.57 | 0.99 | 1.66 | 0.94 | 8.03 |
| NA+B | A | 13 | 69.1 | 12.21 | 2.73 | 2.17 | 0.99 | 1.76 | 0.88 | 5.63 |
| NA+A | B | 12 | 61.6 | 11.89 | 1.56 | 1.50 | 0.99 | 0.60 | 0.92 | 7.93 |
| NA+A+B | A+B | 25 | 66.1 | 12.61 | 1.80 | 1.74 | 0.99 | 0.58 | 0.91 | 7.25 |

*All values expressed as % dry matter; Cal: calibration data set; Val: Validation data set; n: Number of samples used in the validation; NA: North Australia forage data set; A: refers half of the Ethiopian maize and grain legumes crop residue samples; B: Refers another half of the Ethiopian maize and grain legumes crop residue (CR) samples; SD: Standard deviation; SEP: Standard error of performance; SEP(C): Bias corrected standard error of performance;* $R^2_v$*: the coefficient of determination in validation; RPDv = SD/SEP – the ratio of SD (standard deviation of validation data) to SEP(C) in the validation set; Bias: mean difference between laboratory and NIR values; Slope: slope of regression between reference and NIR values.*

Table 3.8 Performance of NIR equations for predicting ADF content (%) of maize and legume CR samples (A+B, A or B) with North Australia (NA), NA+B, NA+A and NA+A+B calibration equations

| Cali | Vali | n | Mean | SD | SEP | SEP(C) | $R^2v$ | Bias | Slope | RPDv |
|---|---|---|---|---|---|---|---|---|---|---|
| Maize | | | | | | | | | | |
| NA | A+B | 203 | 48.2 | 6.12 | 4.35 | 3.98 | 0.69 | -1.78 | 0.71 | 1.54 |
| NA+B | A | 102 | 51.3 | 5.11 | 2.22 | 2.22 | 0.91 | -0.23 | 0.76 | 2.30 |
| NA+A | B | 101 | 42.2 | 2.15 | 2.67 | 2.64 | 0.49 | -0.50 | 0.41 | 0.81 |
| NA+A+B | A+B | 203 | 46.5 | 6.12 | 1.31 | 1.31 | 0.95 | -0.06 | 1.01 | 4.67 |
| Common bean | | | | | | | | | | |
| NA | A+B | 97 | 43.5 | 8.66 | 3.45 | 3.31 | 0.86 | 1.01 | 1.06 | 2.62 |
| NA+B | A | 48 | 48.4 | 7.11 | 3.34 | 2.41 | 0.94 | 2.34 | 1.31 | 2.95 |
| NA+A | B | 49 | 39.5 | 4.87 | 2.61 | 2.41 | 0.76 | -1.05 | 0.98 | 2.02 |
| NA+A+B | A+B | 97 | 44.6 | 8.66 | 1.96 | 1.96 | 0.95 | -0.05 | 1.07 | 4.42 |
| Chickpea | | | | | | | | | | |
| NA | A+B | 80 | 38.3 | 14.87 | 4.76 | 3.88 | 0.96 | 2.80 | 1.22 | 3.83 |
| NA+B | A | 40 | 48.7 | 11.45 | 4.52 | 2.94 | 0.97 | 3.47 | 1.22 | 3.89 |
| NA+A | B | 40 | 30.4 | 8.19 | 1.53 | 1.51 | 0.98 | -0.35 | 0.90 | 5.42 |
| NA+A+B | A+B | 80 | 40.7 | 14.87 | 1.77 | 1.74 | 0.99 | 0.38 | 1.02 | 8.55 |
| Faba bean | | | | | | | | | | |
| NA | A+B | 54 | 42.6 | 13.51 | 8.38 | 5.20 | 0.86 | -6.61 | 1.12 | 2.60 |
| NA+B | A | 27 | 41.5 | 14.36 | 4.46 | 3.18 | 0.99 | 3.20 | 1.23 | 4.52 |
| NA+A | B | 27 | 28.4 | 2.90 | 1.90 | 1.53 | 0.75 | -1.16 | 0.84 | 1.90 |
| NA+A+B | A+B | 54 | 35.8 | 13.51 | 1.68 | 1.69 | 0.99 | 0.17 | 1.07 | 7.99 |
| Soybean | | | | | | | | | | |
| NA | A+B | 25 | 50.7 | 12.44 | 2.99 | 3.05 | 0.99 | -0.16 | 1.30 | 4.08 |
| NA+B | A | 13 | 57.6 | 9.43 | 2.98 | 0.99 | 0.99 | 2.83 | 1.07 | 9.53 |
| NA+A | B | 12 | 41.4 | 1.18 | 1.53 | 0.50 | 0.83 | -1.46 | 1.07 | 2.36 |
| NA+A+B | A+B | 25 | 50.7 | 12.44 | 0.88 | 0.90 | 1.00 | -0.08 | 0.96 | 13.82 |

*All values expressed as % dry matter; Cal: calibration data set; Val: Validation data set; n: Number of samples used in the validation; NA: North Australia forage data set; A: refers half of the Ethiopian maize and grain legumes crop residue samples; B: Refers another half of the Ethiopian maize and grain legumes crop residue (CR) samples; SD: Standard deviation; SEP: Standard error of performance; SEP(C): Bias corrected standard error of performance; $R^2_v$: the coefficient of determination in validation; RPDv = SD/SEP – the ratio of SD (standard deviation of validation data) to SEP(C) in the validation set; Bias: mean difference between laboratory and NIR values; Slope: slope of regression between reference and NIR values.*

## 3.4. Discussion

### 3.4.1. Instrument stability and standardization

An aspect of NIRS measurement, including with NIRS measurement of forages, is that small differences in spectral measurements either within an instrument or between instruments of the same model and manufacturer can lead to large errors in the values of attributes predicted from calibration equations (Williams, 1987). The first problem typically occurs when the instrumental response is fluctuating in time and it is therefore essential to

maintain checks of the stability of the instrument. In the present studies this potential problem was addressed by ensuring that full diagnostic tests were conducted daily and by scanning a laboratory standard kept for this purpose several times a day to monitor any instrument instability between or within days. The low coefficient of variation (Table 3.2) indicated that there was little variation in the CQU instrument within or between days on which calibration models were developed.

A second problem and source of error can occur when calibration models developed on one NIRS instrument are used to predict from spectra collected on a second instrument. Various approaches have been developed for performing accurate calibration transfer (Bouveresse and Massart, 1996a, 1996b). These methods include the use of techniques for adjusting spectra from one instrument to match those from other instruments and adjusting calibrations to account for instrument differences, and thus to develop robust calibrations (Pierna et al., 2013). In the present studies this difficulty was alleviated by the CQU instrument being the same model and manufacturer as the CSIRO instrument originally used to measure the spectra used to develop the NA calibration data set and the NA forage calibrations. The CQU instrument was compared with the CSIRO instrument by regular scanning of sealed standards on both instruments and use of the routine procedure in the ISI software to correct for differences. The CSIRO instrument was considered as ‘primary’ or ‘master’ instrument and the CQU instrument as the secondary or ‘host’ instrument (Bouveresse et al., 1998).

### 3.4.2. Reference values and equation development

The wide range in the reference values for each of the constituents was a consequence of the inclusion of very low to high quality forages in the calibration data set (Table 3.2 and 3.3). A broad range of variation in an attribute is desirable in a calibration data set to encompass the population to be predicted subsequently in routine analysis (Alomar et al., 2009). Thus is was expected that the calibration data base used in the present studies would be sufficiently diverse to allow calibrations of satisfactory accuracy and robustness, and this was confirmed by the evaluation by validation of the calibration equations for each attribute.

NIRS analysis depends on the development of calibration equations relating absorbances of light at various wavelengths in the NIR region to the composition of reference samples determined by conventional procedures such as wet chemistry (Dixon and Coates, 2010).

For NIRS calibration to be used on a set of unknown samples the spectral variation in the unknown population must be represented in the calibration set (Windham et al., 1989). A common approach in developing NIRS calibrations to measure forage attributes has been to develop a broad-based equation encompassing a wide range of plant species, plant maturities and morphological components of plants which are then used to measure attributes in other similar but independent populations (Smith and Flinn, 1991). This was the approach used to develop the NA calibration equations, and was continued in the present study. Marten et al. (1984) and Brown et al. (1990) concluded that broad-based calibrations analysed the nutritive value of individual species with a degree of accuracy similar to that of species-specific calibrations. Shenk and Westerhaus (1993) also found that if enough samples are utilised, broad multi-forage species calibrations can be nearly as accurate as those for single species. Furthermore, Abrams et al. (1987) suggested that broad-based NIRS calibrations would reduce the need for detailed sample information that a producer may not know, but all possible sources of variation should be included in the calibration. An alternative approach is to develop single-plant species calibration equations where the variability in the calibration data set is expected to be reduced but it will be expected that more accurate prediction of attributes of the same plant species will be possible. This latter approach was used for the development of attributes of CR in ILRI laboratories in India. Compared to the present study large calibration data sets were available for sorghum (n=729), pearl millet (n=434), groundnut (n=198) (Sharma et al., 2010) (Table 3.10) and maize stover (n=345) (Ramana Reddy et al., 2013) (Table 3.9). Similarly Fekadu et al. (2010b) developed single-species NIRS calibrations but from relatively small calibration sample sets for maize stover (n=72), common bean haulm (n=75-78) and chickpea haulm (n=77-84).

The calibration model values for $R^2$, SEC, and the SD/SECV ratio all indicated that the calibrations were satisfactory for the purpose of measurement of the attributes in the forages and crop residues. Windham et al. (1989) indicated that the $R^2$ should generally be ≥0.9 when developing calibrations to measure the nutritive value of forages. The lower $R^2$ obtained for DMD (0.93) in the present study compared to the $R^2$ for total N (0.98), NDF (0.97) and ADF (0.97) might have been associated with greater error in the measurement of the reference values during laboratory analyses of in vitro DMD and additional sources of variation associated with the animals used as a source of rumen fluid (Campo et al., 2013; Dixon and Coates, 2010).

Table 3.9 Calibration statistics for prediction of chemical and digestibility of maize stover by NIRS in the ILRI laboratories, India

| | Validation | | | Calibration | | |
|---|---|---|---|---|---|---|
| Attribute | n | R2 | SEV | n | R2 | SEC |
| Nitrogen(%) | 345 | 0.94 | 0.06 | 345 | 0.97 | 0.04 |
| NDF(%) | 345 | 0.94 | 1.60 | 345 | 0.97 | 1.10 |
| ADF(%) | 345 | 0.96 | 1.20 | 345 | 0.97 | 0.90 |
| ADL(%) | 345 | 0.82 | 0.40 | 345 | 0.84 | 0.40 |
| IVOMD (%) | 345 | 0.81 | 0.40 | 345 | 0.92 | 0.30 |

*Source: Ramana Reddy et al. (2013). n: Number of samples used in the calibration or validation; N: Nitrogen; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; ADL: acid detergent lignin; IVOMD, in-vitro organic matter digestibility; $R^2$: Good-of-fitness; SEV: standard errors of validation; SEC = standard errors of calibration.*

The SEC data is the standard error between laboratory reference and NIRS measured values in the calibration set (Li et al., 2011). The $R^2$ and SEC values obtained here for DMD% were higher than those reported by other authors (Albanell et al., 1995; Valdes et al., 1987) in maize stover. The $R^2$ and SEC values for total N% in the present study were also higher than those reported by other authors (Albanell et al., 1995; Fekadu et al., 2010b; Ramana Reddy et al., 2013). The $R^2$ values observed in the present study for NDF% and ADF% were comparable with those reported by some authors (Albanell et al., 1995; Fekadu et al., 2010b; Ramana Reddy et al., 2013) for CR, but higher than the values reported by Fekadu et al. (2010a) in natural pasture ($R^2$= 0.79 and 0.75) and Zimmer et al. (1990) in maize stover ($R^2$= 0.90 - 0.92). However, the SEC for NDF% and ADF% was lower than the values reported by Fekadu et al. (2010a) in natural pasture (SEC=4.44 and 2.95) and lower than the reported SEC values for maize stover (Zimmer et al., 1990) (SEC=1.71 and 1.38) and (Ramana Reddy et al., 2013) (1.1 and 0.90; Table 3.9).

The SD/SECV ratio provides a comparison of the performance of all NIRS calibrations independent of the units of measurement (Park et al., 1998). Sinnaeve et al. (1994) suggested that a ratio >2.5 indicates that the calibration is adequate for quality screening purposes and >3.0 indicates that the calibration should perform well for quantitative analyses. In the present study the RPDc for all the calibrations were > 3.4 supporting the validity of the NIRS calibration models for routine analysis of the forage attributes measured. These RPDc values for the measured attributes were higher than the values reported previously (Alomar et al., 2009; Asekova et al., 2016; Campo et al., 2013;

Cozzolino et al., 2006; Norman et al., 2015; Park et al., 1998) but lower than the RPDc for DMD and total N reported by Norman et al. (2015) in temperate forages.

### 3.4.3. Equation performance

Although the calibration statistics discussed above are useful as a first step to evaluate the quality of NIRS calibration equations, the more stringent and important evaluation is the capacity of a calibration to predict attributes in an independent sample set. Thus in the present study these validations were done by allocation of the Ethiopian CR samples to sub-populations A and B and examining the capacity of the NA calibrations, and of calibrations calculated from the NA+A or NA+B sample sets to predict the remaining Ethiopian samples. Crop residue quality attributes as total N, NDF and ADF were very well predicted by NIRS using the NA+A+B with $R^2_v$ ranging from 0.95 to 0.98 (Tables 3.6-3.8). Except in case of total N predictions of soybean residue of population A+B using NA+A+B calibration equation, the $R^2$ (range 0.94-0.98) reported by Sharma et al. (2010) for total N% concentrations of various CR (Table 3.10) were comparable or lower than the values reported in the current study (Table 3.6) but the SEP (range 0.09-0.13) (Table 3.10) were comparable with the values obtained in total N predictions of maize, common bean, chickpea and faba bean residues in the current study (Table 3.6).

A commonly used measure of the strength of the relationship between a dependent variable and independent variable is the $R^2v$ (Scholtz et al., 2009). However, a constituent with small range of values may show lower correlation coefficients (Windham et al., 1989). Thus, Williams (2001) proposed the use of $R^2v$ together with RPDv for appraisal of analytical efficiency by NIRS. However, use and interpretation of RPDv in the literature revealed mixed results. For instance, Williams (2001) suggested RPDv values of 3.1 – 4.9 classified as fair for screening purposes and RPDv values of 5.0 – 6.4 considered to be good for quality assurance. Several authors are however of the opinion that RPDv values higher than 2.5 in any equation are required for an acceptable predictability (Edney et al., 1994; Mathison et al., 1999). On the other hand, Esbensen et al. (2014) has been critical of the ubiquitous use of the RPDv statistic as a sole index of the quality of any NIR calibration without further criteria. One such criterion is RPDv > 3. In the present study this criteria was met for all measurements except for the total N concentration prediction in soybean residue. Satisfactory RPDv values have been reported for total N and NDF and ADF prediction in soybean (Asekova et al., 2016). The poor prediction of the total N concentration in soybean in the present study may have been associated with the small

population size (n=25) and that this material tends to be spectrally different to the other forages and crop residues. Except for total N prediction of soybean, the RPDv values obtained in the present study were higher than the values obtained in whole plant maize (Campo et al., 2013) and barley straw (Mathison et al., 1999) and comparable with the RPDv values in temperate forages (Norman et al., 2015). In general, the RPDv values obtained in the validation data set of the present study for CR quality attributes measured indicates that the better NIRS predictions of the parameters with good accuracy and further confirmed the improved predictive ability and robustness of the of chemometric models developed for DMD, Total N, NDF and ADF based on the NA dataset.

Table 3.10 Calibration statistics for prediction of chemical and digestibility of sorghum and pearl millet stover and groundnut haulms by NIRS in the ILRI laboratories in India

| Crop residue | Attribute | Min | Max | Mean | SD | SEP | $R^2$ |
|---|---|---|---|---|---|---|---|
| Sorghum(n=729) | N | 0.1 | 2.5 | 0.7 | 0.4 | 0.1 | 0.94 |
| | NDF | 34.2 | 84.3 | 66.8 | 6.5 | 2.7 | 0.83 |
| | ADF | 27.5 | 60.1 | 42.6 | 6.5 | 2.0 | 0.91 |
| | ADL | 1.7 | 12.1 | 4.6 | 1.9 | 0.6 | 0.82 |
| | IVOMD | 30.0 | 77.8 | 49.0 | 6.6 | 1.9 | 0.90 |
| Pearl millet(n=434) | N | 0.2 | 2.9 | 0.99 | 0.55 | 0.13 | 0.94 |
| | NDF | 53.5 | 79.8 | 65.6 | 6.5 | 2.3 | 0.87 |
| | ADF | 31.8 | 55.0 | 42.5 | 4.7 | 2.1 | 0.81 |
| | ADL | 1.9 | 8.0 | 4.8 | 1.3 | 0.5 | 0.84 |
| | IVOMD | 26.1 | 62.4 | 42.8 | 5.9 | 2.0 | 0.83 |
| Groundnut(n=198) | N | 0.83 | 3.4 | 1.9 | 0.63 | 0.09 | 0.98 |
| | NDF | 25.9 | 57.2 | 41.2 | 9.0 | 1.5 | 0.98 |
| | ADF | 17.4 | 47.6 | 32.8 | 9.3 | 1.8 | 0.96 |
| | ADL | 2.5 | 11.1 | 6.7 | 2.3 | 0.8 | 0.88 |
| | IVOMD | 45.4 | 72.7 | 58.5 | 5.5 | 1.5 | 0.93 |

*Source: Sharma et al. (2010).*

*n: Number of samples used in the calibration; N: Nitrogen; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; ADL, acid detergent lignin; IVOMD, in vitro organic matter digestibility; SD, Standard Deviation; SEP: Standard error of prediction; $R^2$: the Good-of-fitness.*

The SEP is the standard error between the predicted values of the validation set and the corresponding laboratory analyses (Li et al., 2011). SEP(C) is the standard error of performance corrected for the observed *bias,* and where *bias* is an estimate of the mean difference between laboratory determined and NIRS predicted values for calibration sets (Smith and Flinn, 1991). The number of samples is important in calibration and small calibration sets may not accurately represent unknown populations (Windham et al.,

1989). Windham et al. (1989) suggested that the minimum number of samples to develop an adequate calibration equation for any forage quality parameters is 50 in a narrow-based population and 150 in a broad-based population. In addition, the calibration population should be representative of major factors influencing sample physical, chemical and botanical characteristics (Shenk et al., 1993; Windham et al., 1989). In this study, each species (except soybean) was representative of a fairly broad-based population since sampling occurred from multiple varieties, harvesting stage, morphological fractions, sites, and seasons. In contrast however, the soybean crop residue samples were collected from a single season, relatively few varieties, one site, one trial, and one harvesting stage.

The potential use of NIRS to measure protein, digestibility and fibrous fractions of CR has been documented in maize (Albanell et al., 1995; Fekadu et al., 2010b; Ramana Reddy et al., 2013; Zimmer et al., 1990) and various food legume species (Fekadu et al., 2010b; Sharma et al., 2010). However, the use of broad-based multi-forage/CR species NIR calibration to predict the nutritive value of CR has not been documented. SEP and $R^2$ values comparable to the present study were also reported for NDF% and ADF% by Sharma et al. (2010) (Table 3.10). Comparable $R^2$v values have also been reported by Cozzolino et al. (2001), Ramana Reddy et al. (2013) and Zimmer et al. (1990) in maize stover. These $R^2$v values were higher than the values reported by Albanell et al. (1995) in maize stover. The DMD was also well predicted ($R^2$v range 0.90-0.98) in the present study and higher than the $R^2$v values reported by Valdes et al. (1987) and Albanell et al. (1995) in maize stover. This is not unexpected, since NIRS was successfully used to predict these attributes in maize stover (Melchinger et al., 1986; Ramana Reddy et al., 2013) and generally in a wide range of forages (Deaville and Flinn, 2000). Norris et al. (1976) were the first to report that NIRS (scanning monochromator instrument) could reasonably predict forage quality in vivo. They found $R^2$v values of 0.78, 0.64, and 0.72, respectively, for DMD, DM intake, and digestible energy intake of grass and legume forages by sheep.

### 3.5. Conclusion

The results reported in this chapter indicate that it was possible to develop robust broad-based forage NIRS calibration equations to measure the attributes of DMD and Total N, NDF and ADF concentrations in residues of maize, common bean, chickpea, faba bean and soybean crops in Ethiopia. NIRS could be used reliably for rapid measurement of large batches of these CR samples from field trials in Ethiopia. Nevertheless, an increase in number of samples in the calibration data sets to represent a greater range in variation

in crop attributes from temporal (e.g. season), spatial (e.g. site or geographic location) and biological (e.g. crop variety, stage of growth at harvest or morphological fractions) would be desirable to improve the accuracy and robustness of the prediction of attributes.

# Chapter 4 Maize grain and stover yield and stover quality as affected by genotype, environment and plant density

## 4.1. Introduction

Crop residues (CR), and particularly maize stover, are important in smallholder systems but their use as animal feedstuffs clearly competes with other demands. Hence, improving the yield and nutritive value of maize stover as a ruminant feedstuff without reducing grain yield or quality as food would be valuable in smallholder farming systems. Yields of maize grain and stover, and stover nutritive values, are potentially influenced by numerous interactions including genotype (G), environment (site and year) (E) and agronomic management (M) including plant density and morphological fractions of the stover. Large resources are invested by plant breeding institutions to identify genotypes most suitable for ranges of environments (e.g. genotypes that possess high yield stability or minimum interaction with the environment), for increased grain yield (Abera et al., 2006; Bogale et al., 2012a; Gambin et al., 2016; Worku and Zelleke, 2008). However, little consideration is usually given to examining the G and E effects on the yield or quality of the CR (Ertiro et al., 2013a) even though these are often very important in crop-livestock systems.

Agronomic management has large effects on grain yield (GY) and can also be expected to affect the yield and characteristics of CR important to their quality as ruminant animal feedstuffs. One usually simple management manipulation is to change plant population density (D). Optimum D of maize depends in part on G (Cox, 1996; Widdicombe and Thelen, 2002a). Maize hybrids have differing optimum plant densities for GY due to their different canopy architecture (Tollenaar and Wu, 1999). Within certain ranges increasing plant D (e.g., 4-10 plants/$m^2$) in maize has increased grain and whole plant yield in association with increases in leaf area index), light interception and whole crop growth rate (Cox, 1996; Cox and Cherney, 2011; Tollenaar and Bruulsema, 1988). Such increases in maize yields have been attributed to greater crowding stress tolerance of modern hybrids (Raymond et al., 2009; Tokatlidis and Koutroubas, 2004), lower lodging frequencies (Tollenaar, 1989), greater N use efficiency (McCullough et al., 1994), higher leaf photosynthesis rates (Dwyer et al., 1991) and more efficient stomatal conductance and leaf photosynthesis under water stress (Dwyer et al., 1992).

Maize hybrids respond differently under various environmental and agronomic (including plant density) factors which influence yields of grain and forage and forage quality (Cox,

1997; Cox and Cherney, 2011; Stanton et al., 2007; Thomison and Jordan, 1995). Decreases in forage quality at high plant density (e.g. range 4.5-15 plant/$m^2$) have also been reported (Cox and Cherney, 2011; Stanton et al., 2007; Widdicombe and Thelen, 2002b). Numerous studies have focused on the effect of row spacing and/or plant population on maize grown for forage or silage in temperate regions. However, because maize grown for this purpose is harvested at much earlier maturity than for grain, this information is of limited value to understand the effects of G and D on the yield and quality of maize stover grown under tropical environments and harvested at grain maturity. In Ethiopia for instance maize hybrids have been selected for improved GY and resistance to stress, and recommended D is 4.4-5.3 plants/$m^2$ depending up on G maturity and E (Admassu et al., 2008; Anley et al., 2013; Baudron et al., 2014). Higher plant D of modern maize hybrids may increase grain and stover yields without reducing stover quality. The present study was therefore initiated to determine the effect of maize G, E and plant D on stover and grain yields and on stover quality as a ruminant feedstuff.

## 4.2. Materials and Methods

### 4.2.1. Site descriptions and experimental design

Field studies were conducted in 2013 and 2014 at three sites in Ethiopia: Bako ($9^0$12'N, $37^0$08'E, 1650masl on clay soil), Hawassa ($7^0$03'N, $38^0$31'E, 1689masl on clay loam soil) and Melkassa ($8^0$24'N, $39^0$21'E, 1550masl on clay loam soil), (Table 4.1 and Appendix Figure A4.1). These sites were chosen to represent major maize growing environments in the sub-humid zone (high potential) (Bako and Hawassa) and the semi-arid (low potential) (Melkassa) in ESA. The experimental design was a randomized complete block with a split-plot arrangement of treatments and three replications. Main plots were plant density (5 or 7 plants/$m^2$) and subplots were three maize hybrids, termed here genotypes representing early maturity (EM) (MH-130, SC-403, and THI3321) (130 day) and three representing medium maturity (MM) (BH-540, BH-543 and BH-546) (145 day). Agronomic and climatic information are given in Table 4.1. All plots were planted by hand with six rows (75-cm wide) by 5.1m long planted at two seeds per hill which were later thinned within 10 days after emergence to achieve plant densities of 5 and 7 plants/$m^2$, respectively. Fertilizer was applied at 46 kg $P_2O_5$/ha (at planting) and 100kg N/ha (33% at planting and 67% 45 days after planting) to each plot. At all sites the crop during the previous season had been maize. Data on GY, total biomass yield and yield related data were collected as a separate agronomic experiment of a PhD student of UQ, QAAFI.

### 4.2.2. Measurements

At the grain harvest maturity stage all plants in the centre two rows of the plot were counted to measure plant D and the above ground biomass was hand-harvested at soil level. After removing the ears with the cob from the husk, the residues (stover) of each plant were collected and the fresh weight measured. Four randomly selected maize plants from each of the three replicated plots were sub-sampled and fresh weights of aboveground biomass were recorded individually. Another four randomly selected maize plants from each of the three replicated plots were sub-sampled, ear removed from the husk and fresh weight of the stover and morphological fractions were recorded individually. Total above-ground plant biomass (stover + ear) (TB), stover sub-samples were mechanically chopped and stored in cotton bags and dried (60$^{o}$C) to determine DM content. Stover sub-samples were ground through a 1 mm screen using laboratory hammer mill (Christy and Norris Limited, England, Type 8 inch), and stored at ambient temperature pending laboratory analyses.

Yields (t/ha) of TB (TBY), grain (GY) and stover (SY) were summed and adjusted for population density. Harvest index (HI) was calculated as the ratio of seed DM yield to total above ground biomass DM yield at harvest. The grain yield (GY) is reported herein on a DM basis. The quality parameters of stover were calculated from the composition and proportions of the various fractions. The yields of total N and digestible DM (DDMY)/ha of the stover were calculated from the DM yield and N content or DMD. The potential utility index (PUI; a measure that integrates GY with DDM stover yield) was calculated (Fleischer et al., 1989; Tolera et al., 2008) as:

$$\text{PUI} = \frac{\text{Grain yield} + \text{DDM stover yield}}{\text{Total above ground biomass DM yield}} \text{ x } 100$$

Neutral detergent fibre digestibility (NDFD) was calculated as 100 x (DMD – (100 – NDF))/NDF assuming that the neutral detergent soluble fraction was completely digestible (Barrière et al., 2003).

### 4.2.3. Laboratory analyses

Forage samples were air-freighted to Australia and, to meet quarantine requirements, were gamma irradiated (25k Gray) at entry. Constituents of the forage materials (concentrations of total N, neutral detergent fibre (NDF) and acid detergent fibre (ADF),

and the dry matter digestibility (DMD)) were determined by near infrared reflectance spectroscopy (NIRS) of dried and ground samples (Chapter 3).

Table 4.1 Planting and harvesting date, monthly and long term (1982-2014) total rainfall and average minimum-maximum temperature in 2013 and 2014 cropping seasons by site

| | Bako | | | Hawassa | | | Melkassa | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2013 | 2014 | 33 years | 2013 | 2014 | 33 years | 2013 | 2014 | 33 years |
| Planting date | 5Jun | 6June | - | 10May | 21May | - | 4July | 9July | - |
| Harvesting date | 5Dec | 15Nov | - | 23Oct | 24Oct | - | 7 Dec | 23Nov | - |
| Total rainfall monthly (mm) | | | | | | | | | |
| May | - | - | - | 134 | 152 | 128 | - | - | - |
| June | 288 | 260 | 255 | 123 | 84 | 106 | - | - | - |
| July | 342 | 222 | 260 | 164 | 73 | 127 | 399 | 165 | 196 |
| August | 301 | 135 | 253 | 153 | 202 | 128 | 122 | 136 | 195 |
| September | 140 | 137 | 142 | 124 | 153 | 129 | 139 | 150 | 105 |
| October | 113 | 71 | 72 | 103 | 95 | 75 | 31 | 83 | 37 |
| November | 45 | 5 | 25 | - | - | - | 15 | 21 | 12 |
| December | 0 | - | 13 | - | - | - | 0 | - | 11 |
| Total | 1228 | 830 | 1019 | 801 | 758 | 694 | 706 | 555 | 556 |
| Monthly average Min-Max temperature ($^{O}$C) | | | | | | | | | |
| May | - | - | - | 14.6-26.3 | 14.4-27.5 | 14.1-27.1 | - | - | - |
| June | 14.7-26.1 | 14.0-27.3 | 14.9-26.0 | 15.0-25.7 | 14.5-27.2 | 14.2-25.7 | - | - | - |
| July | 14.6-25.3 | 14.6-25.3 | 14.9-24.1 | 14.7-24.3 | 14.9-25.1 | 14.3-24.5 | 16.0-26.1 | 17.0-28.4 | 15.8-26.8 |
| August | 15.2-24.4 | 14.6-24.5 | 14.8-24.1 | 14.6-25.1 | 14.2-25.6 | 14.2-24.9 | 16.2-26.4 | 16.1-26.7 | 15.4-26.2 |
| September | 14.7-25.6 | 14.3-25.0 | 14.5-25.1 | 14.0-26.8 | 14.7-25.5 | 13.6-25.7 | 14.7-28.3 | 14.9-27.2 | 14.4-27.5 |
| October | 14.6-27.4 | 14.7-27.4 | 13.2-27.3 | 13.6-26.4 | 13.8-26.7 | 12.3-26.9 | 12.2-28.7 | 12.5-27.4 | 11.7-28.6 |
| November | 13.4-29.5 | 13.6-28.7 | 12.0-28.6 | - | - | - | 11.4-28.0 | 11.4-28.5 | 10.8-28.3 |
| December | 10.3-30.2 | - | 11.2-29.3 | - | - | - | 7.7-27.3 | - | 10.5-27.5 |
| Mean | 13.9-26.9 | 14.3-26.4 | 14.3-26.4 | 14.4-25.8 | 14.4-26.3 | 13.8-25.8 | 13.0-27.5 | 14.4-27.6 | 13.1-27.5 |

In brief the samples were scanned in duplicate using a Foss 6500 NIR spectrometer fitted with a spinning cup module. Chemometric analyses were conducted with WinISI software version 4.6.11. The concentrations of total N, NDF, ADF, and the DMD of the forages, were predicted initially using existing north Australian forage calibrations developed from tropical forages (D.B. Coates and R.M., unpublished). These calibration data sets were expanded by laboratory analyses of a subset of samples (15-20%) selected on the basis of high GH values (Shenk and Westerhaus, 1991b) and revised and modified calibration equations suitable for EA CR were calculated and validated. The modified calibration were used to predict the constituents in the maize stover samples.

### 4.2.4. Statistical analyses

Analysis of variance was performed using the GLM procedure available from SAS (2009). Since interactions were detected for treatments across sites (Tables 4.2 4.5 and 4.8) the results from each site across years were also analysed and are presented separately. In the analysis, replicate was considered as nested within year (Y) and the replication (Y) mean square (MS) was used as the error term for testing the significance of the year MS. At each site the MS for D and Y x D were tested using the D x replication (Y) MS error term. MS for genotype (G) and their interactions with Y and D were tested against the residual MS error term. When averaged across sites and years, the MS for site (S) and Y x S were tested using the S x replication (Y) error term, the MS for D, Y x D, S X D and Y x S x D effects were tested using D x S x replication (Y) error term and MS for G and their interactions with Y, S, and D were tested against the residual MS error term. Means were compared using the LSD test to separate main effects of plant D, G and S where F-tests indicated significant differences ($P<0.05$). Because the EM and MM genotypes had to be harvested at the same time due to experimental constraints rather than at optimal grain maturity stage, the statistical comparisons between EM and MM genotypes were not conducted as a main factor in the ANOVA.

## 4.3. Results

### 4.3.1. Total biomass, grain and stover yields and HI across years by site

Total rainfall was higher in 2013 than 2014 across all sites (Table 4.1). Mean square and mean values for TB, grain, stover and HI across 2 years by site and across sites, and maturity group are presented in Tables 4.2 and 4.3, respectively. Most measures of yield attributes (TBY, SY ad HI) showed significant response to the environmental factor year at the sub-humid sites (Bako and Hawassa), but no response at the semi-arid site Melkassa. TBY and SY were higher ($P<0.05$ or $P<0.01$) and HI was lower ($P<0.01$) in 2013 than in 2014 at Bako and Hawassa (Table 4.3). GY was affected by year ($P<0.05$) at Bako site in the EM group, but not ($P>0.05$) at the other sites.

Higher plant density (D) increased GY at both the sub-humid sites but not at the semi-arid site (Melkassa). Higher plant D increased GY by 5.1% in MM group at Bako and by 19.4% in EM and 11.6% in MM group at Hawassa. Higher plant D also increased ($P<0.05$) TBY and SY in EM genotypes by 28.7% and 37.1% at Bako and by 21.8% and 25.0% at Melkassa, respectively. In the MM genotype group there were also effects on TBY and SY

(P<0.01) at Melkassa (by 16.4% and 17.1%, respectively) and on TBY (P<0.05) at Hawassa by 21.1%. In general, TB, grain and stover yields were higher at a plant D of 7 plants/$m^2$ than at 5 plants/$m^2$ (Table 4.3).

Table 4.2 Early (EM) and Medium (MM) maturing maize genotypes mean square for yield attributes across 2 years by site and pooled across years and sites by maturity group

| | | | EM genotype | | | | MM genotype | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Site | Source | df | TBY | GY | SY | HI | TBY | GY | SY | HI |
| Bako | Year (Y) | 1 | 86* | 7.9* | 109* | 0.076** | 800**** | 19.6 | 805**** | 0.342*** |
| | Error 1 | 4 | 9 | 0.3 | 6 | 0.003 | 2 | 2.7 | 1 | 0.003 |
| | Density (D) | 1 | 232* | 6.2 | 122* | 0.017 | 96 | 1.2* | 57 | 0.007 |
| | Y x D | 1 | 11 | 1.7* | 16* | 0.006* | 19 | 0.0 | 14 | 0.000 |
| | Error 2 | 4 | 14 | 1.4 | 7 | 0.003 | 28 | 0.2 | 19 | 0.001 |
| | Genotype (G) | 2 | 55*** | 14.5**** | 10* | 0.004 | 37* | 8.3**** | 8 | 0.002 |
| | Y x G | 2 | 1 | 1.3* | 1 | 0.002 | 8 | 2.0** | 2 | 0.000 |
| | D x G | 2 | 0 | 0.0 | 0 | 0.000 | 1 | 0.2 | 0 | 0.000 |
| | Y x D x G | 2 | 4 | 0.7 | 1 | 0.000 | 0 | 0.1 | 0 | 0.000 |
| | Error 3 | 16 | 3 | 0.2 | 3 | 0.001 | 9 | 0.3 | 7 | 0.001 |
| | CV% | | 9.0 | 6.5 | 14.3 | 10.0 | 12.9 | 6.8 | 18.5 | 8.8 |
| Hawassa | Year (Y) | 1 | 563** | 3.8 | 357** | 0.115** | 497** | 1.2 | 337*** | 0.082** |
| | Error 1 | 4 | 11 | 1.8 | 5 | 0.002 | 7 | 1.2 | 4 | 0.002 |
| | Density (D) | 1 | 184 | 15.9** | 69 | 0.001 | 172* | 7.5* | 81 | 0.007 |
| | Y x D | 1 | 28** | 0.0 | 21** | 0.002 | 61** | 3.1* | 27* | 0.000 |
| | Error 2 | 4 | 28 | 0.7 | 18 | 0.005 | 18 | 0.5 | 14 | 0.005 |
| | Genotype (G) | 2 | 50**** | 24.4**** | 4 | 0.006* | 54*** | 18.4**** | 23** | 0.017** |
| | Y x G | 2 | 10* | 1.3 | 3 | 0.000 | 20* | 1.0 | 21* | 0.010* |
| | D x G | 2 | 23** | 0.0 | 19** | 0.006* | 2 | 0.6 | 2 | 0.002 |
| | Y x D x G | 2 | 11* | 0.1 | 7 | 0.000 | 0. | 0.2 | 0 | 0.000 |
| | Error 3 | 16 | 2 | 0.5 | 2 | 0.001 | 5 | 0.5 | 3 | 0.002 |
| | CV% | | 7.6 | 9.1 | 13.3 | 8.8 | 9.2 | 8.7 | 14.4 | 12.1 |
| Melkassa | Year (Y) | 1 | 59 | 0.6 | 36 | 0.011 | 38 | 0.3 | 34 | 0.014 |
| | Error 1 | 4 | 55 | 12 | 17 | 0.009 | 22 | 3.3 | 10 | 0.005 |
| | Density (D) | 1 | 102* | 4.1 | 49* | 0.006 | 68**** | 2.8 | 33** | 0.001 |
| | Y x D | 1 | 1 | 0.0 | 1 | 0.000 | 2 | 0.4 | 3 | 0.005* |
| | Error 2 | 4 | 6 | 1.7 | 4 | 0.005 | 0 | 0.6 | 1 | 0.001 |
| | Genotype (G) | 2 | 23* | 1.0 | 12* | 0.004** | 31* | 4.6* | 9 | 0.002 |
| | Y x G | 2 | 2 | 2.3** | 1 | 0.007*** | 0 | 0.3 | 1 | 0.001 |
| | D x G | 2 | 0 | 0.5 | 0 | 0.001 | 13 | 2.5 | 3 | 0.001 |
| | Y x D x G | 2 | 0 | 0.3 | 1 | 0.001 | 0 | 0.0 | 0 | 0.000 |
| | Error 3 | 16 | 5 | 0.4 | 2 | 0.001 | 7 | 0.9 | 3 | 0.001 |
| | CV% | | 12.7 | 11.0 | 14.4 | 7.3 | 14.3 | 21.1 | 14.7 | 12.9 |
| Pooled | Year (Y) | 1 | 213** | 0.9 | 182*** | 0.087** | 1072*** | 5.1 | 920*** | 0.327*** |
| | Error 1 | 4 | 6 | 2.0 | 2 | 0.003 | 13 | 1.0 | 6 | 0.001 |
| | Site (S) | 2 | 96 | 43.4* | 13 | 0.051** | 273*** | 142.8**** | 29* | 0.160**** |
| | Y x S | 2 | 248**** | 5.7**** | 160**** | 0.058**** | 131**** | 8.1**** | 128**** | 0.055**** |
| | Error 2 | 8 | 34 | 6.3 | 12 | 0.005 | 9 | 3.2 | 4 | 0.004 |
| | Density (D) | 1 | 504*** | 24.1*** | 232*** | 0.020* | 324*** | 10.2*** | 165** | 0.013* |
| | Y x D | 1 | 18* | 0.5 | 18** | 0.005* | 38* | 2.1 | 17 | 0.001 |
| | S x D | 2 | 7 | 1.0 | 4 | 0.002 | 6 | 0.7 | 3 | 0.001 |
| | Y x S x D | 2 | 11 | 0.6 | 10* | 0.001 | 22* | 0.7 | 14 | 0.002 |
| | Error 3 | 12 | 16 | 1.3 | 10 | 0.004 | 15 | 0.4 | 11 | 0.003 |
| | Genotype (G) | 2 | 101**** | 28.8**** | 18** | 0.007** | 86**** | 28.2**** | 15* | 0.015*** |
| | Y x G | 2 | 9 | 4.2**** | 1 | 0.003 | 5 | 2.2* | 6 | 0.007** |
| | S x G | 4 | 14** | 5.5**** | 4 | 0.004** | 18* | 1.5* | 12* | 0.003 |
| | Y x S x G | 4 | 2 | 0.4 | 2 | 0.003* | 12 | 0.5 | 9 | 0.002 |
| | D x G | 2 | 8 | 0.2 | 7 | 0.002 | 4 | 2.2* | 0 | 0.003 |
| | Y x D x G | 2 | 7 | 0.6 | 4 | 0.001 | 0 | 0.2 | 0 | 0.000 |
| | S x D x G | 4 | 8 | 0.2 | 6* | 0.003* | 6 | 0.5 | 3 | 0.000 |
| | Y x S x D x G | 4 | 4 | 0.2 | 3 | 0.000 | 0 | 0.1 | 0 | 0.000 |
| | Error 4 | 48 | 4 | 0.3 | 2 | 0.001 | 7 | 0.6 | 4 | 0.001 |
| | CV% | | 9.8 | 8.8 | 14.0 | 8.9 | 12.1 | 11.1 | 16.2 | 11.4 |

**Significant at P<0.05; ** Significant at P<0.01; ***Significant at P<0.001; ***Significant at P<0.0001;*

*TBY: Total biomass yield; GY: Grain yield; SY: Stover yield; HI: harvest index*

Table 4.3 Effects of year, plant density or genotype on maize yield attributes across 2 years by site and maturity group

| Site | Source of variation | | EM genotype* yield (t/ha) and HI | | | | MM genotype* yield (t/ha) and HI | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | TBY | GY | SY | HI | TBY | GY | SY | HI |
| Bako | Year | 2013 | 21.9$^{a}$ | 6.60$^{b}$ | 13.3$^{a}$ | 0.31$^{b}$ | 28.1$^{a}$ | 6.67 | 18.6$^{a}$ | 0.24$^{b}$ |
| | (n=18) | 2014 | 18.8$^{b}$ | 7.54$^{a}$ | 9.8$^{b}$ | 0.40$^{a}$ | 18.7$^{b}$ | 8.14 | 9.1$^{b}$ | 0.44$^{a}$ |
| | P>F | | 0.0353 | 0.0444 | 0.0105 | 0.0067 | <0.0001 | 0.0551 | <0.0001 | 0.0003 |
| | LSD | | 2.742 | 0.898 | 2.134 | 0.050 | 1.338 | 1.529 | 0.876 | 0.047 |
| | Density | 5 | 17.8$^{b}$ | 6.65 | 9.7$^{b}$ | 0.38 | 21.8 | 7.22$^{b}$ | 12.6 | 0.35 |
| | (n=18) | 7 | 22.9$^{a}$ | 7.49 | 13.3$^{a}$ | 0.33 | 25.0 | 7.59$^{a}$ | 15.1 | 0.32 |
| | P>F | | 0.0161 | 0.1003 | 0.0140 | 0.0611 | 0.1387 | 0.0485 | 0.1552 | 0.0899 |
| | LSD | | 3.522 | 1.086 | 2.451 | 0.047 | 4.915 | 0.368 | 3.985 | 0.034 |
| | Genotype (n=12) | | | | | | | | | |
| | 1 | | 18.0$^{b}$ | 5.88$^{c}$ | 10.5$^{b}$ | 0.33 | 21.9$^{b}$ | 6.61$^{c}$ | 13.3 | 0.33 |
| | 2 | | 20.7$^{a}$ | 7.30$^{b}$ | 11.7$^{ab}$ | 0.36 | 23.0$^{ab}$ | 7.34$^{b}$ | 13.5 | 0.34 |
| | 3 | | 22.3$^{a}$ | 8.04$^{a}$ | 12.3$^{a}$ | 0.37 | 25.3$^{a}$ | 8.27$^{a}$ | 14.8 | 0.35 |
| | P>F | | 0.0001 | <0.0001 | 0.0489 | 0.0612 | 0.0370 | <0.0001 | 0.3155 | 0.1388 |
| | LSD | | 1.584 | 0.399 | 1.427 | 0.031 | 2.620 | 0.437 | 2.221 | 0.026 |
| Hawassa | Year | 2013 | 23.9$^{a}$ | 7.83 | 13.9$^{a}$ | 0.33$^{b}$ | 26.8$^{a}$ | 8.55 | 15.8$^{a}$ | 0.33$^{b}$ |
| | (n=18) | 2014 | 16.0$^{b}$ | 7.18 | 7.6$^{b}$ | 0.45$^{a}$ | 19.4$^{b}$ | 8.18 | 9.7$^{b}$ | 0.42$^{a}$ |
| | P>F | | 0.0019 | 0.2191 | 0.0010 | 0.0010 | 0.0012 | 0.3724 | 0.0006 | 0.0021 |
| | LSD | | 3.027 | 1.237 | 2.048 | 0.037 | 2.525 | 1.017 | 1.755 | 0.037 |
| | Density | 5 | 17.6 | 6.84$^{b}$ | 9.4 | 0.40 | 20.9$^{b}$ | 7.90$^{b}$ | 11.3 | 0.39 |
| | (n=18) | 7 | 22.2 | 8.17$^{a}$ | 12.1 | 0.38 | 25.3$^{a}$ | 8.82$^{a}$ | 14.3 | 0.36 |
| | P>F | | 0.0625 | 0.0082 | 0.1241 | 0.6066 | 0.0352 | 0.0159 | 0.0736 | 0.3024 |
| | LSD | | 4.905 | 0.756 | 3.964 | 0.062 | 3.882 | 0.632 | 3.458 | 0.065 |
| | Genotype (n=12) | | | | | | | | | |
| | 1 | | 18.8$^{b}$ | 6.59$^{b}$ | 10.6 | 0.38$^{b}$ | 21.1$^{b}$ | 6.97$^{b}$ | 12.2$^{b}$ | 0.35$^{b}$ |
| | 2 | | 18.7$^{b}$ | 6.78$^{b}$ | 10.3 | 0.38$^{b}$ | 25.3$^{a}$ | 8.76$^{a}$ | 14.3$^{a}$ | 0.36$^{b}$ |
| | 3 | | 22.3$^{a}$ | 9.15$^{a}$ | 11.4 | 0.42$^{a}$ | 22.9$^{b}$ | 9.35$^{a}$ | 11.8$^{b}$ | 0.42$^{a}$ |
| | P>F | | <0.0001 | <0.0001 | 0.1940 | 0.0160 | 0.0007 | <0.0001 | 0.0077 | 0.0038 |
| | LSD | | 1.316 | 0.590 | 1.235 | 0.030 | 1.846 | 0.627 | 1.593 | 0.039 |
| Melkassa | Year | 2013 | 16.0 | 5.29 | 9.3 | 0.33 | 19.5 | 4.44 | 13.1 | 0.23 |
| | (n=18) | 2014 | 18.6 | 5.56 | 11.3 | 0.30 | 17.5 | 4.63 | 11.1 | 0.27 |
| | P>F | | 0.3579 | 0.8309 | 0.2194 | 0.3333 | 0.2600 | 0.7714 | 0.1411 | 0.1632 |
| | LSD | | 1.471 | 0.403 | 0.991 | 0.017 | 4.334 | 1.692 | 2.941 | 0.065 |
| | Density | 5 | 15.6$^{b}$ | 5.09 | 9.2$^{b}$ | 0.33 | 17.1$^{b}$ | 4.26 | 11.1$^{b}$ | 0.25 |
| | (n=18) | 7 | 19.0$^{a}$ | 5.76 | 11.5$^{a}$ | 0.30 | 19.9$^{a}$ | 4.81 | 13.0$^{a}$ | 0.24 |
| | P>F | | 0.0135 | 0.1991 | 0.0290 | 0.3495 | <0.0001 | 0.1022 | 0.0034 | 0.4446 |
| | LSD | | 1.471 | 0.403 | 0.991 | 0.017 | 0.437 | 0.730 | 0.847 | 0.032 |
| | Genotype (n=12) | | | | | | | | | |
| | 1 | | 17.2$^{ab}$ | 5.20 | 10.4$^{ab}$ | 0.30$^{b}$ | 16.7$^{b}$ | 3.87$^{b}$ | 11.1 | 0.24 |
| | 2 | | 16.0$^{b}$ | 5.33 | 9.3$^{b}$ | 0.34$^{a}$ | 19.0$^{a}$ | 4.65$^{ab}$ | 12.5 | 0.24 |
| | 3 | | 18.8$^{a}$ | 5.74 | 11.3$^{a}$ | 0.31$^{b}$ | 19.8$^{a}$ | 5.09$^{a}$ | 12.7 | 0.26 |
| | P>F | | 0.0236 | 0.0966 | 0.0136 | 0.0071 | 0.0285 | 0.0201 | 0.0873 | 0.2442 |
| | LSD | | 1.904 | 0.518 | 1.282 | 0.020 | 2.282 | 0.827 | 1.542 | 0.028 |

*P<0.05 and P<0.01indicates significant and highly significant genotypes mean respectively; Means with no superscript letters are not significantly different (P>0.05); EM: Early maturing; MM: Medium maturing; TBY: Total biomass yield; GY: Grain yield; SY: Stover yield; HI: Harvest index; LSD: Least significant difference (P=0.05); CV: Coefficient of variation; NS: Non-significant; *EM genotypes (1=MH-130; 2=SC-403; 3= TH13321);*MM genotypes (1=BH-540; 2=BH=543; 3=BH-546).*

Plant D did not affect HI in either maturity groups at any site (Table 4.3). Year x D interactions were significant for some measures of yield attributes at each site (Table 4.2).

Genotype affected most yield attributes. The genotypic variance components in EM group were highly significant (P<0.001) for TBY and GY at Bako and Hawassa and for SY, HI (P<0.01) and TBY (P<0.05) at Melkassa, and for SY and HI (P<0.05) at Bako and

Hawassa, respectively (Table 4.2). Genotype means in the EM group varied in TBY at Bako, Hawassa and Melkassa by 4.3, 3.6 and 2.8 t/ha, respectively, in GY at Bako and Hawassa by 2.16 and 2.56 t/ha, respectively and in SY at Bako and Melkassa by 1.8 and 2.0 t/ha, respectively. Genotype means in the MM group differed ($P<0.01$) for all yield measures at Hawassa and for GY ($P<0.0001$) at Bako. Grain yield at Bako, Hawassa and Melkassa varied by 1.66, 2.38 and 1.22 t/ha, respectively, SY at Hawassa varied by 2.5 t/ha and TBY varied ($P<0.05$) at Bako and Melkassa by 3.4 and 3.1 t/ha, respectively. Significant G x Y interactions was observed in some of the yield attributes measured at each site (Table 4.2). The interactions of G x D were significant ($P<0.01$) for TB and stover yields and HI ($P<0.05$) at Hawassa site in EM genotype (Table 4.3).

### 4.3.2. Total biomass, grain and stover yields and HI across years and sites

Productivity differed greatly ($P<0.01$) between years in most yield parameters measured (Table 4.2), but there was only a trend for these effects ($P<0.10$), or no effect ($P>0.10$) on GY, within each maturity group (Table 4.4). Mean stover yields were 27% and 58% higher, and HI 15% and 42% lower in 2013 than in 2014 in EM and MM genotypes, respectively (Table 4.4).

Site had significant effects ($P<0.05$ and $P<0.01$) on most yield parameters measured except for the TBY and SY ($P>0.1$) in the EM group. As expected in both EM and MM groups, productivity was higher in the sub-humid environments (Hawassa and Bako sites) by 30-39% and 63-85% for GY and by 9-22% and 36-48% for HI in EM and MM genotypes, respectively, than in semi-arid environment at Melkassa (Table 4.4).

The higher plant D increased ($P<0.01$ or $P<0.001$) TBY by 26 and 18%, GY by 15 and 9% and SY by 31 and 21% but reduced ($P<0.05$) HI by 9 and 7% in EM and MM genotypes, respectively (Table 4.4). Year x D interactions were important for TBY ($P<0.05$), SY ($P<0.01$) and HI ($P<0.05$) in EM genotypes and for TBY ($P<0.05$) in MM genotypes (Table 4.2).

Genotypes within both maturity group varied ($P<0.05$ or $P<0.01$) in all attributes of yield. GY varied by 1.75 t/ha within both EM and MM genotypes, SY varied by 1.3 and 1.2 t/ha, TBY by 3.1 and 2.8 t/ha, and HI ranged from 0.34-0.36 and from 0.30-0.34 in EM and MM groups, respectively (Table 4.4).

Table 4.4 Effects of year, site, plant density or genotype on maize yield attributes by maturity group

| | EM genotype yield (t/ha) and HI | | | | MM genotype yield (t/ha) and HI | | | |
|---|---|---|---|---|---|---|---|---|
| Source of variation | TBY | GY | SY | HI | TBY | GY | SY | HI |
| Year (Y) (n=54) | | | | | | | | |
| 2013 | 20.6[a] | 6.58 | 12.2[a] | 0.33[b] | 24.8[a] | 6.55 | 15.8[a] | 0.26[b] |
| 2014 | 17.8[b] | 6.76 | 9.6[b] | 0.38[a] | 18.5[b] | 6.98 | 10.0[b] | 0.37[a] |
| P>F | 0.0040 | 0.5421 | 0.0009 | 0.0074 | 0.0008 | 0.0838 | 0.0003 | 0.0001 |
| LSD | 1.315 | 0.763 | 0.812 | 0.031 | 1.910 | 0.525 | 1.345 | 0.020 |
| Site (S) (n=36) | | | | | | | | |
| Bako | 20.3 | 7.07[a] | 11.5 | 0.35[a] | 23.4[a] | 7.40[a] | 13.9[a] | 0.34[b] |
| Hawassa | 19.9 | 7.51[a] | 10.8 | 0.39[a] | 23.1[a] | 8.36[a] | 12.8[ab] | 0.37[a] |
| Melkassa | 17.3 | 5.42[b] | 10.3 | 0.32[b] | 18.5[b] | 4.53[b] | 12.1[b] | 0.25[c] |
| P>F | 0.1196 | 0.0181 | 0.3932 | 0.0063 | 0.0002 | <0.0001 | 0.0174 | <0.0001 |
| LSD | 3.180 | 1.363 | 1.917 | 0.039 | 1.662 | 0.966 | 1.104 | 0.034 |
| Y x S | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Density (D) (n=54) | | | | | | | | |
| 5 | 17.0[b] | 6.19[b] | 9.4[b] | 0.37[a] | 19.9[b] | 6.46[b] | 11.7[b] | 0.33[a] |
| 7 | 21.4[a] | 7.14[a] | 12.3[a] | 0.34[b] | 23.4[a] | 7.07[a] | 14.1[a] | 0.31[b] |
| P>F | 0.0001 | 0.0009 | 0.0004 | 0.0481 | 0.0006 | 0.0003 | 0.0023 | 0.0446 |
| LSD | 1.683 | 0.471 | 1.321 | 0.027 | 1.642 | 0.270 | 1.398 | 0.021 |
| Y x D | 0.0276 | NS | 0.0069 | 0.0340 | 0.0233 | NS | NS | NS |
| S x D | NS | NS | NS | NS | NS | NS | NS | NS |
| Y x S x D | NS | NS | 0.0222 | NS | 0.0492 | NS | NS | NS |
| Genotype (G)* (n=36) | | | | | | | | |
| 1 | 18.0[b] | 5.89[c] | 10.5[b] | 0.34[b] | 19.9[b] | 5.82[c] | 12.2[b] | 0.30[b] |
| 2 | 18.5[b] | 6.47[b] | 10.4[b] | 0.36[a] | 22.4[a] | 6.92[b] | 13.4[a] | 0.31[b] |
| 3 | 21.1[a] | 7.64[a] | 11.7[a] | 0.36[a] | 22.7[a] | 7.57[a] | 13.1[ab] | 0.34[a] |
| P>F | <0.0001 | <0.0001 | 0.0012 | 0.0024 | <0.0001 | <0.0001 | 0.0406 | 0.0001 |
| LSD | 0.887 | 0.278 | 0.721 | 0.015 | 1.244 | 0.356 | 0.992 | 0.017 |
| Y x G | NS | <0.0001 | NS | NS | NS | 0.0272 | NS | 0.0088 |
| S x G | 0.0078 | <0.0001 | NS | 0.0096 | 0.0448 | 0.0436 | 0.0341 | NS |
| Y x S x G | NS | NS | NS | 0.0248 | NS | NS | NS | NS |
| D x G | NS | NS | NS | NS | NS | 0.0253 | NS | NS |
| Y x D x G | NS | NS | NS | NS | NS | NS | NS | NS |
| S x D x G | NS | NS | 0.0378 | 0.0480 | NS | NS | NS | NS |
| Y x S x D x G | NS | NS | NS | NS | NS | NS | NS | NS |

*P<0.05 and P<0.01indicates significant and highly significant genotypes mean respectively; Means with no superscript letters are not significantly different (P>0.05); EM: Early maturing; MM: Medium maturing; TBY: Total biomass yield; GY: Grain yield; SY: Stover yield; HI: Harvest index; LSD: Least significant difference (P=0.05); CV: Coefficient of variation; NS: Non-significant; [*]EM genotypes (1=MH-130; 2=SC-403; 3= TH13321); [*]MM genotypes (1=BH-540; 2=BH=543; 3=BH-546).*

Environment accounted for greater variations in GY (40 and 74%) and SY (52 and 80%) than the G or the G x E interaction and M effects within EM and MM group, respectively. Genotype accounted for a higher proportion of the GY total variation than the M or D effects (23% versus 19%) and (13% versus 5%) but the converse was true for SY (3% and 34%) and (1% versus 12%) and for TBY (8% versus 39%) and (4% versus 16%) within EM and MM genotypes, respectively (Table 4.2).

Year x G interactions were significant (P<0.0001) for GY in EM genotypes and for GY (P<0.05) and HI (P<0.01) in MM genotypes (Table 4.2). Site x G interactions were

significant for most yield variables. Density x G interactions were not significant for any yield variables apart from GY in MM genotypes (Table 4.2).

### 4.3.3. Relationships between stover and grain yields

There were positive regression relationships between stover (Y) and grain (X) yields for data pooled across years, sites and density in EM genotypes: Y=0.68X + 6.32 (r=0.34; P<0.001; n=108) but these were unrelated in MM genotypes: Y=0.16X + 11.84 (r=0.08; P=0.434; n=108).

### 4.3.4. Stover quality across years by site

All stover quality attributes in MM genotypes and stover N and NDF contents in the EM genotype group showed significant (P<0.05 or P<0.01) responses to the environmental factor year at Bako (Table 4.5). Apart from stover N content, all quality attributes were significantly affected by year in both genotype groups at Hawassa. However, at Melkassa only stover fibre fractions were significantly (P<0.01) affected by year in both maturity group (Table 4.5).

Plant D generally had no effect (P>0.05) on stover quality attributes; however higher D decreased the N content (P<0.05) of EM genotypes at Bako site and increased the ADF content (P<0.05) of MM genotypes at Melkassa site. The interactions of Y with D were significant within MM genotypes for stover N (P<0.01) and ADF (P<0.05) contents at Bako and within MM group at Hawassa (Table 4.5).

The DMD of maize stover varied (P<0.05 or P<0.001) within both EM and MM genotypes at Bako by 2.1 and 3.6 percentage units, respectively and by 2.0 and 3.2 percentage units in MM genotypes at Hawassa (P<0.01) and Melkassa (P<0.001), respectively (Table 4.6). The total N content of maize stover only varied within the EM group (P<0.01) at Hawassa (range 0.73-0.84%). Within MM group, N content tended to differ (P=0.078) at Melkassa (range 0.72-0.85%) (Table 4.6).

The interactions of Y with plant D were significant within the MM group for contents of stover N (P<0.01) and ADF (P<0.05) at Bako and NDF (P<0.05) at Hawassa (Table 4.6). The interactions of G with plant D or Y were not significant (P>0.05) for any of the parameters measured at any of the sites among genotypes of either maturity groups (Table 4.5).

Table 4.5 Early (EM) and medium (MM) maturing maize genotypes mean square for stover quality attributes across 2 years by site and pooled across sites and years

| | | | EM genotype | | | | MM genotype | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Site | Source | df | DMD | N | NDF | ADF | DMD | N | NDF | ADF |
| Bako | Year (Y) | 1 | 18.1 | 0.17* | 38.9* | 11.4 | 38.0* | 0.19** | 18.5* | 21.3* |
| | Error 1 | 4 | 3.2 | 0.01 | 4.7 | 3.8 | 2.6 | 0.01 | 2.3 | 0.6 |
| | Density (D) | 1 | 16.8 | 0.03* | 4.3 | 12.9 | 10.4 | 0.03 | 8.2 | 9.6 |
| | Y x D | 1 | 0.4 | 0.00- | 3.3 | 1.0 | 2.8 | 0.03** | 19.1 | 10.8* |
| | Error 2 | 4 | 2.94 | 0.00 | 4.4 | 3.2 | 4.1 | 0.01 | 15.5 | 4.2 |
| | Genotype (G) | 2 | 14.0* | 0.00 | 44.5** | 33.7*** | 42.9*** | 0.01 | 8.10 | 18.2** |
| | Y x G | 2 | 7.8 | 0.00 | 3.7 | 4.3 | 0.4 | 0.01 | 1.8 | 1.3 |
| | D x G | 2 | 1.86 | 0.00 | 3.6 | 4.6 | 0.6 | 0.00 | 2.3 | 1.4 |
| | Y x D x G | 2 | 0.4 | 0.00 | 0.6 | 04 | 1.4 | 0.01 | 1.8 | 0.7 |
| | Error 3 | 16 | 3.5 | 0.01 | 4.4 | 3.0 | 2.6 | 0.00 | 5.1 | 2.0 |
| | CV% | | 3.9 | 11.6 | 2.5 | 3.6 | 3.4 | 9.5 | 2.8 | 2.8 |
| Hawassa | Year (Y) | 1 | 40.8* | 0.07 | 207.7** | 55.2** | 136.9** | 0.09* | 342.5** | 170.2* |
| | Error 1 | 4 | 3.2 | 0.02 | 7.6 | 2.2 | 6.3 | 0.01 | 14.0 | 11.4 |
| | Density (D) | 1 | 12.2 | 0.06 | 42.4 | 21.4 | 0.5 | 0.00 | 1.0 | 0.4 |
| | Y x D | 1 | 0.8 | 0.00 | 0.9 | 0.0 | 0.5 | 0.00 | 21.8* | 5.8 |
| | Error 2 | 4 | 3.6 | 0.02 | 19.1 | 4.6 | 6.5 | 0.01 | 5.5 | 6.5 |
| | Genotype (G) | 2 | 6.3 | 0.05** | 54.2*** | 37.0**** | 13.0** | 0.01 | 34.4** | 12.1* |
| | Y x G | 2 | 1.6 | 0.01 | 14.1 | 1.2 | 6.0 | 0.01 | 1.6 | 2.7 |
| | D x G | 2 | 3.7 | 0.01 | 0.07 | 3.9 | 0.6 | 0.01 | 6.1 | 3.7 |
| | Y x D x G | 2 | 1.0 | 0.01 | 7.9 | 1.0 | 3.3 | 0.01 | 4.8 | 1.0 |
| | Error 3 | 16 | 2.4 | 0.00 | 4.7 | 1.7 | 2.1 | 0.00 | 4.6 | 2.4 |
| | CV% | | 2.9 | 8.3 | 2.8 | 2.8 | 2.7 | 7.6 | 2.8 | 3.3 |
| Melkassa | Year (Y) | 1 | 14.3 | 0.12 | 469.1*** | 176.4** | 0.9 | 0.10 | 319.9** | 143.6** |
| | Error 1 | 4 | 10.9 | 0.06 | 4.0 | 3.3 | 9.9 | 0.04 | 5.6 | 4.3 |
| | Density (D) | 1 | 4.7 | 0.03 | 4.6 | 2.8 | 5.2 | 0.03 | 1.5 | 5.8* |
| | Y x D | 1 | 0.7 | 0.01 | 0.6 | 0.1 | 0.2 | 0.00 | 0.8 | 0.2 |
| | Error 2 | 4 | 1.5 | 0.03 | 6.7 | 2.0 | 1.3 | 0.04 | 0.6 | 0.6 |
| | Genotype (G) | 2 | 8.3 | 0.01 | 1.3 | 25.0** | 32.1*** | 0.06 | 10.4 | 12.7* |
| | Y x G | 2 | 1.7 | 0.01. | 4.8 | 4.8 | 3.7 | 0.01 | 0.3 | 1.0 |
| | D x G | 2 | 3.1 | 0.05 | 6.2 | 3.6 | 2.8 | 0.01 | 0.7 | 0.3 |
| | Y x D x G | 2 | 2.1 | 0.01 | 0.3 | 0.5 | 1.2 | 0.03 | 2.3 | 1.5 |
| | Error 3 | 16 | 4.1 | 0.02 | 2.9 | 3.5 | 2.6 | 0.02 | 3.8 | 2.6 |
| | CV% | | 4.0 | 18.0 | 2.2 | 3.9 | 3.1 | 17.8 | 2.5 | 3.4 |
| Pooled | Year (Y) | 1 | 69.3* | 0.35** | 596.5*** | 193.3*** | 117.8* | 0.37** | 551.8** | 293.0** |
| | Error 1 | 4 | 4.1 | 0.02 | 6.0 | 2.5 | 10.2 | 0.02 | 8.9 | 9.6 |
| | Site (S) | 2 | 24.8**** | 0.30* | 32.0* | 30.9** | 322.7**** | 0.29** | 169.2*** | 118.2*** |
| | Y x S | 2 | 1.9 | 0.01 | 59.6**** | 24.8*** | 29.0**** | 0.01 | 64.5**** | 21.1*** |
| | Error 2 | 8 | 6.6 | 0.04 | 5.2 | 3.4 | 4.3 | 0.02 | 6.5 | 3.4 |
| | Density (D) | 1 | 31.8** | 0.11* | 38.4 | 32.7** | 12.9 | 0.05 | 8.5 | 12.5 |
| | Y x D | 1 | 1.8 | 0.00 | 4.2 | 0.1 | 2.6 | 0.00 | 22.0* | 12.7* |
| | S x D | 2 | 1.0 | 0.00 | 6.5 | 2.2 | 1.6 | 0.01 | 1.1 | 1.6 |
| | Y x S x D | 2 | 0.0 | 0.00 | 0.3 | 0.5 | 0.4 | 0.02 | 9.9 | 2.1 |
| | Error 3 | 12 | 2.7 | 0.02 | 10.1 | 3.3 | 4.0 | 0.02 | 7.2 | 3.8 |
| | Genotype (G) | 2 | 20.6** | 0.02 | 62.8**** | 85.0**** | 67.0**** | 0.03* | 4.0 | 21.4*** |
| | Y x G | 2 | 3.4 | 0.02 | 4.0 | 3.5 | 2.3 | 0.03 | 1.4 | 0.0 |
| | S x G | 4 | 4.0 | 0.02 | 18.6** | 5.4 | 10.5** | 0.03* | 24.4** | 10.8** |
| | Y x S x G | 4 | 3.9 | 0.00 | 9.3 | 3.4 | 3.9 | 0.00 | 1.2 | 2.5 |
| | D x G | 2 | 7.5 | 0.04* | 5.0 | 7.5 | 0.8 | 0.01 | 1.7 | 0.5 |
| | Y x D x G | 2 | 2.9 | 0.00 | 2.2 | 0.9 | 1.6 | 0.03* | 3.5 | 0.9 |
| | S x D x G | 4 | 0.6 | 0.01 | 2.4 | 2.4 | 1.6 | 0.01 | 3.7 | 2.5 |
| | Y x S x D x G | 4 | 0.3 | 0.01 | 3.3 | 0.5 | 2.2 | 0.01 | 2.7 | 1.2 |
| | Error 4 | 48 | 3.3 | 0.01 | 4.0 | 2.7 | 2.4 | 0.01 | 4.5 | 2.3 |
| | CV% | | 3.6 | 12.9 | 2.6 | 3.5 | 3.1 | 12.8 | 2.7 | 3.1 |

Significant at P<0.05; ** Significant at P<0.01; ***Significant at P<0.001; ***Significant at P<0.0001; DMD: Dry matter digestibility, N: Nitrogen, NDF: Neutral detergent fibre; ADF: Acid detergent fibre; *CV: Coefficient of variation.*

Table 4.6 Effects of year, plant density or genotype on maize stover quality attributes (%) by site and maturity group

| Site | Source of variation | | EM genotype* DMD | N | NDF | ADF | MM genotype* DMD | N | NDF | ADF |
|---|---|---|---|---|---|---|---|---|---|---|
| Bako | Year | 2013 | 46.7 | 0.56[b] | 80.2[a] | 49.4 | 46.3[b] | 0.58[b] | 81.3[a] | 50.9[a] |
| | (n=18) | 2014 | 48.1 | 0.69[a] | 78.1[b] | 48.3 | 48.4[a] | 0.72[a] | 79.9[b] | 49.4[b] |
| | P>F | | 0.0748 | 0.0139 | 0.0449 | 0.1588 | 0.0189 | 0.0074 | 0.0485 | 0.0039 |
| | LSD | | 1.644 | 0.092 | 2.019 | 1.804 | 1.497 | 0.079 | 1.417 | 0.713 |
| | Density | 5 | 48.1 | 0.65[a] | 78.8 | 48.2 | 47.9 | 0.68 | 80.1 | 49.6 |
| | (n=18) | 7 | 46.7 | 0.60[b] | 79.5 | 49.4 | 46.8 | 0.62 | 81.1 | 50.7 |
| | P>F | | 0.0752 | 0.0175 | 0.3776 | 0.1154 | 0.1880 | 0.0824 | 0.5065 | 0.2068 |
| | LSD | | 1.588 | 0.038 | 1.930 | 1.658 | 1.879 | 0.071 | 3.645 | 1.903 |
| | Genotype (n=12) | | | | | | | | | |
| | 1 | | 47.7[ab] | 0.65 | 79.4[a] | 47.9[b] | 46.6[b] | 0.64 | 80.7 | 51.0[a] |
| | 2 | | 46.2[b] | 0.61 | 81.0[a] | 50.8[a] | 49.5[a] | 0.69 | 79.7 | 48.7[b] |
| | 3 | | 48.3[a] | 0.6.2 | 77.1[b] | 47.8[b] | 45.9[b] | 0.6.3 | 81.3 | 50.8[a] |
| | P>F | | 0.0386 | 0.4705 | 0.0014 | 0.0009 | 0.0001 | 0.0977 | 0.2327 | 0.0022 |
| | LSD | | 1.618 | 0.063 | 1.805 | 1.502 | 1.391 | 0.054 | 1.948 | 1.219 |
| Hawassa | Year | 2013 | 51.5[b] | 0.76 | 79.8[a] | 48.3[a] | 51.0[b] | 0.77[b] | 79.2[a] | 48.8[a] |
| | (n=18) | 2014 | 53.7[a] | 0.85 | 75.0[b] | 45.8[b] | 54.9[a] | 0.87[a] | 73.2[b] | 44.4[b] |
| | P>F | | 0.0236 | 0.1594 | 0.0064 | 0.0072 | 0.0095 | 0.0493 | 0.0078 | 0.0181 |
| | LSD | | 1.662 | 0.139 | 2.556 | 1.362 | 2.319 | 0.102 | 3.462 | 3.128 |
| | Density | 5 | 53.2 | 0.84 | 76.3 | 46.3 | 53.0 | 0.82 | 76.1 | 46.5 |
| | (n=18) | 7 | 52.0 | 0.76 | 78.4 | 47.8 | 52.8 | 0.81 | 76.4 | 46.7 |
| | P>F | | 0.1383 | 0.1528 | 0.2108 | 0.0983 | 0.7915 | 0.7342 | 0.6981 | 0.8174 |
| | LSD | | 1.751 | 0.130 | 4.049 | 1.992 | 2.357 | 0.998 | 2.160 | 2.362 |
| | Genotype (n=12) | | | | | | | | | |
| | 1 | | 53.4 | 0.73[b] | 78.6[a] | 46.3[b] | 51.7[b] | 0.78 | 78.0[a] | 47.7[a] |
| | 2 | | 52.0 | 0.83[a] | 78.6[a] | 49.0[a] | 53.7[a] | 0.82 | 76.1[b] | 46.4[b] |
| | 3 | | 52.4 | 0.84[a] | 74.9[b] | 45.8[b] | 53.3[a] | 0.85 | 74.6[b] | 45.8[b] |
| | P>F | | 0.1006 | 0.0014 | 0.0008 | <0.0001 | 0.0094 | 0.0675 | 0.0050 | 0.0189 |
| | LSD | | 1.330 | 0.058 | 1.867 | 1.141 | 1.242 | 0.054 | 1.853 | 1.327 |
| Melkassa | Year | 2013 | 50.1 | 0.63 | 81.4[a] | 49.8[a] | 51.9 | 0.75 | 81.2[a] | 49.7[a] |
| | (n=18) | 2014 | 51.3 | 0.75 | 74.2[b] | 45.3[b] | 52.2 | 0.85 | 75.3[b] | 45.7[b] |
| | P>F | | 0.3160 | 0.2346 | 0.0004 | 0.0018 | 0.7831 | 0.1744 | 0.0016 | 0.0044 |
| | LSD | | 3.056 | 0.231 | 1.841 | 1.675 | 2.916 | 0.174 | 2.187 | 1.915 |
| | Density | 5 | 51.1 | 0.72 | 77.5 | 47.3 | 52.4 | 0.83 | 78.0 | 47.3[b] |
| | (n=18) | 7 | 50.3 | 0.66 | 78.2 | 47.8 | 51.6 | 0.77 | 78.4 | 48.1[a] |
| | P>F | | 0.1521 | 0.3367 | 0.4521 | 0.2938 | 0.12 | 0.4487 | 0.1909 | 0.039 |
| | LSD | | 1.133 | 0.150 | 2.393 | 1.293 | 1.072 | 0.187 | 0.712 | 0.738 |
| | Genotype (n=12) | | | | | | | | | |
| | 1 | | 51.6 | 0.67 | 77.5 | 46.0[b] | 51.7[b] | 0.82 | 77.3 | 47.5[ab] |
| | 2 | | 50.1 | 0.68 | 78.1 | 48.9[a] | 53.8[a] | 0.85 | 78.3 | 46.7[b] |
| | 3 | | 50.4 | 0.72 | 77.9 | 47.7[a] | 50.5[b] | 0.72 | 79.1 | 48.8[a] |
| | P>F | | 0.1649 | 0.5456 | 0.6495 | 0.0058 | 0.0006 | 0.0784 | 0.0939 | 0.0213 |
| | LSD | | 1.753 | 0.107 | 1.479 | 1.611 | 1.405 | 0.123 | 1.685 | 1.385 |

*P<0.05 and P<0.01indicates significant and highly significant genotypes mean respectively; Means with no superscript letters are not significantly different (P>0.05); EM: Early maturing; MM: Medium maturing; [*]EM genotypes (1=MH-130; 2=SC-403; 3= TH13321); [*]MM genotypes (1=BH-540; 2=BH=543; 3=BH-546); LSD: DMD: Dry matter digestibility, N: Nitrogen, NDF: Neutral detergent fibre; ADF: Acid detergent fibre; Least significant difference (P=0.05);NS: Non-significant.*

### 4.3.5. Stover quality across years and sites

Effects of year, site, plant D or G on stover DMD and chemical compositions, by maturity group are presented in Table 4.7. Stover quality attributes differed greatly (P<0.05 or P<0.01) between years in all attributes measured within both maturity group (Tables 4.5 and 4.7). When averaged across years and genotypes, site had significant (P<0.05 and P<0.01) effects on stover DMD and N content in the EM group and in all quality attributes

measured in the MM group. Stover DMD and N content were significantly highest at Hawassa and lowest at Bako in both maturity groups. When averaged across years, sites and genotypes, plant D significantly (P<0.05 and P<0.01) affected stover DMD and N and ADF contents within EM genotypes, but did not affect in any quality measured within MM group.

Table 4.7 Effects of year, site, plant density or genotype on maize stover quality attributes (%) by maturity group

| | EM genotype* | | | | MM genotype* | | | |
|---|---|---|---|---|---|---|---|---|
| Source of variation | DMD | N | NDF | ADF | DMD | N | NDF | ADF |
| Year (n=54) | | | | | | | | |
| 2013 | 49.4$^{b}$ | 0.65$^{b}$ | 80.5$^{a}$ | 49.1$^{a}$ | 49.7$^{b}$ | 0.70$^{b}$ | 80.6$^{a}$ | 49.8$^{a}$ |
| 2014 | 51.0$^{a}$ | 0.76$^{a}$ | 75.8$^{a}$ | 46.5$^{b}$ | 51.8$^{a}$ | 0.81$^{a}$ | 76.1$^{b}$ | 46.5$^{b}$ |
| P>F | 0.0145 | 0.0083 | 0.0006 | 0.0009 | 0.0272 | 0.0097 | 0.0014 | 0.0052 |
| LSD | 0.710 | 0.042 | 0.846 | 0.644 | 1.705 | 0.0696 | 1.591 | 1.654 |
| Site (n=36) | | | | | | | | |
| Bako | 47.4$^{c}$ | 0.62$^{c}$ | 79.2 | 48.8 | 47.3$^{b}$ | 0.65$^{b}$ | 80.6$^{a}$ | 50.1$^{a}$ |
| Hawassa | 52.6$^{a}$ | 0.80$^{a}$ | 77.4 | 47.0 | 52.9$^{a}$ | 0.82$^{a}$ | 76.2$^{c}$ | 46.6$^{c}$ |
| Melkassa | 50.7$^{b}$ | 0.69$^{b}$ | 77.8 | 47.5 | 52.0$^{a}$ | 0.80$^{a}$ | 78.2$^{b}$ | 47.7$^{b}$ |
| P>F | <0.0001 | 0.0152 | 0.0235 | 0.0086 | <0.0001 | 0.0019 | 0.0003 | 0.0001 |
| LSD | 0.869 | 0.0519 | 1.036 | 0.789 | 1.130 | 0.075 | 1.389 | 0.996 |
| Density (n=54) | | | | | | | | |
| 5 | 50.8$^{a}$ | 0.74$^{a}$ | 77.5 | 47.2$^{b}$ | 51.1 | 0.78 | 78.1 | 47.8 |
| 7 | 49.7$^{b}$ | 0.67$^{b}$ | 78.7 | 48.3$^{a}$ | 50.4 | 0.73 | 78.6 | 48.5 |
| P>F | 0.0048 | 0.0202 | 0.0744 | 0.0082 | 0.0970 | 0.1368 | 0.2977 | 0.0940 |
| LSD | 0.710 | 0.0424 | 0.846 | 0.644 | 0.837 | 0.058 | 1.124 | 0.817 |
| Genotype (n=36) | | | | | | | | |
| 1 | 50.9$^{a}$ | 0.68 | 78.5$^{a}$ | 46.7$^{b}$ | 50.0$^{b}$ | 0.75$^{ab}$ | 78.7 | 48.7$^{a}$ |
| 2 | 49.4$^{b}$ | 0.71 | 79.2$^{a}$ | 49.6$^{a}$ | 52.3$^{a}$ | 0.79$^{a}$ | 78.0 | 47.3$^{b}$ |
| 3 | 50.4$^{a}$ | 0.73 | 76.7$^{b}$ | 47.1$^{b}$ | 49.9$^{b}$ | 0.73$^{b}$ | 78.4 | 48.4$^{a}$ |
| P>F | 0.0040 | 0.1055 | <0.0001 | <0.0001 | <0.0001 | 0.0497 | 0.4166 | 0.0004 |
| LSD | 0.869 | 0.052 | 1.036 | 0.789 | 0.738 | 0.046 | 1.003 | 0.718 |

*P<0.05 and P<0.01indicates significant and highly significant genotypes mean respectively; Means with no superscript letters are not significantly different (P>0.05); EM: Early maturing; MM: Medium maturing; DMD: Dry matter digestibility, N: Nitrogen, NDF: Neutral detergent fibre; ADF: Acid detergent fibre; LSD: Least significant difference (P=0.05); NS: Non-significant; *EM genotypes (1=MH-130; 2=SC-403; 3= TH13321);*MM genotypes (1=BH-540; 2=BH=543; 3=BH-546).*

Generally, DMD and N content of the stover were higher at the lower plant density while fibre fractions were lower at the higher plant density. The interactions of density with year or site were not significant (P<0.05) for most stover quality measures except the D x Y interactions (P<0.05) for NDF and/or ADF contents within MM genotypes (Table 4.5). Genotypes in both maturity groups generally varied in a number of stover quality attributes (P<0.05 or (P<0.01).

Environment accounted for greater proportions of the stover DMD (77 and 79%) and N content (67 and 70%) of the total variations within EM and MM groups, respectively. Management effects accounted for larger proportion of the variations in stover DMD and N content than the G effects (8% versus 5%) and (12% versus 2%) within EM group, respectively. However, the converse was true for NDF (4% versus 7%) and ADF (8% versus 21%) contents within EM genotypes and for DMD (2% and 11%) and ADF content (2% versus 4%) within MM genotypes (Table 4.5).

Genotype x site interactions were significant for NDF ($P<0.01$) content within EM group and for all quality attributes measured ($P<0.05$ and $P<0.01$) within MM group. There were no genotype interactions ($P>0.05$) with year or plant density except for the G x D interaction for stover N content ($P<0.05$) within EM group (Table 4.5).

### 4.3.6. Relationships between grain yield and stover DMD and total N content

No strong inverse relationships were observed between stover quality attributes (Y) (DMD % or total N %) and GY (X) in either EM or MM genotypes. These were for the EM genotypes: $Y = -0.29X + 52.2$ ($r= -0.16$; $P=0.092$; $n=108$) and $Y = -0.004X + 0.73$ ($r= -0.04$; $P=0.649$; $n=108$) and for MM genotypes: $Y = -0.13X + 51.6$ ($r= -0.08$; $P=0.440$; $n=108$) and $Y= -0.001X + 0.76$ ($r= -0.01$; $P=0.858$; $n=108$), respectively.

### 4.3.7. DDM yield, nitrogen yield (NY) and PUI by site

Stover DDMY and PUI in EM genotypes ($P<0.05$ and $P<0.01$) and all measured attributes in MM group differed greatly ($P<0.01$ or $P<0.0001$) between years at Bako (Table 4.8). The DDMY, NY and PUI in both maturity group differed greatly ($P<0.05$ or $P<0.01$) between years at Hawassa. At Melkassa, NY in EM genotypes differed ($P<0.05$ or $P<0.01$) between years. Among EM genotypes, higher plant D increased ($P<0.01$) DDMY and NY (t/ha) of the stover 33.5 and 25.4%, respectively but decreased the PUI by 5.5% at Bako.

Among the MM genotypes, the higher plant D increased stover DDMY by 15.3% ($P<0.05$) at the Melkassa site. In general, there was a trend for PUI to decrease, and for DDMY and NY to increase, in both maturity groups as the higher plant D in (Table 4.8). In most cases, the interactions of Y with D were not significant ($P>0.05$) except for DDMY ($P<0.05$) at Bako and Hawassa sites among EM genotypes and for DDMY and NY at Hawassa site among MM genotypes (Table 4.8).

Table 4.8 Effects of year, plant density or genotype on maize stover NDFD (%), DDMY (t/ha), NY (kg/ha) and PUI (%) by site and maturity group

| | | EM genotype | | | | MM genotype | | | |
|---|---|---|---|---|---|---|---|---|---|
| Site | Source of variation | NDFD | DDMY | NY | PUI | NDFD | DDMY | NY | PUI |
| Bako | Year (Y) 2013 | 33.5 | 6.17$^{a}$ | 72.7 | 58.8$^{b}$ | 33.9$^{b}$ | 8.57$^{a}$ | 107.0$^{a}$ | 54.5$^{b}$ |
| | (n=18) 2014 | 33.6 | 4.69$^{b}$ | 67.4 | 65.1$^{a}$ | 35.3$^{a}$ | 4.42$^{b}$ | 66.2$^{b}$ | 67.2$^{a}$ |
| | P>F | 0.9632 | 0.0165 | 0.4050 | 0.0040 | 0.0067 | <0.0001 | 0.0003 | 0.0005 |
| | LSD | 2.413 | 1.030 | 15.853 | 2.917 | 0.7.491 | 0.426 | 9.242 | 3.390 |
| | Density (D) 5 | 34.1 | 4.65$^{b}$ | 62.1$^{b}$ | 63.6$^{a}$ | 34.9 | 6.00 | 84.2 | 62.0 |
| | (n=18) 7 | 33.0 | 6.21$^{a}$ | 77.9$^{a}$ | 60.3$^{b}$ | 34.4 | 7.00 | 89.0 | 59.7 |
| | P>F | 0.1461 | 0.0198 | 0.0425 | 0.0204 | 0.1699 | 0.1592 | 0.5528 | 0.0934 |
| | LSD | 1.7.469 | 1.151 | 14.964 | 2.516 | 0.919 | 1.609 | 20.764 | 2.878 |
| | Y x D | NS | 0.0479 | NS | NS | NS | NS | NS | NS |
| | Genotype (G) (n=12) | | | | | | | | |
| | 1 | 34.2 | 4.99$^{b}$ | 66.2 | 60.9 | 33.8$^{b}$ | 6.12 | 79.0 | 59.7$^{a}$ |
| | 2 | 33.6 | 5.34$^{ab}$ | 68.6 | 61.6 | 36.6$^{a}$ | 6.65 | 89.7 | 62.2$^{a}$ |
| | 3 | 32.9 | 5.95$^{a}$ | 75.3 | 63.3 | 33.5$^{b}$ | 6.72 | 91.1 | 60.8$^{ab}$ |
| | P>F | 0.1666 | 0.0198 | 0.2208 | 0.0895 | <0.0001 | 0.4450 | 0.3539 | 0.0179 |
| | LSD | 1.306 | 0.650 | 10.916 | 2.260 | 0.7.670 | 1.056 | 18.885 | 1.631 |
| | Y x G | NS | NS | NS | NS | NS | NS | NS | NS |
| | D x G | NS | NS | NS | NS | NS | NS | NS | NS |
| | Y x D x G | NS | NS | NS | NS | NS | NS | NS | NS |
| | CV% | 4.5 | 13.8 | 18.0 | 4.2 | 2.6 | 18.8 | 25.2 | 3.1 |
| Hawassa | Year (Y) 2013 | 39.1 | 7.17$^{a}$ | 106.2$^{a}$ | 63.2$^{b}$ | 38.2 | 8.04$^{a}$ | 120.9$^{a}$ | 62.4$^{b}$ |
| | (n=18) 2014 | 38.1 | 4.07$^{b}$ | 64.0$^{b}$ | 70.5$^{a}$ | 38.3 | 5.33$^{b}$ | 84.0$^{b}$ | 69.7$^{a}$ |
| | P>F | 0.1461 | 0.0021 | 0.0167 | 0.0002 | 0.7821 | 0.0011 | 0.0115 | 0.0013 |
| | LSD | 1.522 | 1.217 | 29.621 | 1.511 | 1.408 | 0.894 | 23.120 | 2.531 |
| | Density (D) 5 | 38.5 | 4.95 | 78.3 | 67.5 | 38.3 | 5.93 | 91.0 | 66.9 |
| | (n=18) 7 | 38.7 | 6.29 | 91.8 | 66.2 | 38.2 | 7.45 | 113.9 | 65.2 |
| | P>F | 0.7412 | 0.1565 | 0.4485 | 0.3705 | 0.9316 | 0.0575 | 0.1095 | 0.3549 |
| | LSD | 1.655 | 2.131 | 44.556 | 3.547 | 2.245 | 1.603 | 30.939 | 4.375 |
| | Y x D | NS | 0.0208 | NS | NS | NS | 0.0168 | 0.0149 | NS |
| | Genotype (G) (n=12) | | | | | | | | |
| | 1 | 40.6$^{a}$ | 5.62 | 75.6$^{b}$ | 66.5$^{b}$ | 38.1$^{ab}$ | 6.26$^{b}$ | 93.7$^{b}$ | 64.0$^{b}$ |
| | 2 | 38.9$^{b}$ | 5.30 | 83.8$^{ab}$ | 65.8$^{b}$ | 39.2$^{a}$ | 7.59$^{a}$ | 115.9$^{a}$ | 65.6$^{b}$ |
| | 3 | 36.4$^{c}$ | 5.94 | 95.8$^{a}$ | 68.2$^{a}$ | 37.4$^{b}$ | 6.21$^{b}$ | 97.8$^{b}$ | 68.6$^{a}$ |
| | P>F | <0.0001 | 0.2125 | 0.0246 | 0.0073 | 0.0318 | 0.0034 | 0.0124 | 0.0022 |
| | LSD | 1.329 | 0.732 | 14.036 | 1.433 | 1.333 | 0.814 | 14.606 | 2.311 |
| | Y x G | NS | NS | NS | NS | NS | 0.0116 | 0.0334 | 0.0196 |
| | D x G | NS | 0.0032 | NS | 0.0160 | NS | NS | NS | NS |
| | Y x D x G | NS | NS | NS | NS | NS | NS | NS | NS |
| | CV% | 4.0 | 15.0 | 19.1 | 2.5 | 4.0 | 14.1 | 16.5 | 4.0 |
| Melkassa | Year (Y) 2013 | 38.6.9$^{a}$ | 4.64 | 56.4$^{b}$ | 62.3 | 40.7$^{a}$ | 6.76 | 96.7 | 57.4 |
| | (n=18) 2014 | 34.3.8$^{b}$ | 5.81 | 83.8$^{a}$ | 61.1 | 36.4$^{b}$ | 5.79 | 93.2 | 59.8 |
| | P>F | 0.0158 | 0.1234 | 0.0095 | 0.4716 | 0.0065 | 0.0973 | 0.6841 | 0.1937 |
| | LSD | 2.9.736 | 1.669 | 16.235 | 4.268 | 2.301 | 1.247 | 22.480 | 4.196 |
| | Density (D) 5 | 36.7 | 4.66 | 64.8 | 62.6 | 38.9 | 5.83$^{b}$ | 91.2 | 59.1 |
| | (n=18) 7 | 36.4 | 5.78 | 75.4 | 60.8 | 38.3 | 6.72$^{a}$ | 98.7 | 58.1 |
| | P>F | 0.7304 | 0.0513 | 0.2922 | 0.2026 | 0.1080 | 0.0114 | 0.4895 | 0.1240 |
| | LSD | 2.050 | 1.128 | 24.163 | 3.277 | 0.833 | 0.556 | 27.419 | 1.500 |
| | Y x D | NS | NS | NS | NS | NS | NS | NS | NS |
| | Genotype (G) (n=12) | | | | | | | | |
| | 1 | 37.5 | 5.35$^{a}$ | 68.8$^{b}$ | 61.6 | 37.5$^{b}$ | 5.74 | 90.0 | 57.8 |
| | 2 | 36.0 | 4.63$^{b}$ | 61.6$^{b}$ | 62.5 | 40.9$^{a}$ | 6.67 | 104.2 | 59.7 |
| | 3 | 36.2 | 5.68$^{a}$ | 79.9$^{a}$ | 61.0 | 37.4$^{b}$ | 6.40 | 90.8 | 58.3 |
| | P>F | 0.1059 | 0.0038 | 0.0046 | 0.2046 | <0.0001 | 0.0627 | 0.2236 | 0.0821 |
| | LSD | 1.519 | 0.565 | 9.939 | 1.718 | 1.228 | 0.790 | 18.777 | 1.665 |
| | Y x G | NS | NS | NS | 0.0113 | NS | NS | NS | NS |
| | D x G | NS | NS | 0.0494 | NS | NS | NS | NS | NS |
| | Y x D x G | NS | NS | NS | NS | NS | NS | NS | NS |
| | CV% | 4.8 | 12.5 | 16.4 | 3.2 | 3.7 | 14.5 | 22.9 | 3.3 |

*P<0.05 and P<0.01 indicates significant and highly significant genotypes mean respectively; Means with no superscript letters are not significantly different (P>0.05); EM: Early maturing; MM: Medium maturing; NDFD: Neutral detergent fibre digestibility =100 - (DMD – (100 – NDF))/NDF (Barrière et al., 2003); DDMY: digestible dry matter yield; NY: Nitrogen yield; PUI: Potential utility index; LSD: Least significant difference (P=0.05); CV: Coefficient of variation: NS: Non-significant*

Among EM genotypes, DDMY varied (P<0.05) from 4.99-5.95 t/ha at Bako and Melkassa (P<0.01) from 4.63-5.68 t/ha, NY varied at Hawassa (P<0.05) from 75.6-95.8 kg/ha and Melkassa (P<0.01) from 61.6-79.9 kg/ha and PUI varied at Hawassa (P<0.01) from 65.8-68.2% (Table 4.8).

Genotypes within MM group varied in DDMY (P<0.01) from 6.21-7.59 t/ha and NY (P<0.05) from 93.7-115.9 kg/ha at Hawassa and in PUI varied from 64.0-68.6% at Hawassa (P<0.01) and from 59.7-62.2% at Bako (P<0.05). The interactions of G with Y were significant (P<0.05) for DDMY, NY and PUI at Hawassa among MM genotypes and for PUI (P<0.05) at Melkassa among EM genotypes. The interactions of G with D were significant for DDMY (P<0.01) and PUI (P<0.05) at Hawassa and for NY (P<0.05) at Melkassa among EM genotypes (Table 4.8).

### 4.3.8. Stover quality and DDM yield, NY and PUI across sites

The DDMY, NY and PUI differed (P<0.01) between years; yields were higher but PUI was lower in 2013 than 2014 (Table 4.9). Site had significant (P<0.05 and P<0.01) effects on PUI (P<0.001) in both maturity groups and NY (P<0.05) in the MM group. Higher plant D increased DDMY (P<0.01) by 28.2% and 19.1% but decreased PUI by 2.2 (P<0.01) and 1.7 (P<0.05) percentage units in EM and MM group, respectively. Generally, DDMY and NY were highest while PUI was lowest at the higher plant D.

The interactions of Y with D were significant (P<0.05) for DDMY and PUI among EM genotypes (Table 4.8). The DDMY and NY differed greatly (P<0.01) within both EM (range 5.09-5.86 t/ha and 70.2-83.6 kg/ha) and MM (range 6.04-6.97 t/ha and 87.5-103.3 kg/ha) groups, respectively while PUI varied (P<0.001) within the MM group (range 60.5-62.6%) (Table 4.9) but within the EM group. Site x G interactions were significant (P<0.05 or P<0.01) for PUI in both maturity group while D x G interactions were significant (P<0.05) for DDMY and NY within the EM maturity group (Table 4.8).

Table 4.9 Effects of year, site, plant density or genotype NDFD (%), DDMY (t/ha), NY (kg/ha) and PUI (%) by maturity group

| Source of variation | EM genotype* | | | | MM genotype* | | | |
|---|---|---|---|---|---|---|---|---|
| | NDFD | DDMY | NY | PUI | NDFD | DDMY | NY | PUI |
| Year (Y) (n=54) | | | | | | | | |
| 2013 | 37.1 | 5.99[a] | 78.4[a] | 61.4[b] | 37.6 | 7.79[a] | 108.2[a] | 58.1[b] |
| 2014 | 35.4 | 4.86[b] | 71.7[b] | 65.5[a] | 36.7 | 5.18[b] | 81.1[b] | 65.6[a] |
| P>F | 0.0540 | 0.0012 | 0.0068 | 0.0041 | 0.0660 | 0.0002 | 0.0040 | 0.0002 |
| LSD | 0.657 | 0.384 | 7.039 | 0.906 | 1.018 | 0.580 | 12.634 | 1.617 |
| Site (S) (n=36) | | | | | | | | |
| Bako | 33.6[c] | 5.43 | 70.0 | 61.9[b] | 34.6[b] | 6.50 | 86.6[b] | 60.9[b] |
| Hawassa | 38.6[a] | 5.62 | 85.1 | 66.8[a] | 38.2[a] | 6.69 | 102.4[a] | 66.1[a] |
| Melkassa | 56.5[b] | 5.22 | 70..1 | 61.7[b] | 38.6[a] | 6.27 | 94.9[ab] | 58.6[c] |
| P>F | <0.0001 | 0.6183 | 0.0842 | 0.0002 | <0.0001 | 0.2333 | 0.0256 | 0.0001 |
| LSD | 0.805 | 0.471 | 8.620 | 1.109 | 0.903 | 0.513 | 10.559 | 2.184 |
| Y x S | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.001 | <0.0001 |
| Density (D) (n=54) | | | | | | | | |
| 5 | 36.4 | 4.75[b] | 68.4 | 64.6[a] | 37.4 | 5.92[b] | 88.8 | 62.7[a] |
| 7 | 36.0 | 6.09[a] | 81.7 | 62.4[b] | 36.9 | 7.05[a] | 100.5 | 61.0[b] |
| P>F | 0.3147 | 0.0013 | 0.0582 | 0.0064 | 0.2023 | 0.0016 | 0.0563 | 0.0263 |
| LSD | 0.657 | 0.384 | 7.039 | 0.906 | 0.671 | 0.612 | 12.101 | 1.425 |
| Y x D | 0.0392 | 0.0210 | NS | 0.0283 | NS | NS | NS | NS |
| S x D | NS | NS | NS | NS | NS | NS | NS | NS |
| Y x S x D | NS | 0.0260 | NS | NS | NS | NS | NS | NS |
| Genotype (G) (n=36) | | | | | | | | |
| 1 | 37.4[a] | 5.32[b] | 70.2[b] | 63.0 | 36.5[b] | 6.04[b] | 87.5[b] | 60.5[b] |
| 2 | 36.1[b] | 5.09[b] | 71.3[b] | 63.3 | 38.9[a] | 6.97[a] | 103.3[a] | 62.5[a] |
| 3 | 35.2[c] | 5.86[a] | 83.6[a] | 64.2 | 36.1[b] | 6.44[b] | 93.2[b] | 62.6[a] |
| P>F | <0.0001 | 0.0003 | 0.0001 | 0.0582 | <0.0001 | 0.0017 | 0.0066 | 0.0002 |
| LSD | 0.805 | 0.471 | 8.620 | 1.109 | 0.622 | 0.490 | 9.603 | 1.038 |
| Y x G | NS | NS | NS | NS | 0.0180 | NS | NS | NS |
| S x G | 0.0065 | NS | NS | 0.0144 | NS | NS | NS | 0.0025 |
| Y x S x G | NS | NS | NS | 0.0386 | NS | NS | NS | NS |
| D x G | NS | 0.0209 | 0.0377 | NS | NS | NS | NS | NS |
| Y x D x G | NS | NS | NS | NS | NS | NS | NS | NS |
| S x D x G | NS | 0.0147 | NS | NS | NS | NS | NS | NS |
| Y x S x D x G | NS | NS | NS | NS | NS | NS | NS | NS |
| CV% | 4.4 | 13.9 | 18.1 | 3.3 | 3.5 | 15.9 | 21.4 | 3.5 |

*P<0.05 and P<0.01indicates significant and highly significant genotypes mean respectively; Means with no superscript letters are not significantly different (P>0.05); EM: Early maturing; MM: Medium maturing; NDFD: Neutral detergent fibre digestibility; DDMY: digestible dry matter yield; NY: Nitrogen yield; PUI: Potential utility index; LSD: Least significant difference (P=0.05); *EM genotypes (1=MH-130; 2=SC-403; 3= TH13321); *MM genotypes (1=BH-540; 2=BH=543; 3=BH-546); CV: Coefficient of variation: NS: Non-significant.*

## 4.4. Discussion

### 4.4.1. Sources of variation for yield attributes

#### 4.4.1.1. Environment

Farmers and scientists need to identify superior genotypes across a wide range of environmental conditions. In the present study various environments were represented by

combinations of years and experimental sites. Mean GY within EM group at Bako were 14.2% lower, and SY 35.7% higher in 2013 than in 2014 (Table 4.3), and was associated with major differences in HI between the 2 years (0.31 versus 0.40). In the combined analysis, the TBY and SY were 16-58% higher in 2013 than in 2014 in EM and MM genotypes (Table 4.4), and also HI was substantially lower in 2013 than 2014 (Table 4.4). The differences in rainfall between years (Table 4.1) during the cropping season are likely the primary reason for the yield differences between years.

Site was the most important source of variation on most yield parameters measured in both years (Tables 4.4). As expected, productivity was higher in the sub-humid environments (Hawassa and Bako sites) than in the semi-arid environment at Melkassa site (Table 4.4). Presumably, this was associated with differences in rainfall, temperature (Table 4.1), soil type and altitude. The partitioning of variance components indicated that environmental factors (year + site) accounted much of the total variation in TBY (42.5 and 72.3%), GY (39.6 and 74.2%), SY (51.9 and 80.0%), and HI (75.4 and 90.6%) among EM and MM genotypes, respectively. The effects of G and E and their interactions on GY have also been reported in numerous experiments (Abera et al., 2006; Abera et al., 2004; Admassu et al., 2008; Bogale et al., 2012a; Gambin et al., 2016; Tolessa et al., 1993; Worku and Zelleke, 2008). Fodder yield potential of cultivars can be expected to vary under different environmental conditions (Roth, 1994).

#### 4.4.1.2. Management as effects of plant density

The two plant densities levels had been chosen because the available resources only allowed comparison of two levels of plant density at three locations using six genotypes for two consecutive years. It was considered important that one level should be representative of the established level (5 plants/$m^2$), so the density level = 7 plants/$m^2$ was chosen to examine a substantial increase but with low risk of excessive density reducing production, and to examine a level which if advantageous would likely be readily accepted by farmers as a low-risk management modification. Increasing plant D from 5 to 7 plants/$m^2$ improved the TB, grain or stover yields but these yield improvements were not consistent in each of the sites and genotype maturity groups due to the presence of G x E, G x D or D x E interactions for some measures of yield variables. For instance, plant D significantly improved TBY in most sites and GY at Bako and Hawassa ($P<0.05$) but not at Melkassa ($P>0.10$). This suggested that plant D effects are greater in sub-humid than in semi-arid

environments since GY is usually more limited than TBY by reduced resources (Raymond et al., 2009). Sangoi et al. (2002) pointed out that the optimal plant number per area depends on several factors, such as water availability, soil fertility, hybrid maturity group and row spacing. In general, maize biomass yield increases with D up to the point at which interplant competition for resources creates a high level of stress (Kiniry and Echarte, 2005).

In general, higher GY was observed at the higher plant D in the current study. More specifically, the EM genotypes responded to plant D for GY more than the MM genotypes (Tables 4.3 and 4.4). This was in accord with Workayehu et al. (2002) and Bogale et al. (2012b) for maize varieties in Ethiopia and highlights the importance of G choice while manipulating plant D in various maize growing environments. Also optimal plant population D is usually higher for short season than for full-season hybrids (Beech and Basinski, 1975; Brown et al., 1970; Edwards et al., 2005). In other studies with maize Raymond et al. (2009) also reported that 9 plants/$m^2$ resulted in GY that were significantly higher than at 5 plants/$m^2$, but not different from 6 or 7 plants/$m^2$. Widdicombe and Thelen (2002a) reported that the highest plant D evaluated in the northern corn belt of USA, 9 plants/$m^2$, had the highest GY (12 t/ha). Modern maize hybrids are known to have little plasticity in leaf area per plant (Tetio-Kagho and Gardner, 1988a) and little capacity to develop secondary ears at low densities (Tetio-Kagho and Gardner, 1988b).

In the current study, TB and stover yields were generally higher at a plant D of 7 plants/$m^2$ than at 5 plants/$m^2$. Similar results have been reported in studies where whole-plant yield increased by 9 to 33% (Cusicanqui and Lauer, 1999) and 10 to 26% (Cox et al., 1998; Cox, 1996) as plant population densities increased over a range from 5 to 11 plants/$m^2$ in north America temperate environments. The increased plant D affected TB and stover yields more than the GY in the current study. Cox (1997) also reported maize biomass increased with plant densities higher than those required for optimum grain yields.

In the current study the HI at 7 plants/$m^2$ was either lower or equal to the HI obtained at 5 plants/$m^2$. Higher plant D did not ($P>0.05$) reduced HI at each site but reduced ($P<0.05$) HI across sites and years by 8.8 and 6.5% in EM and MM genotypes, respectively (Table 4.4). This is not surprising since there were environmental (site and year) differences ($P<0.05$) and HI is a function of TBY and GY (Table 4.2). This also suggested that improving TBY (GY and SY) without affecting HI could be possible through manipulation of

plant D in selected G and E. HI has been shown to decrease with increased plant D, especially when plant D is above that required for maximum yield (DeLougherty and Crookston, 1979; Genter and Camper, 1973). Conversely, Tollenaar et al. (2006) reported that crowding stress affected DM accumulation but did not affect HI. Kiniry and Echarte (2005) reported that HI of recently released hybrids remained constant when plant D was less than 10 plants/$m^2$, but above this threshold HI decreased linearly by 0.012 units of relative HI per plants/$m^2$. The significant Y x D interactions observed for some yield attributes and the absence significant interactions for S x D for any yield attribute measured shows that plant D was important and consistent across sites but not consistent between years in its effect.

The partitioning of variance components indicated that (Table 4.2), management factor, plant D accounted 38.5 and 15.9% of the total variance in TBY, 19.1 and 4.9% in GY, 33.9 and 12.3% in SY and 7.7 and 2.2% in HI among EM and MM genotypes, respectively. Hence, it is clear that D in the 5-7 plants/m2 had important effects on SY in the present study.

#### 4.4.1.3. Genotype

The significant differences among genotypes for all yield parameters measured across environments and plant D (Table 4.4) indicates that simultaneous genetic improvement of both GY and SY of maize as a dual-purpose crop should be possible. The partitioning of variance components indicated that, G accounted for a smaller proportion of the variance than environmental effects. The variation in grain and stover yields found among genotypes in either maturity group in the current study is in agreement with the previous findings (Anandan et al., 2013; Ertiro et al., 2013a; Geleti et al., 2011; Tolera et al., 1999). Blümmel et al. (2007) also reported that there were highly significant differences among pearl millet cultivars for all productivity (panicles/plant, TBY, GY, SY and HI) variables measured. The older genotypes MH-130 and BH-540 were ranked lowest for all measures of yield attributes (Table 4.4) among EM and MM genotypes, respectively across environments and plant D. Thus, G improvement could contribute to increase GY, SY and HI. However, the presence of significant interactions of G x Y for GY or HI and G x S for TBY, GY and HI or SY in the current study (Table 4.2), indicate that the G differences are not independent of environmental differences among years and sites. Thus, the ranking of

genotypes in terms of TBY, SY and HI will not be consistent although they may be consistent for GY across environments.

In general, the G x E interaction effects in the current study were smaller than G effects. The significant interactions for G x D observed in EM genotype on TBY, SY and HI ($P<0.05$ or $P<0.01$) at Hawassa and on GY ($P<0.05$) across sites (Table 4.2), indicated that G differences are not independent of management level differences of plant D. This can make the ranking of a G at various D levels inconsistent for these attributes. Similarly, a significant G x D interactions have also been observed by other authors in maize in some studies (Aziz et al., 2007; Cox and Cherney, 2011; Widdicombe and Thelen, 2002a). Thomison and Jordan (1995) reported a significant maize G x plant D interaction for GY in a cool, wet year but no interaction in dry year which is similar with (Raymond et al., 2009).

The positive regression relationships between stover (Y) and grain (X) yields showed that simultaneous improvement of both grain and stover yields through manipulating plant D and choice of appropriate genotypes in specific environments is possible.

### 4.4.2. Sources of variation for stover quality attributes

#### 4.4.2.1. Environment and management as plant density

Most stover quality attributes showed significant response to the environmental factors year and site (Table 4.5). There is a wide variation in yield and quality of maize stover due to variety, agro-climatic conditions and management practices (Harika et al., 1995). In the present study, environmental factors (year + site) accounted for much of the total variation in all stover quality attributes measured (Table 4.5) This is in agreement with the previous findings in NDF, ADF, lignin and ash contents of sorghum stover (Rattunde et al., 2001) and in the DMD of pearl millet stover (Bidinger and Blümmel, 2007).

Plant density significantly ($P<0.05$ and $P<0.01$) affected stover DMD and N and ADF contents within EM genotypes across sites (Table 4.7) associated with significant ($P<0.05$) environmental (between years and across sites) differences. However, the general absence of significant differences in DMD and in N, NDF or ADF contents of the stover in most sites with increased plant D from 5 to 7 plants/$m^2$ suggested that it should be possible to improve SY with increased plant D without adversely affecting the quality of the stover. Similarly, Cuomo et al. (1998) observed no differences among plant densities (4.5

to 7.3 plants/$m^2$) for any maize forage nutritive value parameter when comparing leaf and stem, or whole-plant forage nutritive value. Baron et al. (2006) also reported minor effects of plant D (range 7.5 to 12.5 plants/$m^2$) on maize whole-plant nutritive value. In the current study ADF increased by 8.0 percentage unit in MM genotype at Melkassa as plant D increased from 5 to 7 plants/$m^2$, while the corresponding DMD attribute tended (P=0.125) to decrease by 1.2 percentage units. Across sites, N content and DMD decreased by 0.07 and 1.1 percentage units in EM genotypes as plant D increased from 5 to 7 plants/$m^2$ while the corresponding ADF content increased by 11.0 percentage units. Similar trends for nutritive value have been reported as plant D increased; Cox et al. (1998) observed that in vitro true digestibility decreased by 2.4% and NDF increased by 3.1% as plant D increased from 4.5 to 10 plants/$m^2$ and Cusicanqui and Lauer (1999) also observed that in vitro true digestibility decreased 1.6 to 2.3% and NDF increased from 2.0 to 3.5% as plant D increased from 4.5 to 10.5 plants/$m^2$. Stanton et al. (2007) also reported that total N and digestibility decreased as plant population increased. Increasing plant densities increased whole-plant fibre concentrations and slightly decreased digestibility (Cox et al., 1998; Cusicanqui and Lauer, 1999). Bidinger and Blümmel (2007) also reported that plant population (11 plants/$m^2$ versus 5 plant/$m^2$) affected N concentration and digestibility or ME content of pearl millet stover. From the total variation, management factor as D accounted 7.7 and 2.2% in DMD, 11.8 and 5.2% in total N, 4.4 and 0.9% in NDF and 8.1 and 2.4% in ADF of the total variation among EM and MM genotypes, respectively (Table 4.5).

The interactions of Y with D within MM group for stover N, NDF and ADF contents at some sites or across sites (Table 4.5) indicated that the effect of M were not consistent across years in terms of these stover quality attributes. However, the lack of S x D interactions for any stover quality attributes indicated that D effects were consistent across sites.

#### 4.4.2.2. Genotype

The variation found in stover DMD within both EM and MM genotypes at Bako by 2.1 and 3.6 percentage units, respectively and by 2.0 and 3.2 percentage units in MM genotypes at Hawassa (P<0.01) and Melkassa (P<0.001), respectively (Table 4.6). There was also variation among genotypes in stover digestibility (range 1.5-2.4 percentage units in both maturity groups) in the current study (Table 4.7). This is in agreement with Tolera et al. (1999) and Geleti et al. (2011) who observed varietal differences in nutritive value of maize

stover in EA but these studies were limited to one conventional plant D and only at one site and year. Ertiro et al. (2013a) also reported G differences in nutritive value of maize stover in EA with the traditional plant D. Moreover, the variation observed in total N content of maize stover within the EM group ($P<0.01$) at Hawassa (range 0.73-0.84%) is in agreement with the genetic variation for stover fodder quality attributes reported by others in EA and India using the traditional plant D (4.4-5.3 plants/$m^2$) (Anandan et al., 2013; Ertiro et al., 2013a; Zaidi et al., 2013). Blümmel et al. (2007) also reported substantial differences among pearl millet cultivars for stover quality as N content and digestibility. This confirmed the potential for improvement of these attributes by manipulating plant D and exploiting the already existing variability among maize genotypes.

A consequence of the significant S x D and S x G interactions observed in the present study is that a specific plant D or genotype varies with site, and the ranking of genotypes for nutritive value may be inconsistent across sites. Although understanding the importance of G relative to E and M in maize stover quality as a feedstuff may determine opportunities for improving feedstuff quality through either breeding or crop management it needs to be recognized that G x E or G X M interactions would be likely to limit gains from both approaches (Rattunde et al., 2001). In the current study variation in stover quality attributes due to G was generally larger than that due to the G x E or G x D effects in both G groups (Table 4.5). Furthermore, the lack of interactions ($P>0.05$) of G with plant D or year for any of the stover quality measured at each site among genotypes of either maturity groups (Table 4.5) is encouraging, as G differences in stover quality should be consistent across years and management intensities, and thus exploitable by farmers with different levels of plant D in a single year. Testing in multiple E and M would be valuable to ensure where increases in E and M level do occur, but would increase the research investment cost per unit gain (Rattunde et al., 2001). Also, G x D interactions for stover N content ($P<0.05$) within the EM group across sites indicated that G differences for this attribute are not independent of management level. Also G x S interactions for NDF ($P<0.01$) content within the EM group and for all quality attributes measured ($P<0.05$ and $P<0.01$) within the MM group indicated that G differences are not independent of environmental differences (Table 4.5).

The absence of strong inverse relationships observed between stover quality attributes (Y) (DMD % or total N %) and GY (X) in either EM or MM genotypes suggests that there should be no GY penalty to choose genotypes with high nutritive value.

### 4.4.3. Factors affecting stover nutrient yields and PUI

#### 4.4.3.1. Environment and plant density

Nutrient yields (DDMY and NY) (Table 4.9) were higher in 2013 than 2014 within EM group by 23.3% and 9.3% and MM group by 50.4% and 33.4%, respectively. This is mainly due to the difference in SY within EM (12.2 t/ha versus 9.6 t/ha) and MM (15.8 t/ha versus 10.0 t/ha) genotypes in the two years (Table 4.4), but with small changes (lower in 2013 than 2014) in stover DMD within EM (49.4% versus 51.0%) and MM (49.7% versus 51.8%) and N contents within EM (0.65% versus 0.76%) and MM (0.70% versus 0.81%) genotypes (Table 4.7). This is in agreement with the previous findings in pearl millet stover where DDMY differed between two years (Bidinger and Blümmel, 2007) at a specific site. However, the PUI was lower in 2013 than 2014 (Table 4.10) within EM group by 6.7% (61.4% versus 65.5%) and MM group by 12.9% (58.1% versus 65.6%), mainly due to the lack of significant differences between years in GY within both EM (6.58 t/ha versus 6.76 t/ha) ($P=0.542$) and MM (6.55 t/ha versus 6.98 t/ha) ($P=0.084$) coupled with the higher TBY ($P<0.01$) in 2013 than 2014 (Table 4.4).

The increased DDMY ($P<0.01$) while NY tended to increase ($P=0.058$ and $P=0.056$) in both maturity groups as the plant D increased from 5 to 7 plants/$m^2$ (Table 4.9) was expected, since stover biomass increased with the increased plant D (Table 4.4) with minor changes in stover DMD and N content (Table 4.7). Bidinger and Blümmel (2007) also reported that plant population (11 plants/$m^2$ versus 5 plant/$m^2$) affected the DDMY and ME yield of pearl millet stover. However, higher plant D in the current study decreased PUI by 2.2 ($P<0.01$) and 1.7 ($P<0.05$) percentage units in EM and MM group, respectively (Table 4.10), as a result of the reduced HI (Table 4.4). The PUI was not affected ($P>0.05$) by the increased plant D in most sites across both years except at Bako within EM genotypes (Table 4.8). This suggested the possibility of simultaneous selection of maize genotypes that combine improved grain and digestible stover yield across environments.

#### 4.4.3.2. Genotype

The DDMY and NY differed greatly ($P<0.01$) within both EM and MM groups while the PUI varied ($P<0.001$) within MM group but not within EM group (Table 4.10). However, the presence of interactions of G with site in PUI ($P<0.05$ or $P<0.01$) within both maturity groups and with D in DDMY and NY ($P<0.05$) within EM maturity group (Table 4.8)

indicated that genotypes could respond differently in these attributes for different environments and different plant D. Blümmel et al. (2007) also reported that there were substantial differences among pearl millet cultivars for stover DDMY and ME yield.

### 4.5. Conclusion

These results suggest that selection of improved maize genotypes and use of higher plant densities should provide opportunities to increase whole-plant and SY in sub-humid and semi-arid environments. There was considerable evidence that the conventional maize plant density currently being used by farmers and breeders in Ethiopia should be increased in these environments, at least for some recent plant genotypes (e.g. TH13321 and BH-546). However, due to the numerous interactions between G with E or M on the performance of promising genotypes for grain and stover yields and quality, further evaluation of genotypes across environments (years and sites) and M (e,g wide ranges of plant D and fertilizer) levels is warranted to provide greater confidence for revised recommendations. This would need to be done in collaboration with maize breeders, animal nutritionists and smallholder farmers. Furthermore, the low total N content of the whole stover (<0.86%) as observed in many studies is a very important limiting factor for efficient utilization of maize stover by ruminants. Options for improving either the stover quality or its utilization by ruminants need to be explored in smallholder crop-livestock systems. The following, Chapter 5 is concerned with exploring options for improving the quality of stover through higher cutting height of various maize genotypes in contrasting environments.

# Chapter 5 Variation in yield and nutritive value of the morphological fractions in the upper and lower components of maize stover as affected by genotype and environment

## 5.1. Introduction

Maize stover is used for a range of purposes in smallholder systems in East African (EA) farming systems (Valbuena et al., 2012). For instance, in the Ethiopian Rift Valley it has been estimated that on average across districts ~67% is used as ruminant feed while the remainder as used primarily for fuel (~22%) and for soil amendment (~7%) or retained in the field (Baudron et al., 2014). The experiments reported in Chapter 4 and elsewhere have shown that maize grain and residue yields, and the nutritive value of the stover as a ruminant feedstuff often differ among varieties (Blümmel et al., 2013a; Tolera et al., 1999). A further consideration is that maize stover consists of various morphological fractions (stem, leaf blade, leaf sheath, husk and tassel) with differing proportions in the upper and lower components of the stover and with differing nutritive values (Johnson et al., 2010; Li et al., 2014; Tang et al., 2006; Tolera and Sundstøl, 1999). Such distribution of plant fractions and their respective composition can also be expected to vary among maize genotypes and with maturity.

A further consideration important for evaluation of feedstuff resources is that in most previous studies maize stover has been harvested at above ground level the sampling so that the residue comprised the entire stover, termed here as low-cut whole stover (LCS). Field observations in Ethiopia indicate that the cutting height of maize at grain harvest varies with region with some farmers harvesting at a high cut (at the 2$^{nd}$ node below the lowest ear), while in most other regions maize is cut just above the ground at harvest. Such differing harvest practices have practical implications for how much maize stover is available for various purposes and the quality of stover which is stored as a feedstuff. This also has implications for the best approach for feedstuff evaluation to estimate the nutritive value of feed actually consumed. Most research has reported on the nutritive value of whole stover but this may be a poor indicator of the quantity and quality of stover actually fed to and consumed by livestock. Use of the lower fraction of stover (i.e. the lower part of the maize plant) for fuel and soil improvement is logical given that this lower portion is of low quality as a ruminant feedstuff (Tolera and Sundstøl, 1999). Increasing the cutting height of the maize plant at harvest and using the upper fraction as feedstuff is a simple management change which will increase the quality of the harvested stover as a feedstuff

(Bernard et al., 2004) while providing stover for soil amendment and fuel. However, there is little information on the nutritional value for ruminants of various morphological fractions of stover in a variety of environments and there will be a trade-off between quantity and quality of the maize stover available for ruminant feeding. These issues are clearly important for crop-animal farming systems.

The present study was therefore designed to (i) examine the effects of genotype (G) and environment (E) on yield and nutritive value of various morphological fractions in the upper and lower fractions of maize stover; and (ii) to determine the variation among maize genotypes of varying maturity class and in two environments.

## 5.2. Materials and Methods

### 5.2.1. Site descriptions and experimental design

Field studies were conducted in 2013 and 2014 at two sites described in Chapter 4, these being: Bako ($9^0$12'N, $37^0$08'E, 1650 masl on clay soil) (sub-humid) and Melkassa ($8^0$24'N, $39^0$21'E, 1550 masl on clay loam soil) (semi-arid) (Table 4.1; Appendix Figure A5.1). At each site three early (EM) (MH-130, SC-403, and THI3321) (130 day) and three medium (MM) (BH-540, BH-543, and BH-546) (145 day) maturing maize genotypes were examined in a randomized complete block experimental design with three replications using a plant density of 5 plants/$m^2$. The establishment, management and harvesting of the plots and management of data for GY, TBY and other measurements at harvest reported herein were as described in Chapter 4.

### 5.2.2. Measurements and sampling method

The agronomic characteristics measured in four plants selected at random per plot immediately before harvest were: (i) plant height (PH) measured from the ground level to the tip of the plant; (ii) ear height (EH) measured from ground level to the upper most ear insertion, and (iii) above ear height (AEH) as the height from the upper most ear insertion to the tip of the plant. In 2013 three sub-samples were collected from three replicate plots and comprised the following: (1) the top part of the stover sampled by cutting at the $2^{nd}$ node below the first ear attached from the bottom of the plant. This represented high-cut top (HCT) samples and included husk, top stem (top leaf sheath and tassel) and top leaf blade fractions; (2) the remaining bottom part of the stover samples were collected by harvest of the same plant at ground level and represented the high-cut bottom (HCB)

samples. These included bottom stems (which included bottom leaf sheath) and bottom leaf blade fractions. Also (3) low-cut whole stover (LCS) samples were calculated by summation of the above samples and represented stover harvested just above soil level. These harvest procedures were to mimic a harvest scenario of farmers using high or low cut procedures.

In 2014, the three subsamples for each maize genotype were collected just after physiological maturity at Melkassa and a week after physiological maturity at Bako site. Within each plot the HCT and HCB sub-samples were further manually separated into the following morphological fractions for the HCT component: (1) top-leaves (TL); (2) top-stem (including leaf sheath and tassel) (TS) and (3) husk. The HCB component was separated into: (1) bottom-leaves (BL) and (2) bottom-stem (BS). Grain and cob were not included in any of these fractions. Calculations of harvest index (HI), PUI, NDF digestibility and whole stover or stover fraction yields, sub-samples processing and quality parameters, and also laboratory analyses, were as described in Chapter 4. The results, including grain yield (GY), are calculated on a DM basis except where stated otherwise.

### 5.2.3. Statistical analyses

Analyses of variances were performed using the GLM procedure available from SAS (2009). Due to interaction effects of treatment across sites (Tables 5.3, 5.6, 5.8 and 5.9) the results from each site and across sites were analysed and are presented separately for yield and morphological characteristics. Results describing the nutritive value of the residues as feedstuffs are presented averaged across site. In the analysis, replicate was considered as nested within year (Y) and the replication (Y) mean square (MS) was used as an error term for testing the significance of the year MS. At each site, the MS for genotype (G) and their interactions with Y were tested against the residual MS error term. When averaged across sites and years, the MS for site (S) and Y x S were tested using the S x replication (Y) error term while the MS for G and their interactions with Y and S were tested against the residual MS error term. Means were compared using the LSD test to separate G and site effects where F-tests indicated significant differences ($P<0.05$). The statistical comparisons between EM and MM genotypes were not conducted as a main factor in the ANOVA for the reason described in Chapter 4.

## 5.3. Results

### 5.3.1. Plant height at harvest and proportions of the HCT and HCB of the stover

The environmental factor year affected (P<0.05) plant height in both maturity group at Bako and ear height in the MM group at Melkassa (Table 5.1). Site was a major source of variation for most measures of plant height but not for the morphological proportions (Table 5.1). The genotype was a major source of variation for most measures. Genotype TH13321 consistently had higher (P<0.0001) plant height and above ear height than genotype MH-130 at each site and across sites (Table 5.1). Genotype TH13321 also had a higher (P<0.01 and P<0.0001) ear height than the genotype MH-130 within the EM maturity group at Bako and also pooled across sites.

Among the MM genotypes, BH-546 had higher (P<0.0001) above ear height (135.2 and 112.2 cm) than the genotype BH-543 (113.8 and 102.1 cm) at Bako and Melkassa, respectively. When averaged across sites within the MM group, BH-546 also had higher (P<0.0001) above ear height (123.7 cm) than the other genotypes (Table 5.1).

The proportion of the HCT in whole (LCS) stover averaged 67% across the EM and MM groups but varied among both EM and MM genotypes at Bako (P<0.01) and among EM genotypes at Melkassa (P<0.05) (Table 5.1). Across sites, two EM genotypes (TH13321 and SC-403) had a lower (P<0.05) proportion of HCT in the stover than MH-130, while among MM genotypes, BH-543 had lower (P<0.01) HCT proportion of the stover than BH-540 (Table 5.1). Some Y x G interactions were significant (P<0.05 or P<0.01) (Table 5.1).

### 5.3.2. Proportion of morphological fractions within HCT and HCB parts of the stover

On average within genotype classes and across both sites, the proportions of top-leaves, top-stem and husk in the HCT were 18.7 and 22.4, 48.9 and 48.0 and 32.4 and 29.6%, respectively in the EM and MM genotypes. The respective proportions of bottom-leaves and bottom-stem in the HCB were 16.1 and 22.2, and 83.9 and 77.8% (Table 5.2). In both EM and MM genotypes, the proportion of top-leaves was greater, and the top-stem was lower, at Bako than at Melkassa.

Table 5.1 Plant height and proportion (% w/w in LCS) of the HCT and HCB parts of three EM and MM maize genotypes grown at Bako and Melkassa, Ethiopia in 2013 and 2014

| | | EM genotypes | | | | | MM genotypes | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Source of | Plant Height (cm) | | | Proportion (%) | | Plant Height (cm) | | | Proportion (%) | |
| Site | variation | PH | EH | AEH | HCT | HCB | PH | EH | AEH | HCT | HCB |
| Bako | Year (n=9) | | | | | | | | | | |
| | 2013 | 239.1$^{b}$ | 106.9 | 132.2 | 69.7 | 30.3 | 262.4$^{b}$ | 138.7 | 123.8 | 64.0 | 36.0 |
| | 2014 | 244.7$^{a}$ | 112.0 | 132.7 | 73.8 | 26.2 | 280.4$^{a}$ | 152.8 | 127.6 | 63.6 | 36.4 |
| | P>F | 0.0481 | 0.3545 | 0.8914 | 0.2102 | 0.2102 | 0.0462 | 0.0680 | 0.1737 | 0.7693 | 0.7693 |
| | $LSD_{0.05}$ | 5.55 | 13.53 | 9.97 | 7.66 | 7.66 | 17.51 | 15.84 | 6.44 | 3.70 | 3.70 |
| | G (n=6) | | | | | | | | | | |
| | 1 | 212.7$^{b}$ | 100.7$^{b}$ | 112.0$^{b}$ | 75.4$^{a}$ | 24.6$^{b}$ | 264.0 | 135.9$^{b}$ | 128.1$^{a}$ | 66.5$^{a}$ | 33.5$^{b}$ |
| | 2 | 252.9$^{a}$ | 110.6$^{a}$ | 142.3$^{a}$ | 70.7$^{b}$ | 29.3$^{a}$ | 270.1 | 156.3$^{a}$ | 113.8$^{b}$ | 60.8$^{b}$ | 39.2$^{a}$ |
| | 3 | 260.3$^{a}$ | 117.1$^{a}$ | 143.2$^{a}$ | 69.1$^{b}$ | 30.9$^{a}$ | 280.3 | 145.1$^{ab}$ | 135.2$^{a}$ | 64.2$^{a}$ | 35.8$^{b}$ |
| | **Mean** | **241.9** | **109.4** | **132.5** | **71.8** | **28.2** | **271.4** | **145.8** | **125.7** | **63.8** | **36.2** |
| | P>F | <0.0001 | 0.0016 | <0.0001 | 0.0074 | 0.0074 | 0.0676 | 0.0192 | 0.0015 | 0.0071 | 0.0071 |
| | $LSD_{0.05}$ | 10.06 | 6.76 | 8.64 | 3.41 | 3.41 | 13.66 | 12.77 | 8.77 | 2.98 | 2.98 |
| Melkassa | Year (n=9) | | | | | | | | | | |
| | 2013 | 203.4 | 96.6 | 106.9 | 72.4 | 27.6 | 247.8 | 140.8$^{a}$ | 107.1 | 60.6 | 39.4 |
| | 2014 | 211.3 | 100.3 | 111.0 | 71.9 | 28.1 | 228.2 | 122.3$^{b}$ | 106.0 | 62.8 | 37.2 |
| | P>F | 0.6279 | 0.7276 | 0.5240 | 0.7823 | 0.7823 | 0.0506 | 0.0222 | 0.8333 | 0.0764 | 0.0764 |
| | $LSD_{0.05}$ | 41.50 | 27.91 | 16.24 | 4.73 | 4.73 | 19.71 | 14.17 | 13.60 | 2.62 | 2.62 |
| | G (n=6) | | | | | | | | | | |
| | 1 | 188.6$^{b}$ | 90.5$^{b}$ | 98.2$^{c}$ | 75.3$^{a}$ | 24.7$^{b}$ | 235.0 | 129.8 | 105.3$^{ab}$ | 64.6 | 35.4 |
| | 2 | 214.9$^{a}$ | 106.4$^{a}$ | 108.4$^{b}$ | 68.5$^{b}$ | 31.5$^{a}$ | 239.6 | 137.6 | 102.1$^{b}$ | 59.5 | 40.5 |
| | 3 | 218.6$^{a}$ | 98.4$^{ab}$ | 120.2$^{a}$ | 72.8$^{a}$ | 27.2$^{b}$ | 239.5 | 127.2 | 112.2$^{a}$ | 61.0 | 39.0 |
| | **Mean** | **207.4** | **98.4** | **108.9** | **72.2** | **27.8** | **238.0** | **131.5** | **106.5** | **61.7** | **38.3** |
| | P>F | <0.0001 | 0.0085 | <0.0001 | 0.0174 | 0.0174 | 0.6724 | 0.1298 | 0.0390 | 0.0989 | 0.0989 |
| | $LSD_{0.05}$ | 7.49 | 8.58 | 4.19 | 4.19 | 4.19 | 13.20 | 10.77 | 7.58 | 4.82 | 4.82 |
| Pooled | | | | | | | | | | | |
| Year (Y) | 2013 | 221.3 | 101.7 | 119.6 | 71.1 | 28.9 | 255.1 | 139.7 | 115.4 | 62.3 | 37.7 |
| (N=18) | 2014 | 228.0 | 106.2 | 121.9 | 72.9 | 27.1 | 254.3 | 137.5 | 116.8 | 63.2 | 36.8 |
| | P>F | 0.3882 | 0.4796 | 0.4739 | 0.3839 | 0.3839 | 0.8612 | 0.6625 | 0.6605 | 0.1170 | 0.1170 |
| | $LSD_{0.05}$ | 19.31 | 15.79 | 8.09 | 5.13 | 5.13 | 12.08 | 12.85 | 8.01 | 1.27 | 1.27 |
| Site (S) | Bako | 241.9$^{a}$ | 109.4 | 132.5$^{a}$ | 71.8 | 28.2 | 271.4$^{a}$ | 145.8$^{a}$ | 125.7$^{a}$ | 63.8 | 36.2 |
| (n=18) | Melkassa | 207.4$^{b}$ | 98.4 | 108.9$^{b}$ | 72.2 | 27.8 | 238.0$^{b}$ | 131.5$^{b}$ | 106.5$^{b}$ | 61.7 | 38.3 |
| | P>F | 0.0129 | 0.1152 | 0.0037 | 0.7613 | 0.7613 | 0.0028 | 0.0071 | 0.0016 | 0.1133 | 0.1133 |
| | $LSD_{0.05}$ | 22.44 | 15.23 | 10.78 | 3.77 | 3.77 | 14.20 | 7.79 | 7.00 | 2.94 | 2.94 |
| G (n=12) | 1 | 200.6$^{b}$ | 95.6$^{b}$ | 105.1$^{c}$ | 75.3$^{a}$ | 24.7$^{b}$ | 249.5 | 132.9$^{b}$ | 116.7$^{b}$ | 65.5$^{a}$ | 34.5$^{b}$ |
| | 2 | 233.9$^{a}$ | 108.5$^{a}$ | 125.3$^{b}$ | 69.6$^{b}$ | 30.3$^{a}$ | 254.8 | 146.9$^{a}$ | 107.9$^{c}$ | 60.2$^{b}$ | 39.8$^{a}$ |
| | 3 | 239.4$^{a}$ | 107.7$^{a}$ | 131.7$^{a}$ | 71.0$^{b}$ | 29.0$^{a}$ | 259.9 | 136.1$^{b}$ | 123.7$^{a}$ | 62.6$^{b}$ | 37.4$^{a}$ |
| | **Mean** | **224.6** | **103.9** | **120.7** | **72.0** | **28.0** | **254.7** | **138.6** | **116.1** | **62.8** | **37.2** |
| | P>F | <0.0001 | <0.0001 | <0.0001 | 0.0004 | 0.0004 | 0.0701 | 0.0035 | <0.0001 | 0.0018 | 0.0018 |
| | $LSD_{0.05}$ | 5.76 | 5.02 | 4.42 | 2.48 | 2.48 | 8.73 | 7.68 | 5.33 | 2.60 | 2.60 |

*P<0.05 and P<0.01 indicates significant and highly significant genotypes/sites mean respectively; Means with no superscript letters within a column are not significantly different (P>0.05); EM: Early maturing; MM: Medium maturing; G: Genotype; PH: Plant height; EH: Ear insertion height; AEH: Above ear height; HCT: High-cut top; HCB: High-cut bottom; LSD: Least significant difference (P=0.05); *EM genotypes (1=MH-130; 2=SC-403; 3= TH13321);*MM genotypes (1=BH-540; 2=BH=543; 3=BH-546).*

Averaged across sites, the EM genotype SC-403 had a higher (P<0.05) proportion of top-stem (52.8%) than the other two genotypes, and a lower (P<0.05) proportion of husk (28.6%) than genotype MH-130. Also within the HCT stover the top-stem constituted the highest proportion in EM (45.4-52.8%) and MM (43.9-46.6%) followed by the husk in EM (28.6 and 35.5%) and MM (28.8-30.9%) and then top-leaves in EM (18.5-19.1%) and MM (21.1-23.1%). Similarly, within the HCB stover bottom-stem formed the highest proportion in EM (82.8-85.5%) and MM (77.0-78.8%). The proportions of top-stem and top-leaves fractions were affected by site (P<0.05 and P<0.0001) (Table 5.2).

Table 5.2 Proportion of morphological fractions (% w/w of HCT and HCB stover components) of the three EM and MM maize genotypes grown at Bako and Melkassa, Ethiopia in 2014

| | | EM genotypes* | | | | | MM genotypes* | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | % of total HCT | | | % of total HCB | | % of total HCT | | | % of total HCB | |
| Site | G | TL | TS | Husk | BL | BS | TL | TS | Husk | BL | BS |
| Bako | 1 | 21.6 | 42.8 | 35.6 | 18.6 | 81.4 | 26.6 | 46.6 | 26.8 | 25.1 | 74.9 |
| (n=3) | 2 | 23.7 | 47.6 | 28.6 | 16.0 | 84.0 | 28.2 | 43.9 | 28.0 | 24.4 | 75.6 |
| | 3 | 21.2 | 46.7 | 32.2 | 13.9 | 86.1 | 24.3 | 44.3 | 31.4 | 22.6 | 77.4 |
| | **Mean** | **22.2** | **45.7** | **32.1** | **16.1** | **83.9** | **26.4** | **44.9** | **28.7** | **24.0** | **76.0** |
| | P>F | 0.139 | 0.301 | 0.077 | 0.160 | 0.160 | 0.213 | 0.419 | 0.118 | 0.452 | 0.452 |
| | $LSD_{0.05}$ | 2.96 | 7.88 | 6.04 | 5.33 | 5.33 | 4.996 | 5.54 | 4.81 | 5.08 | 5.08 |
| | CV | 5.9 | 7.6 | 8.3 | 14.6 | 2.8 | 8.4 | 5.4 | 7.4 | 9.3 | 3.0 |
| Melkassa | 1 | 16.7 | 48.0$^{b}$ | 35.3 | 15.8 | 84.2 | 19.1 | 49.9 | 30.9 | 19.6 | 80.4 |
| (n=3) | 2 | 13.4 | 58.0$^{a}$ | 28.6 | 17.2 | 82.8 | 18.1 | 51.5 | 30.3 | 17.9 | 82.1 |
| | 3 | 15.7 | 50.4$^{b}$ | 33.9 | 15.4 | 84.6 | 18.0 | 51.6 | 30.4 | 23.3 | 76.7 |
| | **Mean** | **15.3** | **52.1** | **32.6** | **16.1** | **83.9** | **18.4** | **51.0** | **30.6** | **20.3** | **79.7** |
| | P>F | 0.627 | 0.027 | 0.224 | 0.851 | 0.851 | 0.926 | 0.909 | 0.957 | 0.195 | 0.195 |
| | $LSD_{0.05}$ | 9.18 | 6.47 | 9.33 | 8.69 | 8.69 | 8.83 | 11.86 | 6.00 | 6.80 | 6.80 |
| | CV | 26.5 | 5.5 | 12.6 | 23.7 | 4.6 | 21.2 | 10.3 | 8.7 | 14.8 | 3.8 |
| Effects | | | | | | | | | | | |
| G (n=6) | 1 | 19.1 | 45.4$^{b}$ | 35.5$^{a}$ | 17.2 | 82.8 | 22.9 | 48.3 | 28.8 | 22.3 | 77.7 |
| | 2 | 18.6 | 52.8$^{a}$ | 28.6$^{b}$ | 16.6 | 83.4 | 23.1 | 47.7 | 29.2 | 21.2 | 78.8 |
| | 3 | 18.5 | 48.5$^{b}$ | 33.0$^{ab}$ | 14.6 | 85.4 | 21.1 | 48.0 | 30.9 | 23.0 | 77.0 |
| | **Mean** | **18.7** | **48.9** | **32.4** | **16.1** | **83.9** | **22.4** | **48.0** | **29.6** | **22.2** | **77.8** |
| | P>F | 0.917 | 0.011 | 0.025 | 0.393 | 0.393 | 0.521 | 0.972 | 0.327 | 0.520 | 0.520 |
| | $LSD_{0.05}$ | 4.01 | 4.24 | 4.62 | 4.23 | 4.23 | 4.21 | 5.44 | 3.19 | 3.53 | 3.53 |
| Site | Bako | 22.2$^{a}$ | 45.7$^{b}$ | 32.1 | 16.1 | 83.9 | 26.4$^{a}$ | 44.9$^{b}$ | 28.7 | 24.0 | 76.0 |
| (n=9) | Melkassa | 15.3$^{b}$ | 52.1$^{a}$ | 32.6 | 16.1 | 83.9 | 18.4$^{b}$ | 51.0$^{a}$ | 30.6 | 20.3 | 79.7 |
| | P>F | 0.011 | <0.0001 | 0.755 | 0.987 | 0.987 | 0.006 | 0.046 | 0.104 | 0.119 | 0.119 |
| | $LSD_{0.05}$ | 3.27 | 3.46 | 3.77 | 3.46 | 3.46 | 3.44 | 4.44 | 2.61 | 2.88 | 2.88 |
| Interaction | Site x G | 0.280 | 0.223 | 0.860 | 0.468 | 0.468 | 0.600 | 0.613 | 0.232 | 0.093 | 0.093 |
| | CV | 16.1 | 6.5 | 10.7 | 19.7 | 3.8 | 14.1 | 8.5 | 8.1 | 12.0 | 3.4 |

*P<0.05 and P<0.01 indicates significant and highly significant genotypes/sites mean respectively; Means with no superscript letters within a column are not significantly different (P>0.05); EM: Early maturing; MM: Medium maturing; HCT: High-cut top; HCB: High-cut bottom; TL: Top-leaves; TS: Top-stem; BL: Bottom-leaves; BS: Bottom-stem; G: Genotype; LSD: Least significant difference (P=0.05); CV: Coefficient of variation;.*[*]*EM genotypes (1=MH-130; 2=SC-403; 3= TH13321);* [*]*MM genotypes (1=BH-540; 2=BH=543; 3=BH-546).*

### 5.3.3. Grain and crop residue (CR) yields

Apart from HI (P<0.05) at Bako, the yield attributes of EM genotypes were not affected by year (Table 5.3). In MM genotypes, yields of grain and HCT and HI were affected (P<0.05 or P<0.0001) by year at Bako, but not at Melkassa for all the yield variables (Table 5.3). The GY, TBY and HI (P<0.05) in EM genotypes and GY, CobY, TBY and HI (P<0.05 or P<0.01) in MM genotypes were affected by site (Table 5.3). Most yield attributes in both EM and MM genotypes were affected by genotype but there were also Y x G or G x S interactions (Table 5.3).

The genotypic variance components within EM and MM group were significant (P<0.05 P<0.01 or P<0.001) for most yield attributes but there were also Y x G or G x S

interactions for some yield attributes in the EM group but not in the MM group except the Year x G interaction (P<0.05) for GY at Bako (Table 5.3).

Table 5.3 Mean square for yield attributes of the EM and MM maize genotypes across 2 years by site and pooled across 2 sites and years

| | | EM genotypes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Source of | | | Crop residue (CR) yield | | | | | | |
| Site | variation | df | GY | LCSY | HCTY | HCBY | CobY | TCRY | TBY | HI |
| Bako | Year | 1 | 1.1 | 2.4 | 0.1 | 1.4 | 0.01 | 2.7 | 0.3 | 0.005* |
| | Error 1 | 4 | 0.5 | 0.3 | 0.5 | 0.3 | 0.00 | 0.4 | 1.7 | 0.000 |
| | Genotype (G) | 2 | 7.7**** | 10.4**** | 3.0** | 2.5*** | 0.06** | 11.5**** | 35.6**** | 0.003* |
| | Y x G | 2 | 0.4 | 2.5** | 1.4* | 0.2 | 0.01 | 2.9** | 4.4** | 0.001 |
| | Error 2 | 8 | 0.1 | 0.2 | 0.2 | 0.1 | 0.00 | 0.2 | 0.3 | 0.000 |
| | CV% | | 5.3 | 5.3 | 6.9 | 11.1 | 5.0 | 4.4 | 3.3 | 4.4 |
| Melkassa | Year (Y) | 1 | 0.3 | 0.8 | 0.4 | 0.1 | 0.11 | 1.5 | 3.3 | 0.000 |
| | Error 1 | 4 | 2.9 | 3.6 | 1.9 | 0.4 | 0.06 | 4.4 | 13.6 | 0.002 |
| | Genotype (G) | 2 | 1.0* | 1.5 | 1.7* | 0.3 | 0.06**** | 2.2* | 6.0* | 0.000 |
| | Y x G | 2 | 0.9* | 0.4 | 0.4 | 0.2 | 0.02** | 0.5 | 2.8 | 0.001** |
| | Error 2 | 8 | 0.2 | 0.4 | 0.2 | 0.1 | 0.00 | 0.4 | 1.1 | 0.000 |
| | CV% | | 8.2 | 8.6 | 8.1 | 16.4 | 3.10 | 7.5 | 7.7 | 2.5 |
| Pooled | Year (Y) | 1 | 1.4 | 0.2 | 0.0 | 0.4 | 0.03 | 0.1 | 0.8 | 0.002 |
| | Error 1 | 4 | 2.0 | 1.8 | 0.8 | 0.5 | 0.03 | 2.2 | 7.9 | 0.001 |
| | Site (S) | 1 | 22.1* | 11.7 | 5.2 | 1.3 | 0.10 | 14.0 | 71.2* | 0.010* |
| | Y x S | 1 | 0.1 | 2.9** | 0.5 | 1.1** | 0.10**** | 4.1** | 2.8 | 0.003** |
| | Error 2 | 4 | 1.5 | 2.2 | 1.6 | 0.2 | 0.03 | 2.6 | 7.3 | 0.001 |
| | Genotype (G) | 2 | 5.9**** | 9.6**** | 4.1**** | 2.0**** | 0.10**** | 11.4**** | 32.5**** | 0.001* |
| | Y x G | 2 | 0.8* | 0.9 | 0.2 | 0.3 | 0.00 | 1.0 | 1.9 | 0.002** |
| | S x G | 2 | 2.7**** | 2.4** | 0.6 | 0.7** | 0.02** | 2.3** | 9.2*** | 0.001** |
| | Y x S x G | 2 | 0.5 | 2.0* | 1.6** | 0.1 | 0.03** | 2.5** | 5.3** | 0.000 |
| | Error 3 | 16 | 0.1 | 0.3 | 0.2 | 0.1 | 0.00 | 0.3 | 0.7 | 0.000 |
| | CV% | | 6.6 | 6.9 | 7.5 | 13.6 | 4.2 | 6.0 | 5.5 | 3.7 |
| | | | | | MM genotypes | | | | | |
| Bako | Year | 1 | 10.4* | 9.2 | 3.9* | 1.1 | 0.02 | 10.1 | 0.0 | 0.030**** |
| | Error 1 | 4 | 0.9 | 1.8 | 0.4 | 0.6 | 0.02 | 2.2 | 5.7 | 0.000 |
| | Genotype (G) | 2 | 4.1*** | 4.8** | 1.1* | 1.8*** | 0.04** | 5.5** | 17.8*** | 0.001* |
| | Y x G | 2 | 1.4* | 0.3 | 0.4 | 0.0 | 0.01 | 0.3 | 2.8 | 0.001 |
| | Error 2 | 8 | 0.2 | 0.3 | 0.2 | 0.1 | 0.00 | 0.3 | 0.6 | 0.000 |
| | CV% | | 5.7 | 5.8 | 7.8 | 7.2 | 4.8 | 5.2 | 4.4 | 3.7 |
| Melkassa | Year (Y) | 1 | 0.7 | 1.6 | 0.1 | 0.9 | 0.00 | 1.6 | 0.2 | 0.006 |
| | Error 1 | 4 | 1.4 | 1.6 | 0.4 | 0.4 | 0.01 | 1.8 | 6.4 | 0.001 |
| | Genotype (G) | 2 | 3.0* | 2.7* | 0.8 | 1.1* | 0.00 | 2.9* | 11.6** | 0.002* |
| | Y x G | 2 | 0.1 | 0.1 | 0.0 | 0.0 | 0.00 | 0.1 | 0.4 | 0.000 |
| | Error 2 | 8 | 0.4 | 0.4 | 0.2 | 0.2 | 0.01 | 0.4 | 1.2 | 0.000 |
| | CV% | | 15.0 | 6.7 | 8.2 | 12.7 | 9.7 | 5.9 | 7.6 | 7.6 |
| Pooled | Year (Y) | 1 | 8.3** | 9.3** | 2.7** | 2.0** | 0.01 | 9.9** | 0.1 | 0.031** |
| | Error 1 | 4 | 0.3 | 0.3 | 0.0 | 0.1 | 0.01 | 0.3 | 1.1 | 0.001 |
| | Site (S) | 1 | 78.9** | 6.7 | 5.0 | 0.1 | 0.40* | 10.4 | 146.8* | 0.087*** |
| | Y x S | 1 | 2.8** | 1.5 | 1.3* | 0.0 | 0.01 | 1.8* | 0.1 | 0.005** |
| | Error 2 | 4 | 2.0 | 3.2 | 0.8 | 0.9 | 0.02 | 3.6 | 10.9 | 0.001 |
| | Genotype (G) | 2 | 6.9**** | 6.6**** | 1.7** | 2.6**** | 0.03 | 7.4**** | 27.4**** | 0.003** |
| | Y x G | 2 | 0.8 | 0.1 | 0.2 | 0.1 | 0.00 | 0.1 | 1.3 | 0.001 |
| | S x G | 2 | 0.2 | 0.9 | 0.3 | 0.2 | 0.01 | 1.0 | 2.1 | 0.000 |
| | Y x S x G | 2 | 0.8 | 0.3 | 0.3 | 0.0 | 0.01 | 0.3 | 2.0 | 0.000 |
| | Error 3 | 16 | 0.3 | 0.4 | 0.2 | 0.1 | 0.01 | 0.4 | 0.9 | 0.000 |
| | CV% | | 9.4 | 6.3 | 8.0 | 10.2 | 7.2 | 5.5 | 5.9 | 5.5 |

*Significant at P<0.05; ** Significant at P<0.01; ***Significant at P<0.001; ****Significant at P<0.0001; CV: Coefficient of variation; EM: Early maturing; MM: medium maturing; GY: Grain yield; LCSY: Low-cut whole stover yield (HCTY + HCBY) ; HCTY: High-cut top yield; HCBY: High-cut bottom yield; CobY: Cob yield; TCRY: Total crop residue yield; TBY: Total biomass yield; HI: Harvest index.*

Table 5.4 Yield attributes of three EM maize genotypes grown at Bako and Melkassa, Ethiopia in 2013 and 2014

| | | EM genotypes yield (t/ha) and HI | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Source of | | Crop residue (CR) yield | | | | | | |
| Site | variation | GY | LCSY | HCTY | HCBY | CobY | TCRY | TBY | HI |
| Bako | Year (n=9) | | | | | | | | |
| | 2013 | 6.40 | 9.19 | 6.40 | 2.80 | 1.34 | 10.54 | 16.94 | 0.38$^{b}$ |
| | 2014 | 6.90 | 8.47 | 6.23 | 2.24 | 1.30 | 9.76 | 16.66 | 0.41$^{a}$ |
| | P>F | 0.2159 | 0.0589 | 0.6330 | 0.0920 | 0.1854 | 0.0647 | 0.6772 | 0.0120 |
| | $LSD_{0.05}$ | 0.95 | 0.77 | 0.91 | 0.70 | 0.08 | 0.85 | 1.68 | 0.02 |
| | G (n=6) | | | | | | | | |
| | MH-130 | 5.43$^{c}$ | 7.90$^{b}$ | 5.96$^{b}$ | 1.94$^{c}$ | 1.21$^{b}$ | 9.11$^{b}$ | 14.54$^{c}$ | 0.37$^{b}$ |
| | SC-403 | 6.87$^{b}$ | 8.25$^{b}$ | 5.84$^{b}$ | 2.41$^{b}$ | 1.37$^{a}$ | 9.62$^{b}$ | 16.49$^{b}$ | 0.42$^{a}$ |
| | TH13321 | 7.66$^{a}$ | 10.34$^{a}$ | 7.13$^{a}$ | 3.21$^{a}$ | 1.38$^{a}$ | 11.72$^{a}$ | 19.38$^{a}$ | 0.40$^{ab}$ |
| | **Mean** | **6.65** | **8.83** | **6.31** | **2.52** | **1.32** | **10.15** | **16.80** | **0.40** |
| | P>F | <0.0001 | <0.0001 | 0.0016 | 0.0002 | 0.0027 | <0.0001 | <0.0001 | 0.0105 |
| | $LSD_{0.05}$ | 0.47 | 0.62 | 0.58 | 0.37 | 0.09 | 0.60 | 0.74 | 0.02 |
| Melkassa | Year (n=9) | | | | | | | | |
| | 2013 | 4.95 | 7.48 | 5.41 | 2.07 | 1.13 | 8.62 | 13.57 | 0.36 |
| | 2014 | 5.23 | 7.90 | 5.69 | 2.21 | 1.29 | 9.19 | 14.42 | 0.36 |
| | P>F | 0.7491 | 0.6659 | 0.6847 | 0.6714 | 0.2511 | 0.5904 | 0.6495 | 0.9289 |
| | $LSD_{0.05}$ | 2.24 | 2.49 | 1.79 | 0.82 | 0.33 | 2.73 | 4.82 | 0.06 |
| | G (n=6) | | | | | | | | |
| | MH-130 | 4.96$^{b}$ | 7.57 | 5.69$^{a}$ | 1.88 | 1.14$^{b}$ | 8.71$^{ab}$ | 13.67$^{b}$ | 0.36 |
| | SC-403 | 4.77$^{b}$ | 7.26 | 4.97$^{b}$ | 2.29 | 1.17$^{b}$ | 8.42$^{b}$ | 13.19$^{b}$ | 0.36 |
| | TH13321 | 5.53$^{a}$ | 8.25 | 6.00$^{a}$ | 2.25 | 1.33$^{a}$ | 9.58$^{a}$ | 15.12$^{a}$ | 0.36 |
| | **Mean** | **5.09** | **7.69** | **5.55** | **2.14** | **1.21** | **8.90** | **13.99** | **0.36** |
| | P>F | 0.0314 | 0.0778 | 0.0109 | 0.1406 | <0.0001 | 0.0404 | 0.0348 | 0.8341 |
| | $LSD_{0.05}$ | 0.55 | 0.88 | 0.60 | 0.47 | 0.05 | 0.89 | 1.43 | 0.01 |
| Pooled | Year | | | | | | | | |
| Year (Y) | 2013 | 5.68 | 8.34 | 5.90 | 2.43 | 1.24 | 9.58 | 15.25 | 0.37 |
| (n=18) | 2014 | 6.06 | 8.18 | 5.96 | 2.22 | 1.29 | 9.48 | 15.54 | 0.39 |
| | P>F | 0.4531 | 0.7452 | 0.8606 | 0.4212 | 0.4105 | 0.8509 | 0.7729 | 0.2358 |
| | $LSD_{0.05}$ | 1.30 | 1.23 | 0.83 | 0.65 | 0.17 | 1.36 | 2.60 | 0.03 |
| Site (S) | Bako | 6.65$^{a}$ | 8.83 | 6.31 | 2.52 | 1.32 | 10.15 | 16.80$^{a}$ | 0.40$^{a}$ |
| (n=18) | Melkassa | 5.09$^{b}$ | 7.69 | 5.55 | 2.14 | 1.21 | 8.90 | 13.99$^{b}$ | 0.36$^{b}$ |
| | P>F | 0.0180 | 0.0816 | 0.1422 | 0.0546 | 0.1606 | 0.0816 | 0.0354 | 0.0367 |
| | $LSD_{0.05}$ | 1.12 | 1.37 | 1.15 | 0.39 | 0.17 | 1.49 | 2.50 | 0.03 |
| Genotype | MH-130 | 5.19$^{c}$ | 7.74$^{b}$ | 5.83$^{b}$ | 1.91$^{c}$ | 1.17$^{c}$ | 8.91$^{b}$ | 14.11$^{b}$ | 0.37$^{b}$ |
| (n=12) | SC-403 | 5.82$^{b}$ | 7.75$^{b}$ | 5.40$^{c}$ | 2.35$^{b}$ | 1.27$^{b}$ | 9.02$^{b}$ | 14.84$^{b}$ | 0.39$^{a}$ |
| | TH13321 | 6.60$^{a}$ | 9.29$^{a}$ | 6.56$^{a}$ | 2.73$^{a}$ | 1.36$^{a}$ | 10.65$^{a}$ | 17.25$^{a}$ | 0.38$^{ab}$ |
| | **Mean** | **5.87** | **8.26** | **5.93** | **2.33** | **1.27** | **9.53** | **15.40** | **0.38** |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0111 |
| | $LSD_{0.05}$ | 0.33 | 0.49 | 0.38 | 0.27 | 0.05 | 0.49 | 0.74 | 0.01 |

*P<0.05 and P<0.01indicates significant and highly significant genotypes/sites mean respectively; Means with no superscript letters within a column are not significantly different (P>0.05); EM: Early maturing; G: Genotype; GY: Grain yield; LCSY: Low-cut whole stover yield (HCTY + HCBY) ; HCTY: High-cut top yield; HCBY: High-cut bottom yield; CobY: Cob yield; TCRY: Total crop residue yield; TBY = Total biomass yield; HI: Harvest index; LSD: Least significant difference (P=0.05).*

At the Bako and Melkassa sites the GY among EM group varied from 5.43-7.66 t/ha and from 4.77-5.53 t/ha, respectively. The HCT yield varied from 5.84-7.13 t/ha and from 4.97-6.00 t/ha, respectively (Table 5.4). At Bako, the grain and HCT yields of MM genotypes varied from 6.51-8.13 t/ha and from 5.93-6.78 t/ha, respectively while the GY at Melkassa

Table 5.5 Yield attributes of three MM maize genotypes grown at Bako and Melkassa, Ethiopia in 2013 and 2014

| | | MM genotypes yield (t/ha) and HI | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Source of | | Crop residue (CR) yield | | | | | | |
| Site | variation | GY | LCSY | HCTY | HCBY | CobY | TCRY | TBY | HI |
| Bako | Year (n=9) | | | | | | | | |
| | 2013 | 6.46$^{b}$ | 10.65 | 6.79$^{a}$ | 3.85 | 1.36 | 12.00 | 18.47 | 0.35$^{b}$ |
| | 2014 | 7.98$^{a}$ | 9.22 | 5.86$^{b}$ | 3.36 | 1.29 | 10.51 | 18.49 | 0.43$^{a}$ |
| | P>F | 0.0251 | 0.0871 | 0.0345 | 0.2336 | 0.3473 | 0.0977 | 0.9853 | P<0.0001 |
| | $LSD_{0.05}$ | 1.21 | 1.76 | 0.82 | 0.98 | 0.18 | 1.93 | 3.12 | 0.01 |
| | G (n=6) | | | | | | | | |
| | BH-540 | 6.51$^{b}$ | 8.92$^{b}$ | 5.93$^{b}$ | 2.99$^{b}$ | 1.26$^{b}$ | 10.17$^{b}$ | 16.69$^{c}$ | 0.39$^{ab}$ |
| | BH-543 | 7.01$^{b}$ | 10.30$^{a}$ | 6.27$^{ab}$ | 4.04$^{a}$ | 1.31$^{b}$ | 11.61$^{a}$ | 18.62$^{b}$ | 0.37$^{b}$ |
| | BH-546 | 8.13$^{a}$ | 10.58$^{a}$ | 6.78$^{a}$ | 3.80$^{a}$ | 1.41$^{a}$ | 12.00$^{a}$ | 20.13$^{a}$ | 0.40$^{a}$ |
| | **Mean** | **7.22** | **9.93** | **6.33** | **3.61** | **1.32** | **11.26** | **18.48** | **0.39** |
| | P>F | 0.0004 | 0.0023 | 0.0461 | 0.0003 | 0.0074 | 0.0015 | 0.0003 | 0.0259 |
| | $LSD_{0.05}$ | 0.55 | 0.77 | 0.65 | 0.34 | 0.08 | 0.78 | 1.07 | 0.02 |
| Melkassa | Year (n=9) | | | | | | | | |
| | 2013 | 4.06 | 9.37 | 5.66 | 3.71 | 1.11 | 10.48 | 14.54 | 0.27 |
| | 2014 | 4.46 | 8.77 | 5.50 | 3.27 | 1.11 | 9.88 | 14.34 | 0.31 |
| | P>F | 0.5136 | 0.3722 | 0.6323 | 0.2173 | 0.9845 | 0.3939 | 0.8733 | 0.0983 |
| | $LSD_{0.05}$ | 1.56 | 1.67 | 0.86 | 0.84 | 0.14 | 1.76 | 3.30 | 0.05 |
| | G (n=6) | | | | | | | | |
| | BH-540 | 3.85$^{b}$ | 8.54$^{b}$ | 5.51 | 3.02$^{b}$ | 1.12 | 9.66$^{b}$ | 13.51$^{b}$ | 0.28$^{b}$ |
| | BH-543 | 3.84$^{b}$ | 8.84$^{b}$ | 5.25 | 3.59$^{ab}$ | 1.09 | 9.93$^{b}$ | 13.77$^{b}$ | 0.28$^{b}$ |
| | BH-546 | 5.08$^{a}$ | 9.83$^{a}$ | 5.98 | 3.85$^{a}$ | 1.13 | 10.96$^{a}$ | 16.04$^{a}$ | 0.31$^{a}$ |
| | **Mean** | **4.26** | **9.07** | **5.58** | **3.49** | **1.11** | **10.18** | **14.44** | **0.29** |
| | P>F | 0.0149 | 0.0155 | 0.0668 | 0.0319 | 0.7855 | 0.0131 | 0.0074 | 0.0469 |
| | $LSD_{0.05}$ | 0.85 | 0.81 | 0.61 | 0.59 | 0.14 | 0.80 | 1.46 | 0.03 |
| Pooled | | | | | | | | | |
| Year (Y) | 2013 | 5.26$^{b}$ | 10.01$^{a}$ | 6.23$^{a}$ | 3.78$^{a}$ | 1.24 | 11.25$^{a}$ | 16.50 | 0.31$^{b}$ |
| (n=18) | 2014 | 6.22$^{a}$ | 8.99$^{b}$ | 5.68$^{b}$ | 3.31$^{b}$ | 1.20 | 10.20$^{b}$ | 16.41 | 0.37$^{a}$ |
| | P>F | 0.0069 | 0.0039 | 0.0018 | 0.0097 | 0.3860 | 0.0053 | 0.8120 | 0.0020 |
| | $LSD_{0.05}$ | 0.52 | 0.47 | 0.21 | 0.28 | 0.10 | 0.53 | 0.98 | 0.02 |
| Site (S) | Bako | 7.22$^{a}$ | 9.93 | 6.33 | 3.61 | 1.32$^{a}$ | 11.26 | 18.48$^{a}$ | 0.39$^{a}$ |
| (n=18) | Melkassa | 4.26$^{b}$ | 9.07 | 5.58 | 3.49 | 1.11$^{b}$ | 10.18 | 14.44$^{b}$ | 0.29$^{b}$ |
| | P>F | 0.0031 | 0.2186 | 0.0644 | 0.7212 | 0.0107 | 0.1660 | 0.0215 | 0.0004 |
| | $LSD_{0.05}$ | 1.29 | 1.65 | 0.82 | 0.87 | 0.13 | 1.77 | 3.06 | 0.02 |
| Genotype | BH-540 | 5.18$^{b}$ | 8.73$^{c}$ | 5.72$^{b}$ | 3.01$^{b}$ | 1.19 | 9.91$^{c}$ | 15.10$^{c}$ | 0.34$^{b}$ |
| (n=12) | BH-543 | 5.43$^{b}$ | 9.57$^{b}$ | 5.76$^{b}$ | 3.81$^{a}$ | 1.20 | 10.77$^{b}$ | 16.20$^{b}$ | 0.33$^{b}$ |
| | BH-546 | 6.60$^{a}$ | 10.21$^{a}$ | 6.38$^{a}$ | 3.82$^{a}$ | 1.27 | 11.48$^{a}$ | 18.08$^{a}$ | 0.36$^{a}$ |
| | **Mean** | **5.74** | **9.50** | **5.95** | **3.55** | **1.22** | **10.72** | **16.46** | **0.34** |
| | P>F | <0.0001 | <0.0001 | 0.0056 | <0.0001 | 0.0580 | <0.0001 | <0.0001 | 0.0021 |
| | $LSD_{0.05}$ | 0.46 | 0.51 | 0.41 | 0.31 | 0.08 | 0.51 | 0.83 | 0.02 |

*P<0.05 and P<0.01 indicates significant and highly significant genotypes/sites mean respectively; Means with no superscript letters within a column are not significantly different (P>0.05); MM: medium maturing; G: Genotype; GY: Grain yield; LCSY: Low-cut whole stover yield (HCTY + HCBY); HCTY: High-cut top yield; HCBY: High-cut bottom yield; CobY: Cob yield; TCRY: Total crop residue yield; TBY = Total biomass yield; HI: Harvest index; LSD: Least significant difference (P=0.05).*

varied from 3.84-5.08 t/ha (Table 5.6). Wider variability was observed in yields of HCT than of the HCB component of the stover in both years within EM genotypes and HCT comprised 71.8% and 72.2% of the whole stover at Bako and, Melkassa, respectively (Table 5.1). Stover yields of the HCT of the MM genotypes comprised 63.8, 61.7 and

62.8% of the LCSY at Bako, Melkassa and pooled across sites, respectively (Table 5.1). Genotype TH13321 consistently had higher GY, most measures of crop residue yields and TBY compared to genotypes SC-403 genotype MH-130 (Table 5.4). With similar HI at Bako, the genotype BH-546 was higher ($P<0.05$) for all measures of yield parameters than the older genotype BH-540 (Table 5.5). Most yield variables were higher ($P<0.05$) in genotype BH-546 than the other MM genotypes at Melkassa and across sites (Table 5.5).

### 5.3.4. Composition and digestibility of stover components

The stover DMD and N generally showed no response to the environmental factor year (Table 5.6). An exception was the N content of HCT ($P<0.05$) within the MM group at Melkassa. The NDF and ADF showed a similar pattern although there were more exceptions (Table 5.6). In general, the HCT component had higher DMD% and total N concentration, but lower concentrations of NDF and ADF, than the HCB. The HCT fraction was higher in DMD ($P<0.0001$) than the LCS by 2.0-3.0 percentage units (Table 5.8).

The DMD and ADF of HCT and HCB were affected by site ($P<0.05$ or $P<0.01$) within the MM group (Table 5.7). The mean DMD was higher ($P<0.01$) and mean fibre contents were lower ($P<0.05$ or $P<0.01$) at Melkassa than at Bako within the MM group.

There were large variations due to genotype on DMD and fibre concentrations of stover at each site (Table 5.6). The DMD of HCT varied ($P<0.0001$ and $P<0.01$) within the MM genotype at Bako ($P<0.01$) (range 50.9-54.1%) and at Melkassa ($P<0.0001$) (range 53.7-56.8%) (data not shown) and across years and sites (range 52.3-55.4%, (Table 5.7), but did not differ ($P>0.05$) among the EM group (Tables 5.6 and 5.7). The HCT stover and LCS of the genotype BH-543 had higher ($P<0.001$) DMD (55.4% and 51.9%) than the other MM genotypes, respectively (Table 5.7). The DMD of HCB and LCS varied ($P<0.01$) within both EM (range 41.8-46.6% and 48.5-51.0%) and MM (range 43.3-46.5% and 49.6-51.9% genotypes, respectively while the EM genotype SC-403 had a lower ($P<0.05$) DMD than the other EM genotypes (Table 5.7).

There was little variation in total N concentration (Table 5.7). The total N content of HCB across sites varied ($P<0.05$) within the EM group (range 0.49 – 0.59%) (Table 5.7). The mean N content of HCT component of the stover within the MM genotypes across sites varied ($P<0.05$) from 0.86-0.97%. Genotype BH-543 had the highest ($P<0.05$) N content

(Table 5.7). There were often Y x G interactions (P<0.05 and P<0.01) for some measures of stover quality attributes within EM and MM genotype groups (Table 5.6).

Table 5.6 Mean square for DMD and total N, NDF and ADF contents of HCT, HCB and LCS of EM and MM maize genotypes across 2 years by site and pooled across 2 sites

| EM genotypes | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | DMD | | | N | | | NDF | | | ADF | | |
| Site[#] | Source | df | HCT | HCB | LCS | HCT | HCB | LCS | HCT | HCB | LCS | HCT | HCB | LCS |
| 1 | Y | 1 | 0.6 | 8.3 | 4.9 | 0.03 | 0.12 | 0.06 | 5.0 | 0.4 | 3.8 | 0.0 | 2.6 | 2.1 |
| | Error 1 | 4 | 0.4 | 11.0 | 1.6 | 0.02 | 0.02 | 0.02 | 11.0 | 19.5 | 12.9 | 2.8 | 13.3 | 4.4 |
| | G | 2 | 2.6 | 67.4** | 7.9** | 0.01 | 0.01 | 0.00 | 26.6* | 138.7** | 48.9** | 9.8* | 131.9** | 25.9** |
| | Y x G | 2 | 2.4 | 23.3 | 7.0* | 0.02* | 0.01 | 0.02* | 19.3* | 42.5 | 25.0* | 5.8* | 26.2 | 10.5* |
| | Error 2 | 8 | 2.1 | 5.7 | 0.9 | 0.01 | 0.01 | 0.00 | 3.2 | 12.7 | 3.5 | 1.2 | 7.1 | 1.7 |
| 2 | Y | 1 | 1.6 | 19.9 | 3.8 | 0.01 | 0.01 | 0.01 | 131.6* | 132.6* | 131.1* | 31.7 | 99.2** | 44.7* |
| | Error 1 | 4 | 12.8 | 2.9 | 9.2 | 0.07 | 0.06 | 0.07 | 9.2 | 7.5 | 8.7 | 5.2 | 3.0 | 4.6 |
| | G | 2 | 3.1 | 44.9**** | 13.4** | 0.00 | 0.03 | 0.01 | 3.2 | 40.1** | 10.6** | 12.2** | 37.6*** | 24.0*** |
| | Y x G | 2 | 0.3 | 0.4 | 0.8 | 0.02 | 0.07** | 0.03 | 0.3 | 0.4 | 0.2 | 0.5 | 0.3 | 1.1 |
| | Error 2 | 8 | 1.4 | 0.9 | 1.2 | 0.01 | 0.01 | 0.01 | 1.2 | 2.8 | 0.8 | 0.9 | 1.6 | 1.1 |
| P | Y | 1 | 2.1 | 27.0 | 8.7 | 0.04 | 0.11 | 0.06 | 93.9* | 73.6 | 89.7* | 16.3 | 67.0 | 33.2 |
| | Error 1 | 4 | 6.5 | 6.5 | 5.1 | 0.04 | 0.03 | 0.04 | 7.4 | 14.3 | 9.0 | 5.6 | 11.0 | 6.1 |
| | Site (S) | 1 | 33.8 | 43.5 | 35.0 | 0.01 | 0.02 | 0.01 | 0.2 | 9.1 | 0.5 | 4.0 | 1.0 | 1.0 |
| | Y x S | 1 | 0.1 | 1.2 | 0.0 | 0.00 | 0.03 | 0.01 | 42.7*** | 59.4* | 45.3*** | 15.4** | 34.8* | 13.6** |
| | Error 2 | 4 | 6.7 | 7.4 | 5.7 | 0.05 | 0.05 | 0.05 | 12.7 | 12.6 | 12.6 | 2.3 | 5.3 | 2.9 |
| | G | 2 | 5.4 | 81.8**** | 20.3**** | 0.00 | 0.03* | 0.01 | 13.4* | 106.4*** | 32.4*** | 20.5**** | 95.2**** | 40.9**** |
| | Y x G | 2 | 0.7 | 12.6* | 2.0 | 0.02 | 0.05** | 0.03* | 8.4* | 25.4 | 11.8* | 1.5 | 11.9 | 2.5 |
| | S x G | 2 | 0.4 | 30.6** | 1.1 | 0.01 | 0.01 | 0.00 | 16.4** | 72.5** | 27.1*** | 1.5 | 74.3*** | 9.1** |
| | YxSxG | 2 | 1.9 | 11.1 | 5.8* | 0.02 | 0.03* | 0.02 | 11.2* | 17.5 | 13.4* | 4.8* | 14.6 | 9.1** |
| | Error 3 | 16 | 1.8 | 3.3 | 1.0 | 0.01 | 0.01 | 0.01 | 2.2 | 7.8 | 2.2 | 1.0 | 4.3 | 1.4 |
| | CV% | | 2.6 | 4.1 | 2.0 | 10.6 | 14.1 | 10.6 | 1.9 | 3.6 | 1.9 | 2.3 | 3.9 | 2.5 |
| MM genotypes | | | | | | | | | | | | | | |
| | | | DMD | | | N | | | NDF | | | ADF | | |
| Site[#] | Source | df | HCT | HCB | LCS | HCT | HCB | LCS | HCT | HCB | LCS | HCT | HCB | LCS |
| 1 | Y | 1 | 5.7 | 13.1 | 0.2 | 0.02 | 0.13 | 0.05 | 0.0 | 0.4 | 0.1 | 4.5 | 1.4 | 3.8 |
| | Error 1 | 4 | 2.6 | 21.7 | 6.4 | 0.04 | 0.05 | 0.04 | 11.8 | 18.4 | 13.6 | 3.1 | 12.7 | 4.7 |
| | G | 2 | 17.6** | 12.4 | 8.6 | 0.02 | 0.00 | 0.01 | 8.7 | 9.3 | 3.8 | 12.6* | 1.0 | 3.5 |
| | Y x G | 2 | 0.2 | 8.1 | 1.0 | 0.01 | 0.02 | 0.01 | 0.1 | 0.6 | 0.1 | 0.1 | 1.8 | 0.0 |
| | Error 2 | 8 | 1.6 | 6.5 | 2.7 | 0.01 | 0.01 | 0.01 | 2.7 | 4.3 | 3.1 | 1.5 | 5.6 | 2.7 |
| 2 | Y | 1 | 17.8 | 27.4 | 24.0 | 0.12* | 0.06 | 0.10 | 195.8** | 128.3* | 170.2** | 73.8** | 68.7 | 79.7* |
| | Error 1 | 4 | 3.2 | 13.1 | 6.0 | 0.01 | 0.03 | 0.02 | 3.9 | 8.7 | 4.9 | 1.9 | 9.5 | 3.8 |
| | G | 2 | 16.3**** | 22.1** | 10.3*** | 0.02 | 0.00 | 0.01 | 6.7* | 0.1 | 2.2 | 10.0** | 14.3* | 4.1 |
| | Y x G | 2 | 4.1** | 26.6** | 9.7** | 0.00 | 0.04** | 0.01 | 0.8 | 20.4** | 4.2* | 0.3 | 19.0* | 3.7 |
| | Error 2 | 8 | 0.4 | 1.7 | 0.5 | 0.01 | 0.00 | 0.01 | 0.9 | 2.2 | 0.7 | 0.5 | 3.0 | 1.2 |
| P | Y | 1 | 1.7 | 39.2 | 10.0 | 0.13 | 0.18 | 0.15 | 98.8* | 72.0 | 88.4 | 20.9 | 25.3 | 24.3 |
| | Error 1 | 4 | 5.6 | 32.9 | 12.2 | 0.03 | 0.04 | 0.03 | 9.3 | 17.6 | 11.6 | 4.0 | 18.4 | 7.5 |
| | Site (S) | 1 | 71.1*** | 343.5*** | 135.1**** | 0.09 | 0.13 | 0.10 | 8.6 | 51.4 | 20.1 | 19.0* | 92.7** | 32.4** |
| | Y x S | 1 | 21.7*** | 1.3 | 14.1** | 0.02 | 0.01 | 0.00 | 96.9**** | 56.8*** | 81.9**** | 57.5**** | 44.8** | 59.2**** |
| | Error 2 | 4 | 0.3 | 1.9 | 0.2 | 0.02 | 0.05 | 0.03 | 6.3 | 9.5 | 6.9 | 0.9 | 3.7 | 0.9 |
| | G | 2 | 33.8**** | 33.2** | 18.7*** | 0.03* | 0.00 | 0.01 | 15.2** | 3.9 | 5.0 | 22.4**** | 10.7 | 6.5 |
| | Y x G | 2 | 3.1 | 21.3* | 7.6* | 0.00 | 0.04* | 0.01 | 0.6 | 8.0 | 2.3 | 0.0 | 6.4 | 1.5 |
| | S x G | 2 | 0.0 | 1.4 | 0.2 | 0.01 | 0.00 | 0.00 | 0.1 | 5.5 | 1.0 | 0.2 | 4.7 | 1.0 |
| | YxSxG | 2 | 1.2 | 13.3 | 3.1 | 0.01 | 0.02 | 0.01 | 0.2 | 13.0* | 1.9 | 0.5 | 14.4 | 2.3 |
| | Error 3 | 16 | 1.0 | 4.1 | 1.6 | 0.01 | 0.01 | 0.01 | 1.8 | 3.3 | 1.9 | 1.0 | 4.3 | 1.9 |
| | CV% | | 1.9 | 4.5 | 2.5 | 9.6 | 14.3 | 10.2 | 1.7 | 2.3 | 1.8 | 2.3 | 3.8 | 2.9 |

**Significant at P<0.05; ** Significant at P<0.01; ***Significant at P<0.001; ****Significant at P<0.0001;[#]Site1: Bako; [#]Site 2: Melkassa; P: Pooled across both sites and years; DMD: Dry matter digestibility, N: Nitrogen, NDF: Neutral detergent fibre; ADF: Acid detergent fibre; HCT: High-cut top; HCB: High-cut bottom; LCS: Low-cut whole stover; EM: Early maturing; MM: medium maturing; Y: Year; G: Genotype; CV: Coefficient of variation.*

Table 5.7 Stover quality attributes (%) of HCT, HCB and LCS of three EM and MM maize genotypes grown at Bako and Melkassa , Ethiopia in 2013 and 2014

| Source of variation | EM Genotypes | DMD | | | N | | | NDF | | | ADF | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HCT | HCB | LCS | HCT | HCB | LCS | HCT | HCB | LCS | HCT | HCB | LCS |
| Year (Y) | 2013 | 51.6 | 43.9 | 49.4 | 0.76 | 0.50 | 0.68 | 77.9$^{a}$ | 79.4 | 78.3$^{a}$ | 45.3 | 54.3 | 47.9 |
| (n=18) | 2014 | 52.1 | 45.6 | 50.4 | 0.83 | 0.61 | 0.77 | 74.7$^{b}$ | 76.5 | 75.2$^{b}$ | 44.0 | 51.6 | 46.0 |
| | P>F | 0.6018 | 0.1121 | 0.2620 | 0.3553 | 0.1258 | 0.2704 | 0.0236 | 0.0860 | 0.0343 | 0.1644 | 0.0687 | 0.0799 |
| | $LSD_{0.05}$ | 2.36 | 2.37 | 2.09 | 0.18 | 0.16 | 0.18 | 2.52 | 3.50 | 2.78 | 2.20 | 3.06 | 2.28 |
| Site (S) | Bako | 50.9 | 43.7 | 48.9 | 0.78 | 0.53 | 0.71 | 76.4 | 77.4 | 76.7 | 45.0 | 52.8 | 47.1 |
| (n=18) | Melkassa | 52.8 | 45.9 | 50.9 | 0.81 | 0.58 | 0.74 | 76.3 | 78.4 | 76.9 | 44.3 | 53.1 | 46.8 |
| | P>F | 0.0880 | 0.0720 | 0.0689 | 0.7223 | 0.5744 | 0.6942 | 0.9146 | 0.4446 | 0.8528 | 0.2578 | 0.6816 | 0.5852 |
| | $LSD_{0.05}$ | 2.40 | 2.51 | 2.22 | 0.21 | 0.22 | 0.21 | 3.30 | 3.29 | 3.29 | 1.41 | 2.14 | 1.58 |
| Genotype | MH-130 | 52.6 | 46.0$^{a}$ | 51.0$^{a}$ | 0.80 | 0.57$^{a}$ | 0.75 | 76.4$^{ab}$ | 77.5$^{b}$ | 76.7$^{b}$ | 43.6$^{b}$ | 52.5$^{b}$ | 45.8$^{b}$ |
| (n=12) | SC-403 | 51.3 | 41.8$^{b}$ | 48.5$^{b}$ | 0.78 | 0.49$^{b}$ | 0.69 | 77.3$^{a}$ | 81.1$^{a}$ | 78.5$^{a}$ | 46.1$^{a}$ | 56.0$^{a}$ | 49.1$^{a}$ |
| | TH13321 | 51.7 | 46.6$^{a}$ | 50.2$^{a}$ | 0.79 | 0.59$^{a}$ | 0.74 | 75.2$^{b}$ | 75.2$^{b}$ | 75.2$^{c}$ | 44.3$^{b}$ | 50.4$^{c}$ | 46.0$^{b}$ |
| | **Mean** | **51.9** | **44.8** | **49.9** | **0.79** | **0.55** | **0.72** | **76.3** | **77.9** | **76.8** | **44.7** | **53.0** | **47.0** |
| | P>F | 0.0752 | <0.0001 | <0.0001 | 0.7812 | 0.0183 | 0.2452 | 0.0109 | 0.0003 | 0.0002 | <0.0001 | <0.0001 | <0.0001 |
| | $LSD_{0.05}$ | 1.15 | 1.57 | 0.87 | 0.07 | 0.07 | 0.07 | 1.28 | 2.41 | 1.27 | 0.88 | 1.80 | 1.03 |
| Source of variation | MM genotypes | DMD | | | N | | | NDF | | | ADF | | |
| | | HCT | HCB | LCS | HCT | HCB | LCS | HCT | HCB | LCS | HCT | HCB | LCS |
| Year (Y) | 2013 | 53.3 | 44.2 | 49.9 | 0.85 | 0.61 | 0.76 | 78.9$^{a}$ | 80.9 | 79.6 | 44.9 | 55.5 | 48.8 |
| (n=18) | 2014 | 53.7 | 46.3 | 51.0 | 0.97 | 0.75 | 0.89 | 75.6$^{b}$ | 78.1 | 76.5 | 43.3 | 53.8 | 47.2 |
| | P>F | 0.6124 | 0.3358 | 0.4165 | 0.1128 | 0.0987 | 0.0985 | 0.0313 | 0.1135 | 0.0508 | 0.0857 | 0.3063 | 0.1472 |
| | $LSD_{0.05}$ | 2.19 | 5.31 | 3.23 | 0.16 | 0.19 | 0.17 | 2.83 | 3.89 | 3.15 | 1.86 | 3.97 | 2.54 |
| Site (S) | Bako | 52.1$^{b}$ | 42.1$^{b}$ | 48.5$^{b}$ | 0.86 | 0.62 | 0.77 | 77.7 | 80.7 | 78.8 | 44.8$^{a}$ | 56.2$^{a}$ | 49.0$^{a}$ |
| (n=18) | Melkassa | 54.9$^{a}$ | 48.3$^{a}$ | 52.4$^{a}$ | 0.96 | 0.74 | 0.88 | 76.7 | 78.3 | 77.3 | 43.4$^{b}$ | 53.0$^{b}$ | 47.1$^{b}$ |
| | P>F | 0.0001 | 0.0002 | <0.0001 | 0.1212 | 0.1654 | 0.1384 | 0.3089 | 0.0802 | 0.1633 | 0.0108 | 0.0075 | 0.0037 |
| | $LSD_{0.05}$ | 0.51 | 1.27 | 0.45 | 0.14 | 0.20 | 0.16 | 2.33 | 2.85 | 2.43 | 0.90 | 1.78 | 0.87 |
| Genotype | BH-540 | 52.8$^{b}$ | 43.3$^{b}$ | 49.6$^{b}$ | 0.89$^{ab}$ | 0.70 | 0.83 | 77.3$^{a}$ | 78.8 | 77.8 | 44.6$^{a}$ | 55.7 | 48.4 |
| (n=12) | BH-543 | 55.4$^{a}$ | 46.5$^{a}$ | 51.9$^{a}$ | 0.97$^{a}$ | 0.68 | 0.85 | 76.1$^{b}$ | 79.9 | 77.6 | 42.5$^{b}$ | 54.2 | 47.2 |
| | BH-546 | 52.3$^{b}$ | 45.8$^{a}$ | 49.9$^{b}$ | 0.86$^{b}$ | 0.67 | 0.79 | 78.3$^{a}$ | 79.7 | 78.8 | 45.2$^{a}$ | 54.0 | 48.5 |
| | **Mean** | **53.5** | **45.2** | **50.5** | **0.91** | **0.68** | **0.83** | **77.2** | **79.5** | **78.1** | **44.1** | **54.6** | **48.0** |
| | P>F | <0.0001 | 0.0036 | 0.0008 | 0.0283 | 0.8434 | 0.2466 | 0.0031 | 0.3319 | 0.1036 | <0.0001 | 0.1167 | 0.0608 |
| | $LSD_{0.05}$ | 0.86 | 1.74 | 1.10 | 0.08 | 0.08 | 0.07 | 1.16 | 1.57 | 1.19 | 0.87 | 1.80 | 1.21 |

*P<0.05 and P<0.01 indicates significant and highly significant genotypes mean respectively; Means with no superscript letter are not significantly different (P>0.05); DMD: Dry matter digestibility, N: Nitrogen, NDF: Neutral detergent fibre; ADF: Acid detergent fibre; HCT: High-cut top; HCB: High-cut bottom; LCS: Low-cut whole stover; EM: Early maturing; MM: medium maturing; LSD: Least significant difference (P=0.05).*

### 5.3.5. Nutrient composition and digestibility of stover morphological fractions

The nutrient composition and DMD varied substantially among the components of the whole stover (Table 5.8). The HCT stover was higher (P<0.0001) in DMD than the HCB and LCS at both sites. The differences were (in percentage units): 7.2 and 2.0 at Bako and 6.9 and 1.9 at Melkassa in the EM genotypes, and 10.0 and 3,6 at Bako and 6.6 and 2.5 at Melkassa in the MM genotypes, respectively (Table 5.8). Similarly, the HCT component had higher (P<0.0001) N but lower ADF concentrations than the HCB component and LCS at both sites. In general, there was a narrower range in NDF concentrations than in the other stover quality parameters.

The environmental factor year significantly affected the NDF and ADF contents of stover components within both EM and MM genotypes (Table 5.8) at Melkassa, but not at Bako (P>0.05). Genotype was a major source of variation for most measures of stover quality in each site and across sites (Table 5.8). Generally, there were no Y x morphological fraction interactions (P>0.05) for any measures of stover quality (Table 5.8).

The DMD and ADF content of stover components within the MM group was affected by site (P<0.01) (Table 5.8).

The results from 2014, when the stover was separated into five morphological fractions, showed that there were large differences (P<0.0001) in the DMD and nutrient concentrations among the leaf, husk and stem fractions, and between the upper and lower stem fractions of the maize stover (Table 5.9). Digestibility ranged from 41.3-59.7% and 37.8-59.3% at Bako and from 44.5-59.6% and 47.0-61.3% at Melkassa in EM and MM genotypes respectively.

The total N concentration of the stover fractions at Bako ranged from 0.44-1.47% and 0.37-1.75%, and at Melkassa from 0.51-1.11% and 0.66-1.55%, in EM and MM genotypes respectively. When averaged across sites and genotypes, TL and BL had higher (P<0.0001) DMD and total N contents and lower NDF and ADF contents than the other fractions. Conversely BS had lower (P<0.05) DMD and total N concentrations and higher ADF contents.

Table 5.8 Stover quality attributes (%) of HCT, HCB and LCS averaged across two years and three EM and MM maize genotypes grown at Bako and Melkassa

| Site | Stover MF | EM genotypes DMD | N | NDF | ADF | MM genotypes DMD | N | NDF | ADF |
|---|---|---|---|---|---|---|---|---|---|
| Bako (n=18) | HCT | 50.9[a] | 0.78[a] | 76.4 | 45.0[c] | 52.1[a] | 0.86[a] | 77.7[c] | 44.8[c] |
| | HCB | 43.7[c] | 0.53[c] | 77.4 | 52.8[a] | 42.1[c] | 0.62[c] | 80.7[a] | 56.2[a] |
| | LCS | 48.9[b] | 0.71[b] | 76.7 | 47.1[b] | 48.5[b] | 0.77[b] | 78.8[b] | 48.9[b] |
| | P>F | <0.0001 | <0.0001 | 0.3589 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | $LSD_{0.05}$ | 1.144 | 0.044 | 1.529 | 1.135 | 1.234 | 0.062 | 1.094 | 1.113 |
| Effects | Year (Y) | 0.2906 | 0.1494 | 0.6906 | 0.6894 | 0.9298 | 0.3140 | 0.9351 | 0.5190 |
| | Genotype (G) | <0.0001 | 0.1571 | <0.0001 | <0.0001 | 0.0004 | 0.0563 | 0.0216 | 0.0184 |
| | Y x MF | 0.6632 | 0.1833 | 0.8652 | 0.7771 | 0.0736 | 0.2760 | 0.9642 | 0.9081 |
| | G x MF | 0.0004 | 0.0952 | 0.0749 | <0.0001 | 0.5221 | 0.8451 | 0.1156 | 0.4708 |
| | Y x G x MF | 0.3949 | 0.7656 | 0.7026 | 0.5557 | 0.7210 | 0.7618 | 0.9876 | 0.9220 |
| | CV% | 3.5 | 9.6 | 2.9 | 3.5 | 3.8 | 12.1 | 2.0 | 3.3 |
| Melkassa (n=18) | HCT | 52.8[a] | 0.81[a] | 76.3[b] | 44.3[c] | 54.9[a] | 0.96[a] | 76.7[b] | 43.4[c] |
| | HCB | 45.9[c] | 0.58[c] | 78.4[a] | 53.1[a] | 48.3[c] | 0.74[c] | 78.3[a] | 53.0[a] |
| | LCS | 50.9[b] | 0.74[b] | 76.9[b] | 46.8[b] | 52.4[b] | 0.88[b] | 77.3[b] | 47.1[b] |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0006 | <0.0001 |
| | $LSD_{0.05}$ | 0.772 | 0.053 | 0.807 | 0.711 | 0.664 | 0.047 | 0.733 | 0.816 |
| Effects | Year (Y) | 0.3912 | 0.6743 | 0.0150 | 0.0182 | 0.1374 | 0.0871 | 0.0051 | 0.0147 |
| | Genotype (G) | <0.0001 | 0.0207 | <0.0001 | <0.0001 | <0.0001 | 0.0807 | 0.0222 | <0.0001 |
| | Y x MF | 0.1298 | 0.9955 | 0.9992 | 0.0167 | 0.7550 | 0.5664 | 0.2251 | 0.9317 |
| | G x MF | 0.0037 | 0.4159 | 0.0102 | 0.1946 | 0.0008 | 0.2306 | 0.1713 | 0.0153 |
| | Y x G x MF | 0.9399 | 0.5405 | 0.9728 | 0.9526 | 0.0320 | 0.3455 | 0.0111 | 0.0466 |
| | CV% | 2.3 | 11.0 | 1.5 | 2.2 | 1.9 | 8.1 | 1.4 | 2.5 |
| Pooled (n=36) | HCT | 51.9[a] | 0.79[a] | 76.3[b] | 44.7[c] | 53.5[a] | 0.91[a] | 77.2[c] | 44.1[c] |
| | HCB | 44.8[c] | 0.55[c] | 77.9[a] | 53.0[a] | 45.2[c] | 0.68[c] | 79.5[a] | 54.6[a] |
| | LCS | 49.9[b] | 0.72[b] | 76.8[b] | 47.0[b] | 50.5[b] | 0.83[b] | 78.1[b] | 48.0[b] |
| | P>F | <0.0001 | <0.0001 | 0.0010 | <0.0001 | <0.0001 | <0.0001 | 0.0001 | <0.0001 |
| | $LSD_{0.05}$ | 0.676 | 0.034 | 0.848 | 0.657 | 0.687 | 0.038 | 0.646 | 0.677 |
| Effects | Year (Y) | 0.2119 | 0.2322 | 0.0425 | 0.0827 | 0.4055 | 0.0993 | 0.0574 | 0.1815 |
| | Site (S) | 0.0534 | 0.6581 | 0.7653 | 0.7173 | <0.0001 | 0.1399 | 0.1486 | 0.0064 |
| | Genotype (G) | <0.0001 | 0.0040 | <0.0001 | <0.0001 | <0.0001 | 0.0166 | 0.0028 | <0.0001 |
| | Y x MF | 0.1858 | 0.4878 | 0.8996 | 0.1157 | 0.0592 | 0.8131 | 0.7499 | 0.9718 |
| | S x MF | 0.9164 | 0.8330 | 0.3969 | 0.3003 | <0.0001 | 0.8523 | 0.0945 | 0.0320 |
| | Y x S x MF | 0.8142 | 0.4811 | 0.8855 | 0.4728 | 0.2160 | 0.1566 | 0.4857 | 0.8639 |
| | G x MF | <0.0001 | 0.3454 | 0.0087 | 0.0002 | 0.0071 | 0.2436 | 0.0187 | 0.0157 |
| | Y x G x MF | 0.3811 | 0.5903 | 0.6980 | 0.5167 | 0.4106 | 0.3240 | 0.5532 | 0.5761 |
| | S x G x MF | 0.0021 | 0.1348 | 0.1650 | <0.0001 | 0.9374 | 0.9699 | 0.6260 | 0.8098 |
| | Y x S x G x MF | 0.7321 | 0.6624 | 0.8383 | 0.8262 | 0.3385 | 0.9049 | 0.1484 | 0.2216 |
| | CV% | 2.9 | 10.3 | 2.3 | 2.9 | 2.9 | 10.0 | 1.8 | 2.9 |

*P<0.05 and P<0.01 indicates significant and highly significant genotypes/sites mean respectively; Means with no superscript letters within a column are not significantly different (P>0.05); EM: Early maturing; MM: Medium maturing; DMD; Dry matter digestibility; N: Nitrogen; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; HCT: High-cut top; HCB: High-cut bottom; LCS: Low-cut whole stover (calculated based on the proportion of HCT and HCB); MF: Morphological fraction; LSD: Least significant difference (P=0.05); CV: Coefficient of variation.*

Table 5.9 Stover quality attributes (%) of HCT, HCB and LCS averaged across three EM and MM maize genotypes grown at Bako and Melkassa in 2014

| Site | Stover MF | EM genotypes | | | | MM genotypes | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | DMD | N | NDF | ADF | DMD | N | NDF | ADF |
| Bako (n=9) | TL | 58.5$^{a}$ | 1.47$^{a}$ | 65.6$^{d}$ | 42.1$^{e}$ | 57.3$^{b}$ | 1.65$^{b}$ | 66.5$^{g}$ | 41.4$^{g}$ |
| | TS | 46.6$^{d}$ | 0.69$^{cd}$ | 75.3$^{c}$ | 47.9$^{b}$ | 45.8$^{f}$ | 0.64$^{de}$ | 80.6$^{c}$ | 50.2$^{c}$ |
| | Husk | 52.4$^{b}$ | 0.54$^{ef}$ | 83.9$^{a}$ | 42.9$^{de}$ | 55.3$^{c}$ | 0.59$^{e}$ | 83.4$^{b}$ | 41.2$^{g}$ |
| | BL | 59.7$^{a}$ | 1.47$^{a}$ | 68.0$^{d}$ | 45.3$^{c}$ | 59.3$^{a}$ | 1.75$^{a}$ | 68.2$^{f}$ | 44.3$^{f}$ |
| | BS | 41.3$^{f}$ | 0.44$^{f}$ | 79.2$^{b}$ | 53.9$^{a}$ | 37.8$^{h}$ | 0.37$^{f}$ | 84.4$^{a}$ | 60.4$^{a}$ |
| | HCT | 51.1$^{bc}$ | 0.82$^{b}$ | 75.9$^{c}$ | 45.0$^{cd}$ | 51.6$^{d}$ | 0.90$^{c}$ | 77.7$^{e}$ | 45.3$^{e}$ |
| | HCB | 44.4$^{e}$ | 0.61$^{de}$ | 77.3$^{bc}$ | 52.4$^{a}$ | 43.0$^{g}$ | 0.71$^{d}$ | 80.5$^{c}$ | 56.5$^{b}$ |
| | LCS | 49.4$^{c}$ | 0.77$^{bc}$ | 76.2$^{c}$ | 46.8$^{bc}$ | 48.4$^{e}$ | 0.83$^{c}$ | 78.8$^{d}$ | 49.4$^{d}$ |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | G x MF | 0.0619 | 0.0074 | 0.0702 | 0.0010 | 0.2189 | 0.0020 | <0.0001 | <0.0001 |
| | $LSD_{0.05}$ | 2.232 | 0.112 | 2.672 | 2.225 | 1.255 | 0.087 | 0.632 | 0.528 |
| | CV | 4.7 | 13.9 | 3.7 | 5.0 | 2.7 | 9.8 | 0.9 | 1.1 |
| Melkassa (n=9) | TL | 54.7$^{c}$ | 1.11$^{a}$ | 62.6$^{d}$ | 41.9$^{de}$ | 56.5$^{c}$ | 1.55$^{a}$ | 64.6$^{d}$ | 40.6$^{d}$ |
| | TS | 50.4$^{e}$ | 0.80$^{b}$ | 73.5$^{c}$ | 45.6$^{c}$ | 52.4$^{e}$ | 0.91$^{d}$ | 75.4$^{b}$ | 44.9$^{c}$ |
| | Husk | 57.0$^{b}$ | 0.77$^{b}$ | 78.7$^{a}$ | 39.4$^{f}$ | 61.3$^{a}$ | 0.95$^{cd}$ | 75.6$^{b}$ | 36.0$^{e}$ |
| | BL | 59.6$^{a}$ | 1.10$^{a}$ | 61.4$^{d}$ | 41.1$^{e}$ | 60.1$^{b}$ | 1.38$^{b}$ | 63.8$^{d}$ | 40.7$^{d}$ |
| | BS | 44.5$^{g}$ | 0.51$^{c}$ | 78.5$^{a}$ | 52.7$^{a}$ | 47.0$^{g}$ | 0.66$^{f}$ | 78.5$^{a}$ | 53.6$^{a}$ |
| | HCT | 53.1$^{d}$ | 0.83$^{b}$ | 73.5$^{c}$ | 43.0$^{d}$ | 55.9$^{c}$ | 1.04$^{c}$ | 73.4$^{c}$ | 41.3$^{d}$ |
| | HCB | 46.9$^{f}$ | 0.60$^{c}$ | 75.7$^{b}$ | 50.8$^{b}$ | 49.5$^{f}$ | 0.80$^{e}$ | 75.6$^{b}$ | 51.1$^{b}$ |
| | LCS | 51.3$^{e}$ | 0.77$^{b}$ | 74.2$^{bc}$ | 45.2$^{c}$ | 53.6$^{d}$ | 0.95$^{cd}$ | 74.2$^{bc}$ | 44.9$^{c}$ |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | G x MF | <0.0001 | 0.0120 | 0.0168 | 0.0016 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | $LSD_{0.05}$ | 1.161 | 0.131 | 1.784 | 1.309 | 1.099 | 0.101 | 1.625 | 1.319 |
| | CV | 2.3 | 17.0 | 2.6 | 3.1 | 2.1 | 10.3 | 2.4 | 3.1 |
| Pooled (n=18) | TL | 56.6$^{b}$ | 1.29$^{a}$ | 64.1$^{e}$ | 42.0$^{ef}$ | 56.9$^{c}$ | 1.60$^{a}$ | 65.6$^{f}$ | 41.0$^{f}$ |
| | TS | 48.5$^{f}$ | 0.75$^{b}$ | 74.4$^{d}$ | 46.7$^{c}$ | 49.1$^{f}$ | 0.78$^{d}$ | 78.0$^{c}$ | 47.5$^{c}$ |
| | Husk | 54.7$^{c}$ | 0.65$^{c}$ | 81.3$^{a}$ | 41.1$^{f}$ | 58.3$^{b}$ | 0.77$^{d}$ | 79.5$^{b}$ | 38.6$^{g}$ |
| | BL | 59.7$^{a}$ | 1.29$^{a}$ | 64.7$^{e}$ | 43.2$^{de}$ | 59.7$^{a}$ | 1.57$^{a}$ | 66.0$^{f}$ | 42.5$^{e}$ |
| | BS | 42.9$^{h}$ | 0.47$^{d}$ | 78.9$^{b}$ | 53.3$^{a}$ | 42.4$^{h}$ | 0.52$^{e}$ | 81.4$^{a}$ | 57.0$^{a}$ |
| | HCT | 52.1$^{d}$ | 0.83$^{b}$ | 74.7$^{d}$ | 44.0$^{d}$ | 53.7$^{d}$ | 0.97$^{b}$ | 75.6$^{e}$ | 43.3$^{d}$ |
| | HCB | 45.6$^{g}$ | 0.61$^{c}$ | 76.5$^{c}$ | 51.6$^{b}$ | 46.3$^{g}$ | 0.75$^{d}$ | 78.1$^{c}$ | 53.8$^{b}$ |
| | LCS | 50.4$^{e}$ | 0.77$^{b}$ | 75.2$^{cd}$ | 46.0$^{c}$ | 51.0$^{e}$ | 0.89$^{c}$ | 76.5$^{d}$ | 47.2$^{c}$ |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | $LSD_{0.05}$ | 1.241 | 0.085 | 1.585 | 1.274 | 0.823 | 0.066 | 0.860 | 0.701 |
| Effects | Site (S) | 0.0975 | 0.2821 | 0.1328 | 0.1039 | 0.0060 | 0.2330 | 0.0095 | 0.0046 |
| | S x MF | <0.0001 | <0.0001 | 0.0048 | 0.0744 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | G x MF | 0.0014 | <0.0001 | 0.0076 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | G x S x MF | 0.0050 | 0.4917 | 0.1135 | 0.0038 | 0.0358 | 0.5776 | 0.0007 | 0.0109 |
| | CV | 3.7 | 15.5 | 3.2 | 4.2 | 2.4 | 10.1 | 1.7 | 2.3 |

*P<0.05 and P<0.01 indicates significant and highly significant genotypes/sites mean respectively; Means with no superscript letters within a column are not significantly different (P>0.05); EM: Early maturing; MM: Medium maturing; DMD; Dry matter digestibility; N: Nitrogen; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; TL: Top leaves; BL: Bottom Leaves; TS: Top stem; BS: Bottom stem; HCT: High-cut top (calculated based on the proportion of TL, TS and Husk); HCB: High-cut bottom (calculated based on the proportion of BL and BS); LCS: Low-cut whole stover (calculated based on the proportion of HCT and HCB); G: Genotype; LSD: Least significant difference (P=0.05); CV: Coefficient of variation.*

The DMD% of the morphological fractions (Table 5.9) decreased (P<0.05) in the following order: BL>TL>husk>HCT>LCS>TS>HCB>BS in EM genotypes and BL>husk>TL>HCT>LCS>TS>HCB>BS in MM genotypes.
The N % of the morphological fractions decreased (P<0.05) in the following order:
TL=BL>HCT= LCS=TS>husk=HCB>BS in EM genotypes and
TL=BL>HCT> LCS>TS=husk=HCB>BS in MM genotypes

The DMD and NDF and ADF contents of the morphological fractions of MM were affected by site (P<0.05) (Table 5.9). When averaged across genotypes and sites, there were significant interaction effects (P<0.05 and P<0.0001) on all the quality attributes measured in both EM and MM genotypes (P<0.01) in 2014 except the ADF content (P=0.07) of stover fractions in EM genotype group (Table 5.9).

## 5.4. Discussion

### 5.4.1. Plant dimensions and the proportions of morphological fractions at harvest

The change in harvest procedure to a high cutting height decreased the amount of harvested stover (HCT versus LCT) available as ruminant feedstuff by 27.8-38.3%, this range depending on both environmental (year and site) and genotype effects. Genotypes TH13321 and SC-403 among the EM group had a lower (P<0.05) proportion of HCT in the stover than MH-130 (Table 5.1) associated with higher plant height and ear height. Among MM genotypes, BH-543 had lower (P<0.01) HCT than BH-540 associated with higher ear height (Table 5.1). The major advantage of the high-cut harvest was that as expected the harvested HCT material was of substantially higher value as a ruminant feedstuff. Also genotypes within each maturity group varied in the proportion in the HCT and HCB. The HCB in the MM group was also greater than that in EM genotypes associated with the differences in plant height and ear height (Table 5.1). This difference could provide options for farmers to select more suitable genotypes or cutting height according to their circumstances. The differences in top-stem and husk fractions among EM genotypes within HCT stover are consistent with Tolera et al. (1999) also in maize stover.

### 5.4.2. Grain and CR yields of EM and MM genotypes

The difference between years on some measures of yield attributes at Bako, are likely due primarily to the differences in rainfall in 2013 (1228 mm) and 2014 (830 mm) (Table 4.1). The higher rainfall favoured more HCTY than the GY at Bako (Table 5.5). Moreover, the

difference between sites in GY, TBY or HI within EM and MM group are likely due a combination of edaphic and weather factors between the sites in each year (Table 4.1), and are consistent with the findings of (Ertiro et al., 2013a) of the effects of environmental factors on GY and SY.

There was more stover in the HCT fraction (which included the husk component) than HCB, but this was obviously a consequence of the height of cut selected for the “high-cut” procedure. In the EM and MM genotype classes, the proportions of the HCT were 71.8-72.2% and 61.7-63.8%, respectively as proportions in the total stover (Table 5.1). These yields of the stover components were similar to those reported by Hoskinson et al. (2007) and Wilhelm et al. (2011). It is obvious if a different cutting height at harvest were chosen, then this would directly affect the proportions in the HCT and HCB fractions.

In the current study, the variation generally observed among genotypes was greater for SY than GY. The genotype variation in GY and LCSY within the EM and MM genotypes was in agreement with previous reports on maize (Ertiro et al., 2013a; Tolera et al., 1999). However, the mean GY, LCSY, TCRY and TBY (averaged across sites in both years) in the current study were higher but the mean HI were lower (EM 0.38 and MM 0.34 versus 0.40) than the values reported by Tolera et al. (1999) but which were limited to one site and year. This might be due to the differences in the numbers of genotypes and environments (more sites and years) were examined in the current study.

### 5.4.3. Nutrient content and digestibility of stover components

Differences between years in total N, NDF and ADF contents in stover fractions at Melkassa and also across sites (Table 5.6) were apparently associated with rainfall (Table 4.1), higher rainfall being associated with higher NDF and ADF contents at Melkassa (data not shown) and higher NDF contents across sites in 2013 than in 2014 (Table 5.7). Similarly, Ørskov et al. (1990) observed generally lower degradability of barley, wheat and oat straws grown in years with high rainfall due to a lower proportions of soluble fractions in the straws. The differences between sites ($P<0.05$ or $P<0.01$) in some quality attributes within the MM group (Table 5.7) was presumably due a combination of edaphic and weather differences (Table 4.1) and are consistent with (Ertiro et al., 2013a).

The higher ($P<0.01$) DMD and the lower ($P<0.05$) ADF content among MM genotypes at Melkassa than at Bako (Table 5.7) may be associated with (1) the differences in stover

sampling date relative to physiological maturity in 2014, and (2) environmental factors. The growing conditions at Bako were, compared with Melkassa, characterized by periods of high humidity and absence of moisture stress throughout the crop growth stage. These characteristics have been reported to decrease digestibility because of increased concentrations of lignin and NDF (Buxton, 1996). Moderate water stress (e.g. in semi-arid environments like Melkassa) often delays maturation (Halim et al., 1989) so that stover quality is higher for a longer time (Buxton, 2004). These factors may also have contributed to the higher stover digestibility at Melkassa than Bako. Joshi et al. (1995) also reported that moderate water stress may increase cell solubles and thus digestibility, e.g. in conditions that lead to low GY. In accord with this study the lower GY obtained at Melkassa than at Bako (4.26 versus 7.22 t/ha) (Table 5.5) was associated with high stover quality.

The high cutting height of maize stover in the current study increased the total N content and DMD of HCT compared to whole stover but also resulted in a large HCB proportion containing less digestible stem which was left in the field to be grazed or used for other purposes. These responses varied among genotypes within the EM and MM genotype groups. On average DMD was 1.7-3.6 percentage units higher, while NDF was 0.3-1.1 and ADF (1.8-4.1) percentage units lower, in HCT than in whole stover. Also N concentration was higher in the HCT by 0.05-0.09 percentage units (Tables 5.8 and 5.9), although this HCT component of the whole stover would still be expected to be deficient in N for ruminants.

The genotype variation in nutrient contents and digestibility of each component of the stover within both the EM and MM group in the current study was in agreement with the previous reports on maize silage and stover (Ertiro et al., 2013a; Kennington et al., 2005; Liang et al., 2015; Tolera et al., 1999). The DMD of HCT of all genotypes in both years was >51% while the DMD of HCB of all genotypes in both years was <47% (Table 5.7). This is in agreement with the report of Tolera and Sundstøl (1999) that the lower portion of maize stover is less digestible. In the current study the stem with leaf sheath was the largest fraction of the stover component of HCB dry matter (77.8%-83.9%) while the remaining 16.1%-22.2% was leaf blade (Table 5.2).

All genotypes within the EM and MM genotype in all stover components were below the critical threshold level of N required by rumen microbes (CSIRO, 2007; Van Soest, 1994).

Similar findings have been previously reported for maize whole stover (Anandan et al., 2013; Ertiro et al., 2013a; Tolera et al., 1999). The variability observed for important quality attributes within the stover components of EM and MM genotypes in the present study further confirmed the potential for improvement by exploiting existing variability among maize genotypes (Ertiro et al., 2013a). The occurrence of G and E effects, and interactions of these as G x E interactions, also suggests that it should be possible to identify genotypes suitable for specific environments where the HCT fraction is of higher quality as a ruminant feedstuff.

### 5.4.4. Nutrient composition and digestibility of morphological fractions within the stover components

When averaged across sites and genotypes (n=18) leaf blade (top-leaves and bottom-leaves) had higher total N content and DMD, and lower NDF and ADF contents ($P<0.0001$), than the stem fractions (Table 5.9). This is consistent with previous studies on maize (Li et al., 2014; Tang et al., 2008; Tang et al., 2006; Tolera and Sundstøl, 1999). Furthermore, DMD of bottom-leaves was usually higher ($P<0.05$) than that of top-leaves even though the NDF and ADF concentrations were in general similar. A higher DMD without change on NDF can only be explained by the NDF digestibility being higher ($P<0.0001$) in the bottom-leaves fraction (EM 37.5% and MM 38.8%) than in the top-leaves fraction (EM 32.1 and MM 34.2%) (values not shown).

The HCT stover component had higher ($P<0.0001$) DMD and total N content but lower NDF and ADF contents than the HCB stover component within both EM and MM genotypes in both years (Tables 5.8 and 5.9). Such differences could be attributed to the transition from older to younger tissues (Kalmbacher, 1983). In general, the greater DMD of the leaf, than of the other components mainly reflected lower NDF and ADF concentrations, which was consistent with previous findings (Lynch et al., 2014; Tang et al., 2008; Tolera and Sundstøl, 1999). The DMD of MM husk (58.3%) was lower ($P<0.0001$) than of bottom-leaves (59.7%), but higher than that of other maize components including the top-leaves (56.9%). This was associated with lower ADF content (38.6%) of husk of those other morphological fractions (Table 5.9). Tang et al. (2008) reported that husk was of higher IVOMD (70.2%) than the other morphological fractions. Similarly McGee et al. (2012) reported that husk not only had higher IVDMD (59.0%) than leaf blade (45.7%) but was also more palatable, and cattle performance was better when more husk than leaf was being consumed. The digestibility of the husk can range from 60-

75% (Fernandez-Rivera and Klopfenstein, 1989; Gutierrez-Ornelas and Klopfenstein, 1991). Leaf and husk are the part of the stover utilized most by grazing cattle (Fernandez-Rivera and Klopfenstein, 1989). Relatively small amounts of stem or cob are consumed (Klopfenstein et al., 2013).

In the present study the bottom-stem had the lowest ($P<0.0001$) DMD and the highest NDF and ADF contents. The present results were in agreement with the findings of Tang et al. (2008), in which genotype and morphological fraction of maize stover had interaction effects on NDF and ADF contents and IVOMD. Wang et al. (2006) also reported significant interactions between variety and the morphological fraction of rice straw on NDF and ADF contents. The site x morphological fraction interactions showed that the variation in the attributes is dependent on environment, and the genotype x morphological fraction interactions showed that the variation in the attributes is not independent of genotypes.

### 5.5. Conclusion

This study established that a simple change to 'high-cut' maize at harvest (e.g. to two internodes below the lowest ear) had large effects on the nutritional quality of maize stover as a ruminant feedstuffs. At this high cutting height, substantial amounts (72.0% in EM and 62.8% in MM) of the total stover was available as livestock feed while leaving a stubble portion which was less palatable and of lower nutritive value, but available for soil amendment, aftermath grazing and for fuel. There were genotype effects on the amounts of HCT and HCB components of the stover.

Higher cutting height improved the DMD and total N content of HCT stover over whole stover. However, the N concentrations in the HCT were usually <0.98 % and generally deficient in N for ruminants. This would continue to be an important constraint to intake and productivity by ruminants. Improved utilization of maize stover by ruminants can only be addressed by providing other higher N feedstuffs (as forages or supplements) to provide the necessary additional diet N. Chapters 6 and 7 deal with assessing the extent of genetic variation in seed and haulm yields, and haulm quality among existing popular common bean varieties harvested either at seed or early maturity at harvest for improved utilization of low-quality maize stover by ruminants.

# Chapter 6 Variability in yield and the nutritive value for ruminants of the post-harvest residues of common bean: Effects of variety and environment

## 6.1. Introduction

*Phaseolus vulgaris L.,* beans, common bean, haricot bean, kidney bean or field beans (Zelalem, 2014), is a very important grain legume crop both globally and in ESA (Aserse et al., 2012; Beebe et al., 2010; Ferris and Kaganzi, 2008) mostly consumed as mature seed (Lin et al., 2008) and is an important component of many small-farmer cropping systems (Aserse et al., 2012; Mekbib, 1997). The CR as from cereals is often stacked after threshing for animal feed during the dry season (Gurmu, 2013; Kassa et al., 2014; Mengistu, 1985; Yoseph et al., 2014; Zelalem, 2014) and are of often higher nutritive value than cereal CR. However the use of food legume CR in the feeding of livestock has received little attention from either plant or animal scientists (Capper, 1990).

New varieties of common bean are continually being developed by plant breeding centres including in EA but these programmes have focused mainly on improvement in seed yield for human food (Tullu et al., 2001). Research information on the feeding value of the CR of common bean is limited (Aredo and Musimba, 2003a; Ayoade et al., 1983; Ebro et al., 2005; Pieltain et al., 1996) but smallholder crop-livestock farmers consider the CR for livestock feed and seed of common bean as joint products (Mekbib, 1997).

The EA highlands has high varietal diversity of common bean (Fivawo and Msolla, 2012) which is important for the simultaneous improvement of seed and CR yields through genetic variation (Tullu et al., 2001). A major problem for the common bean improvement programme in EA has been the lack of high-yielding genotypes that consistently perform well across highly variable environments (Mekbib, 2002). The present study was designed to: (1) assess the extent of genetic variation in seed and haulm yields, and haulm quality among existing popular common bean varieties, (2) determine the main and interaction effects of variety and environment (E) as represented by site on seed and haulm yields, and haulm quality attributes, and (3) determine the association between the CR attributes and seed yield.

## 6.2. Materials and Methods

### 6.2.1. Site and trials descriptions

These four sites in the West, South-west and North-west regions of Ethiopia comprised part of a major N2Africa project (Appendix, Figure A6.1) during the 2013 cropping season. The sites were a subset selected as those most appropriate within the N2Africa project (Farrow, 2014) examining varieties of a number of legume food crops. The varieties were chosen to represent those well adapted and commonly grown in the major common bean agro-ecology crop-livestock systems of Ethiopia (Table 6.1). The choice of varieties was made with the N2Africa project team (researchers and local extension experts) at each site. The selected varieties were different at two sites (Shalla (Trial 1) and Bako-Tibe (Trial 2). Seed was obtained from agricultural research centres.

**Trial 1 (*Shalla wereda*/district trial site)**

This site (7.281N latitude, 38.447E longitude) was in the West Arsi Zone, Oromia (ca. 290 km south of Addis Ababa, Ethiopia) in the central Rift valley at 1500-2300 meters above sea level (masl). It represented a semi-arid climate with an erratic, unreliable and low rainfall (Dinka et al., 2010). The mean annual rainfall (1978 - 2013) was 773 mm (range 496 to 1053 mm), while the mean annual minimum and maximum temperatures were 14.0$^{o}$C and 28.7$^{o}$C, respectively. The site received annual rainfall of 925 mm and 920 mm during the 2012 and 2013 cropping seasons, respectively (MARC, 2014). The area is characterized by a short rainy season from February/March to April followed by a main rainy season from June to September, and with the remaining months generally dry (Dinka et al., 2010).

**Trial 2 (*Bako-Tibe* district trial sites)**

There were two sub-sites about 5 km apart at *Dambi Dima* (9.110N latitude, 37.800E longitude; 1692 masl) and *Oda Haro* (9.400N latitude, 37.190E longitude;1698 masl) with similar agro-ecology and soil types in the sub-humid region of western Ethiopia, located ca. 250 km west of Addis Ababa. The measurements at the two sub-sites (3 replications in each site) were averaged and considered to represent the *Bako-Tibe* site. The rainfall pattern is bimodal, with a short rainy season which begins in March and continues intermittently until the main rainy season from June to October (Hassen et al., 2006). The area received annual rainfall of 887 mm and 1431 mm during the 2012 and 2013 cropping

seasons, respectively. The minimum, maximum and mean monthly temperatures recorded during the 2013 cropping season were 12.9, 29.1 and 21.0$^{o}$C respectively.

Table 6.1 Trial sites, agro-ecologies and major soil types and crops grown in each site in 2013

| Trial No. | Site (varieties) | Major soil type | AEZ* | Altitude (m.a.s.l**) | Major crops grown | Date (Sowing/ harvesting) |
|---|---|---|---|---|---|---|
| 1. | Shalla (9 varieties) | Andosols | SA2, SM2, M2 | 1696 | Maize, teff$^{\Delta}$, CB, finger millet, sorghum | 03 July 2013/23 &29 Oct, 2013 |
| 2. | Bako-Tibe (6 varieties) | Alfisols$^{\#}$ | M2, SH2 | 1692 | Maize, teff, CB, sorghum | 27 June 2013/13 & 26 Oct 2013 |
| 3. | Boricha (9 varieties) | Eutric fluvisols@ | SM1,M2 | 1818 | Maize, CB, teff and ensete$^{¥}$ | 07 August 2013/07 & 11 Nov 2013 |
| 4. | Mandura (9 varieties) | red laterite$ | M1, SH1 | 1477 | Finger millet, sorghum, maize and CB | 24 August 2013/19 & 21Nov 2013 |

*Source:$^{@}$ (Asfaw et al., 2013); $^{\$}$ (Emiru, 2014) ; $^{*}$(Farrow, 2014); $^{\#}$(Negassa et al., 2005); AEZ: Agro- ecological zones; $^{**}$m.a.s.l: meters above sea level;SM1:sub-moist hot to warm lowlands; M2: moist tepid to cool mid highlands; M1: moist hot to warm lowlands; SH1:sub-humid hot to warm lowlands; SH2 sub-humid tepid to cool mid highlands; SA2: Semi-arid tepid to cool mid highlands; SM2: Sub-moist tepid to cool mid-highlands; $^{\Delta}$Teff (Eragrostis tef); $^{¥}$ensete (Ensete ventricosum); CB: Common bean.*

**Trial 3 (*Boricha* district trial site)**

The *Boricha* trial site is located in South-western Ethiopia (6.947N latitude and 38.222E longitude) *ca.*314 km south of the capital Addis Ababa. The district elevation ranges between 1650 and 1932 masl with bimodal rainfall and receives a mean annual rainfall amount of 963 mm (15 years average) (Asfaw et al., 2013). Annual temperature varies from 20–33$^{o}$C (Quinlan et al., 2015).

**Trial 4 (*Mandura* district trial site)**

*Mandura* trial site is situated in North western Ethiopia (11.118N latitude and 36.722E longitude) ca. 546 km North west from Addis Ababa. The district altitudes range between 1,015 and 1,480 masl**.** The mean annual rainfall amounts to 1,942 mm (25 years average).

The minimum, maximum, and annual mean temperatures of the area are 16.8, 27.4 and 24.5$^{o}$C respectively (Emiru, 2014).

### 6.2.2. Experimental design and measurements

In each of the sites common bean varieties were examined in a randomized complete-block design with three replications. Trials were hand planted from the 27 June to the 24 August 2013 during the main rainy season (Table 6.1), and fertilizer (4.5 kg N and 11.5 kg $P_2O_5$ per hectare) and recommended inoculant (HB-429) were applied. This rhizobium strain had been developed nationally (Soil testing centre, Addis Ababa) and was used by farmers in the area for common bean. Additional details about the procedures are available elsewhere (N2Africa, 2014). Plot size was 3 x 4 m (12 $m^2$) with 8 rows of plants (40 cm between rows) and 10 cm between plants within rows. The sampling and measurements of seed and total biomass yields reported herein were done in collaboration with the N2 Africa project team, and the data on plant height at harvest and yields of seed and total biomass were provided by this project team. However, the decisions in relation to the selection of the most appropriate sites and CR fractions, and the sampling and measurement of these CR fractions, were the responsibility of the candidate.

At seed maturity plants were harvested from the middle 2 x 2 m (4 $m^2$) area of each plot with ten plants selected randomly from the middle two rows used to measure plant height. A 1.0 m long row was used for each genotype for total biomass sampling. The number of plants were counted, cut to the soil surface, and then carefully separated (avoiding leaf loss) into haulms (stems and leaves) and pods. Pods were counted and shelled to separate the seed and pod wall. Following measurement of fresh weight the haulm, pod wall and seed samples were placed into cotton bags, sun-dried and later oven-dried. Sample processing and laboratory analyses were conducted as described for maize stover (Chapters 3 and 4). The remaining plants in each plot were harvested for seed yield. The seed and CR yields are reported in a dry weight basis.

Total above ground biomass yields were calculated from haulm + pod wall (HPW) + seed yields at harvest. Haulm yield was calculated as the total biomass minus pod, and pod wall as pod minus seed. The haulm was separated into leaf and stem fractions and leaf to stem ratio (LSR) was calculated. Harvest index (HI), digestible DM yield (DDMY) (t/ha), nitrogen yield (NY) (kg/ha), potential utility index (PUI), and quality parameters of HPW were calculated as described in Chapter 4.

### 6.2.3. Statistical analyses

Analysis of variance was undertaken using the procedure as described in Chapter 5. The model $Y_{ij}= \mu + t_i + e_{ij}$ was used for each of the trials, where $Y_{ij}$ represents the $j^{th}$ observation (j = 1, 2,….., ni) on the $i^{th}$ variety (i = 1, 2, . . ., k). μ represents overall mean effect, $t_i$ represents the $i^{th}$ variety effect and $e_{ij}$ represents the random error present in the $j^{th}$ observation on the $i^{th}$ variety. The model $Y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ij}$ was used to analyse site effects across Trials (3 and 4), where $Y_{ij}$ is the mean of variety *i* in site *j*, μ is the overall mean, $\alpha_i$ and $\beta_j$ are the main variety and site (S) effects, $(\alpha\beta)_{ij}$ is the variety x S interaction effect, and $\varepsilon_{ij}$ is the residual associated with variety *i* in site *j*. Some interactions were detected for treatments across Trials 3 and 4 (Table 6.3), the data from these trials were analysed and are presented separately. Linear relationships between yield, composition and residue digestibility was analysed by SAS Proc Corr. The comparison of means between varieties and sites was carried out using Duncan's multiple range tests at 5% level of significance where F-tests were significant ($P<0.05$).

## 6.3. Results

### 6.3.1. Variation in yields of seed, post-harvest residues and total biomass

Seed, HPW and total biomass yields ranged from 0.79-2.62 t/ha, 0.74-2.54 t/ha and 1.53-5.17 t/ha, respectively and HI from 0.44 - 0.52 (Tables 6.2 and 6.3) across trials. Seed and HPW yields were 3-4 times greater in Trial 1 than Trial 2, but HI was similar. Seed yield varied among varieties in Trials 1 and 4 ($P < 0.001$), but not in Trials 2 and 3 ($P>0.05$) (Tables 6.2 and 6.3). Similarly, there was variation among varieties ($P<0.05$ and $P<0.001$) for HPW and total biomass yields except in Trial 2. This was associated with much lower yields of both seed and HPW in Trial 2 (0.80 and 0.74 t/ha, respectively) than in the other three trials (1.32-2.62 t/ha for seed yield, and 1.61-2.54 t/ha for HPW yield). HI generally differed among varieties (Tables 6.2 and 6.3). The highest seed (3.47 t/ha) and HPW (3.36 t/ha) yielding varieties (Nasir and ECAB0081, respectively) were in Trial 1, whereas the lowest were in Trials 4 and 2 (0.46 t/ha for seed) and (0.52 t/ha for HPW) for varieties (Argene and Loko, respectively) (Tables 6.2 and 6.3).

Wider ranges in seed yield (mean 1.42 t/ha, range 2.05 - 3.47 t/ha) and HPW yield (mean 1.77 t/ha, range 1.59 - 3.36 t/ha) were observed in Trial 1 than the other trials. Among the tested varieties, Nasir and ECAB0081 gave the highest seed and HPW yields, but not consistently the highest HI. The lowest seed and HPW producing varieties (Awash- 1 in

Trials 1 and 4, Loko and Dimtu in Trials 2 and 3, respectively) also tended to have the higher HI (Tables 6.2 and 6.3). Variety H-Dume, followed by variety Ibado, tended to be higher in HPW, seed and total biomass yields over the other varieties in Trials 2 and 4, although not significantly different in Trial 2 (Table 6.2). The varieties Dinknesh, Nasir, H-Dume and SARI in Trial 3 were higher than the other varieties in yield related attributes (Table 6.3).

Table 6.2 Yield, HPW morphological fractions and HI of common bean varieties harvested at seed maturity stage at *Shalla* (Trial 1) and *Bako-Tibe* (Trial 2) in 2013 (n=3)

| | Yield (t/ha) | | | Morphological fractions (% w/w) | | | |
|---|---|---|---|---|---|---|---|
| Trial 1 Variety | Seed | HPW | TB | Leaf | Stem | Pod wall | HI |
| A-Melka | 2.18$^{d}$ | 1.75$^{e}$ | 3.94$^{d}$ | 6.4$^{d}$ | 69.2$^{b}$ | 24.3$^{c}$ | 0.55$^{ab}$ |
| Awash-1 | 2.05$^{d}$ | 1.59$^{e}$ | 3.63$^{d}$ | 6.5$^{cd}$ | 68.8$^{b}$ | 24.7$^{c}$ | 0.56$^{a}$ |
| Deme | 2.83$^{bc}$ | 2.91$^{bc}$ | 5.74$^{b}$ | 7.5$^{b}$ | 63.0$^{cd}$ | 29.5$^{b}$ | 0.49$^{cd}$ |
| Dimtu | 2.53$^{dc}$ | 2.47$^{d}$ | 5.01$^{c}$ | 4.8$^{e}$ | 73.3$^{a}$ | 22.0$^{d}$ | 0.51$^{cd}$ |
| Dinknesh | 2.37$^{dc}$ | 2.30$^{d}$ | 4.67$^{c}$ | 6.5$^{cd}$ | 68.9$^{b}$ | 24.5$^{c}$ | 0.51$^{cd}$ |
| ECAB0056 | 2.55$^{dc}$ | 2.83$^{c}$ | 5.39$^{bc}$ | 6.5$^{cd}$ | 69.1$^{b}$ | 24.3$^{c}$ | 0.47$^{d}$ |
| ECAB0081 | 3.13$^{ab}$ | 3.36$^{a}$ | 6.48$^{a}$ | 8.4$^{a}$ | 61.4$^{c}$ | 30.2$^{ab}$ | 0.48$^{cd}$ |
| GLP2 | 2.52$^{dc}$ | 2.47$^{d}$ | 4.99$^{c}$ | 7.6$^{b}$ | 63.1$^{c}$ | 29.3$^{b}$ | 0.50$^{cd}$ |
| Nasir | 3.47$^{a}$ | 3.19$^{ab}$ | 6.66$^{a}$ | 7.0$^{c}$ | 62.0$^{c}$ | 31.0$^{a}$ | 0.52$^{bc}$ |
| **Mean** | **2.62** | **2.54** | **5.17** | **6.8** | **66.5** | **26.6** | **0.51** |
| P>F | 0.0005 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.004 |
| $LSD_{0.05}$ | 0.51 | 0.33 | 0.73 | 0.5 | 1.6 | 1.3 | 0.04 |
| CV (%) | 11.3 | 7.5 | 8.1 | 4.3 | 1.4 | 2.9 | 4.7 |
| Trial 2 Variety | | | | | | | |
| Anger | 0.74 | 0.60 | 1.34 | 4.1$^{d}$ | 69.2$^{c}$ | 26.8$^{c}$ | 0.55$^{ab}$ |
| Dimtu | 0.79 | 0.71 | 1.50 | 3.8$^{e}$ | 71.2$^{b}$ | 25.0$^{d}$ | 0.52$^{abc}$ |
| Dinknesh | 0.78 | 0.77 | 1.55 | 4.5$^{c}$ | 67.4$^{d}$ | 28.1$^{b}$ | 0.50$^{bc}$ |
| H-Dume | 0.93 | 0.95 | 1.88 | 7.7$^{a}$ | 63.5$^{e}$ | 28.8$^{a}$ | 0.49$^{c}$ |
| Ibado | 0.86 | 0.85 | 1.72 | 4.6$^{c}$ | 71.0$^{b}$ | 24.3$^{d}$ | 0.50$^{bc}$ |
| Loko | 0.67 | 0.52 | 1.20 | 6.8$^{b}$ | 72.6$^{a}$ | 20.6$^{e}$ | 0.57$^{a}$ |
| **Mean** | **0.79** | **0.74** | **1.53** | **5.2** | **69.2** | **25.6** | **0.52** |
| P>F | 0.892 | 0.367 | 0.653 | <0.0001 | <0.0001 | <0.0001 | 0.030 |
| $LSD_{0.05}$ | 0.50 | 0.45 | 0.95 | 0.2 | 0.8 | 0.7 | 0.05 |
| CV (%) | 34.8 | 33.6 | 34.0 | 2.4 | 0.6 | 1.6 | 4.8 |

*P<0.01 indicates highly significant genotypes mean; Means with no superscript letters with a column of each trial are not significantly different (P>0.05); HPW: Haulm + Pod walls; TB: Total biomass; HI: harvest index; LSD: Least significant difference* (P=0.05)*; NS: Non-significant; CV: Coefficient of variation.*

When data were combined across Trials 3 and 4 (Table 6.3), differences among varieties were substantial (P <0.05 and < 0.001) for yield related attributes other than HI. Site affected (P<0.001) yield of seed, HPW and total biomass, but not HI (Table 6.3). There were variety x site (V x S) interaction effects on yields of seed (P=0.011), HPW (P<0.0001)

and total biomass (P<0.0001), but not for HI (P=0.83) (Table 6.3). In general, the variation observed among varieties in each trial was higher for yield of HPW than of seed.

Table 6.3 Effects of variety and site on yield, HPW morphological fractions and HI of common bean varieties harvested at seed maturity stage at *Boricha* (Trial 3)*, Mandura* (Trial 4) (n=3) and across both sites (n=6) in 2013

| | Yield (t/ha) | | | Morphological fractions (% w/w) | | | |
|---|---|---|---|---|---|---|---|
| Trial 3 Variety | Seed | HPW | TB | Leaf | Stem | Pod wall | HI |
| A-Melka | 1.81 | 2.43$^{a}$ | 4.24$^{ab}$ | 5.3$^{ef}$ | 73.4 | 21.3 | 0.42 |
| Argene | 1.28 | 1.98$^{ab}$ | 3.26$^{bc}$ | 8.6$^{a}$ | 60.4 | 31.0 | 0.40 |
| Awash-1 | 1.64 | 2.18$^{ab}$ | 3.82$^{abc}$ | 7.7$^{abc}$ | 65.1 | 27.3 | 0.44 |
| Dimtu | 1.24 | 1.36$^{b}$ | 2.60$^{c}$ | 5.0$^{f}$ | 69.2 | 25.8 | 0.48 |
| Dinknesh | 2.09 | 2.55$^{a}$ | 4.64$^{a}$ | 7.8$^{ab}$ | 60.4 | 31.8 | 0.44 |
| H-Dume | 1.88 | 2.50$^{a}$ | 4.38$^{ab}$ | 7.7$^{ab}$ | 59.8 | 32.4 | 0.43 |
| Ibado | 1.20 | 1.40$^{b}$ | 2.60$^{c}$ | 6.4$^{de}$ | 67.0 | 26.6 | 0.46 |
| Nasir | 2.03 | 2.59$^{a}$ | 4.62$^{ab}$ | 6.5$^{cde}$ | 56.9 | 36.6 | 0.44 |
| SARI | 1.82 | 2.55$^{a}$ | 4.38$^{ab}$ | 7.1$^{bcd}$ | 68.1 | 24.9 | 0.42 |
| **Mean** | **1.67** | **2.17** | **3.84** | **6.9** | **64.5** | **28.6** | **0.44** |
| P>F | 0.188 | 0.033 | 0.022 | <0.0001 | 0.053 | 0.215 | 0.895 |
| $LSD_{0.05}$ | 0.81 | 0.86 | 1.37 | 1.21 | 10.13 | 11.23 | 0.11 |
| CV ( %) | 27.9 | 23.0 | 20.6 | 10.2 | 9.1 | 22.7 | 14.9 |
| Trial 4 variety | | | | | | | |
| A-Melka | 0.92$^{d}$ | 1.08$^{d}$ | 1.99$^{d}$ | 8.7$^{a}$ | 65.1$^{ab}$ | 26.3$^{c}$ | 0.46$^{b}$ |
| Argene | 0.46$^{e}$ | 0.59$^{e}$ | 1.05$^{e}$ | 8.4$^{ab}$ | 66.8$^{a}$ | 24.7$^{c}$ | 0.44$^{b}$ |
| Awash-1 | 1.14$^{cd}$ | 1.20$^{d}$ | 2.34$^{d}$ | 8.1$^{b}$ | 62.6$^{bcd}$ | 29.3$^{b}$ | 0.49$^{a}$ |
| Dimtu | 1.59$^{b}$ | 1.96$^{bc}$ | 3.55$^{bc}$ | 5.6$^{ef}$ | 63.7$^{bc}$ | 30.7$^{ab}$ | 0.45$^{b}$ |
| Dinknesh | 1.55$^{b}$ | 1.88$^{bc}$ | 3.43$^{bc}$ | 5.3$^{f}$ | 64.2$^{bc}$ | 30.6$^{ab}$ | 0.45$^{b}$ |
| H-Dume | 1.88$^{a}$ | 2.29$^{a}$ | 4.17$^{a}$ | 5.4$^{ef}$ | 62.4$^{cd}$ | 32.2$^{a}$ | 0.45$^{b}$ |
| Ibado | 1.61$^{ab}$ | 2.07$^{ab}$ | 3.68$^{ab}$ | 7.4$^{c}$ | 60.4$^{d}$ | 32.2$^{a}$ | 0.44$^{b}$ |
| Nasir | 1.35$^{bc}$ | 1.72$^{c}$ | 3.07$^{c}$ | 6.4$^{d}$ | 62.1$^{cd}$ | 31.6$^{ab}$ | 0.44$^{b}$ |
| SARI | 1.39$^{bc}$ | 1.75$^{bc}$ | 3.15$^{bc}$ | 5.8$^{e}$ | 62.6$^{bcd}$ | 31.6$^{ab}$ | 0.44$^{b}$ |
| **Mean** | **1.32** | **1.61** | **2.94** | **6.8** | **63.3** | **29.9** | **0.45** |
| P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0038 | 0.0002 | 0.0088 |
| $LSD_{0.05}$ | 0.28 | 0.31 | 0.58 | 0.45 | 2.58 | 2.82 | 0.02 |
| CV (%) | 12.3 | 11.2 | 11.5 | 3.9 | 2.4 | 5.4 | 2.9 |
| **Site** | | | | | | | |
| Boricha | 1.67$^{a}$ | 2.17$^{a}$ | 3.84$^{a}$ | 6.9 | 64.5 | 28.6 | 0.44 |
| Mandura | 1.32$^{b}$ | 1.61$^{b}$ | 2.94$^{b}$ | 6.8 | 63.3 | 29.9 | 0.45 |
| P>F | Effects across both Trials (3 and 4) (n=6) | | | | | | |
| Variety (V) | 0.0006 | 0.0003 | <0.0001 | <0.0001 | 0.035 | 0.061 | 0.84 |
| Site (S) | 0.0007 | <0.0001 | <0.0001 | 0.4727 | 0.357 | 0.361 | 0.31 |
| V x S | 0.011 | <0.0001 | <0.0001 | <0.0001 | 0.042 | 0.257 | 0.83 |
| $LSD_{0.05}$ | 0.40 | 0.45 | 0. 70 | 0.60 | 5.30 | 5.90 | 0.06 |

*P<0.05 and P<0.01 indicates significant and highly significant varieties mean respectively; Means with no superscript letters with a column of each trial are not significantly different (P>0.05); HPW: Haulm + Pod walls; TB: Total biomass; HI: harvest index; LSD: Least significant difference (P=0.05); CV: Coefficient of variation.*

### 6.3.2. Variation in morphological characteristics

On average across varieties at harvest the stem fraction constituted the highest proportion of the HPW followed by pod wall. Trial means for stem, pod wall and leaf ranged from 63.3-69.2%, 25.6-29.9% and 5.2-6.9% HPW, respectively. The leaf proportion in HPW was ≤ 8.7% with means for the various trials ranging from 5.2-6.9% (Tables 6.2 and 6.3) and LSR varied from 7.7-10.9% (Tables 6.4 and 6.5).

Table 6.4 Morphological characteristics and nutrient yields of HPW and PUI of common bean varieties harvested at seed maturity stage at *Shalla* (Trial 1) and *Bako-Tibe* (Trial 2) in 2013 (n=3)

| Trial 1 Variety | Plant height (cm) | LSR (%) | N yield (kg/ha) | DDM yield (t/ha) | PUI (%) |
|---|---|---|---|---|---|
| A-Melka | 45.8 | 9.3$^{c}$ | 12.2$^{e}$ | 0.94$^{f}$ | 79.2$^{c}$ |
| Awash-1 | 42.9 | 9.5$^{c}$ | 18.0$^{cd}$ | 0.91$^{f}$ | 81.2$^{ab}$ |
| Deme | 46.6 | 12.0$^{b}$ | 27.8$^{b}$ | 1.74$^{bc}$ | 79.6$^{c}$ |
| Dimtu | 45.7 | 6.5$^{d}$ | 15.1$^{de}$ | 1.26$^{e}$ | 75.7$^{d}$ |
| Dinknesh | 44.8 | 9.4$^{c}$ | 21.3$^{c}$ | 1.21$^{e}$ | 76.8$^{d}$ |
| ECAB0056 | 45.2 | 9.5$^{c}$ | 27.0$^{b}$ | 1.58$^{cd}$ | 76.8$^{d}$ |
| ECAB0081 | 50.7 | 13.7$^{a}$ | 42.0$^{a}$ | 2.17$^{a}$ | 81.7$^{a}$ |
| GLP2 | 46.9 | 12.0$^{b}$ | 30.6$^{b}$ | 1.50$^{d}$ | 80.6$^{abc}$ |
| Nasir | 50.7 | 11.2$^{b}$ | 26.9$^{b}$ | 1.81$^{b}$ | 79.3$^{c}$ |
| **Mean** | **46.6** | **10.3** | **24.5** | **1.46** | **79.0** |
| P>F | 0.9392 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| $LSD_{0.05}$ | 13.3 | 1.09 | 5.39 | 0.23 | 1.65 |
| CV (%) | 16.5 | 6.1 | 12.7 | 9.1 | 1.2 |
| Trial 2 Variety | | | | | |
| Anger | 32.8 | 5.9$^{d}$ | 7.9 | 0.26 | 74.0 |
| Dimtu | 33.3 | 5.4$^{e}$ | 8.8 | 0.33 | 74.4 |
| Dinknesh | 32.5 | 6.7$^{c}$ | 8.2 | 0.38 | 74.4 |
| H-Dume | 34.8 | 12.1$^{a}$ | 10.2 | 0.52 | 77.1 |
| Ibado | 34.7 | 6.5$^{c}$ | 7.2 | 0.36 | 71.0 |
| Loko | 32.2 | 9.4$^{b}$ | 6.9 | 0.24 | 76.3 |
| **Mean** | **33.4** | **7.7** | **8.2** | **0.35** | **74.5** |
| P>F | 0.7606 | <0.0001 | 0.693 | 0.067 | 0.079 |
| $LSD_{0.05}$ | 4.90 | 0.35 | 4.75 | 0.19 | 4.04 |
| CV (%) | 8.1 | 2.52 | 31.9 | 30.6 | 3.0 |

*P<0.01indicates highly significant genotypes mean; Means with no superscript letters with a column of each trial are not significantly different (P>0.05); LSR: Leaf to stem ratio; N: Nitrogen; DDM: Digestible dry matter; PUI: Potential utility index LSD: Least significant difference* (P=0.05)*; CV: Coefficient of variation.*

Table 6.5 Effects of variety and site on morphological characteristics and nutrient yields of HPW and PUI of common bean varieties harvested at seed maturity stage at *Boricha* (Trial 3)*, Mandura* (Trial 4) (n=3) and across both sites (n=6) in 2013

| Trial 3 Variety | Plant height (cm) | LSR (%) | N yield (kg/ha) | DDM yield (t/ha) | PUI (%) |
|---|---|---|---|---|---|
| A-Melka | 45.0 | 7.2$^{f}$ | 18.9$^{a}$ | 1.09$^{a}$ | 67.6 |
| Argene | 43.3 | 14.3$^{a}$ | 17.1$^{a}$ | 0.95$^{abc}$ | 68.6 |
| Awash-1 | 45.3 | 11.8$^{c}$ | 17.8$^{a}$ | 1.01$^{ab}$ | 69.9 |
| Dimtu | 44.3 | 7.2$^{f}$ | 9.4$^{b}$ | 0.63$^{c}$ | 71.8 |
| Dinknesh | 47.7 | 13.0$^{b}$ | 18.2$^{a}$ | 1.22$^{a}$ | 71.0 |
| H-Dume | 45.7 | 12.9$^{b}$ | 20.0$^{a}$ | 1.21$^{a}$ | 70.8 |
| Ibado | 41.7 | 9.5$^{e}$ | 9.6$^{b}$ | 0.65$^{bc}$ | 71.4 |
| Nasir | 48.3 | 11.3$^{c}$ | 18.0$^{a}$ | 1.25$^{a}$ | 71.0 |
| SARI | 45.3 | 10.4$^{d}$ | 20.9$^{a}$ | 1.16$^{a}$ | 68.8 |
| **Mean** | **45.2** | **10.9** | **16.7** | **1.02** | **70.1** |
| P>F | 0.09 | <0.0001 | 0.016 | 0.014 | 0.961 |
| $LSD_{0.05}$ | 4.14 | 0.79 | 6.79 | 0.37 | 8.00 |
| CV (%) | 5.3 | 4.2 | 23.6 | 21.3 | 6.7 |
| Trial 4Variety | | | | | |
| A-Melka | 40.3 | 13.3$^{a}$ | 10.2$^{c}$ | 0.53$^{c}$ | 72.5 |
| Argene | 37.9 | 12.6$^{b}$ | 6.3$^{d}$ | 0.29$^{d}$ | 71.9 |
| Awash-1 | 41.9 | 13.0$^{ab}$ | 10.9$^{c}$ | 0.59$^{c}$ | 73.7 |
| Dimtu | 45.5 | 8.7$^{de}$ | 16.4$^{a}$ | 0.91$^{b}$ | 70.4 |
| Dinknesh | 45.4 | 8.2$^{e}$ | 15.8$^{ab}$ | 0.86$^{b}$ | 70.1 |
| H-Dume | 46.7 | 8.6$^{e}$ | 14.4$^{ab}$ | 1.06$^{a}$ | 70.6 |
| Ibado | 46.0 | 12.3$^{b}$ | 17.0$^{a}$ | 1.07$^{a}$ | 73.0 |
| Nasir | 43.7 | 10.3$^{c}$ | 14.6$^{ab}$ | 0.87$^{b}$ | 72.6 |
| SARI | 44.3 | 9.3$^{d}$ | 12.6$^{bc}$ | 0.87$^{b}$ | 71.8 |
| **Mean** | **43.5** | **10.7** | **13.1** | **0.78** | **71.8** |
| P>F | 0.107 | <0.0001 | <0.0001 | <0.0001 | 0.147 |
| $LSD_{0.05}$ | 6.18 | 0.65 | 3.16 | 0.13 | 2.79 |
| CV (%) | 8.2 | 3.5 | 13.9 | 9.6 | 2.3 |
| P>F | Effects across both Trials (3 and 4) (n=6) | | | | |
| **Site** | | | | | |
| Boricha | 45.2 | 10.9 | 16.7$^{a}$ | 1.0178$^{a}$ | 70.1 |
| Mandura | 43.5 | 10.7 | 13.1$^{b}$ | 0.7839$^{b}$ | 71.8 |
| Variety (V) | 0.1147 | <0.0001 | 0.0318 | 0.0007 | 0.951 |
| Site (S) | 0.0899 | 0.2412 | 0.0002 | <0.0001 | 0.080 |
| V x S | 0.2536 | <0.0001 | <0.0001 | 0.0003 | 0.761 |
| $LSD_{0.05}$ | 4.10 | 0.52 | 3.70 | 0.20 | 4.20 |

*P<0.05 and P<0.01 indicates significant and highly significant genotypes mean respectively; Means with no superscript letters with a column of each trial are not significantly different (P>0.05); LSR: Leaf to stem ratio; N: Nitrogen;; DDM: Digestible dry matter; PUI: Potential utility index; LSD: Least significant difference* (P=0.05)*; CV: Coefficient of variation.*

There were generally substantial differences (P<0.01) amongst varieties in the proportions of the morphological fractions (leafs, stems and pod walls) in the HPW (Tables 6.2 and

6.3), and in LSR (P<0.0001) in the haulm fraction (Tables 6.4 and 6.5). Variety Dimtu consistently had the lowest LSR, and ECAB0081, H-Dume, Argene and Awash-Melka the highest LSR in Trials 1, 2, 3 and 4, respectively (Tables 6.4 and 6.5). There were no differences (P>0.05) in plant height at harvest among varieties within any of the trials.

When data were combined across Trials 3 and 4 (Tables 6.3 and 6.5), there was variation among varieties for LSR (P<0.0001) (Table 6.3) and leaf (P <0.0001) and stem (P=0.035) proportions (Table 6.3). Site had no effect on the proportions of the morphological fractions or LSR while there were (Table 6.5). V x S effects on LSR (P<0.0001) (Table 6.5) and proportions of leaf (P<0.0001) and stem (P=0.04) (Table 6.3).

### 6.3.3. Variation in post-harvest residue composition and DMD

Total N concentrations in the haulm and pod wall fractions, and HPW, tended to be higher in Trial 2 than Trials 1, 3 and 4 (Tables 6.6 and 6.7). Conversely, mean HPW DMD tended to be higher in Trial 1 (56.9%), than in Trials 2, 3 and 4 (46.7-48.8%). Trial mean values for HPW N, DMD, NDF and ADF ranged from 0.77-1.14%, 46.7-57.0%, 64.8-73.9%and 50.2-58.5%, respectively (Tables 6.6 and 6.7). Also in Trials 1 and 2 there were wide differences (P<0.01) amongst the varieties for each of the quality attributes in HPW, pod wall, and haulm (Table 6.6). In Trial 1 total N content of HPW varied two-fold (0.61-1.25%). In Trials 2 and 4 the total N content in HPW varied from 0.86-1.32% and 0.64-1.11%, respectively (Tables 6.6 and 6.7). However, there was relatively small variation in HPW N concentration (0.69-0.89%) in Trial 3 (Table 6.7). Large variations of the range (14.0 and 13.0 percentage units) in DMD were observed in Trial 1 and 2, respectively. Also there tended to be appreciable variation in DMD (ca. 4.0 and 6.0 percentage units in the HPW among varieties in Trial 3 and 4, respectively (Table 6.7).

When data were combined across Trials 3 and 4 (Table 6.7), site affected (P<0.05) HPW DMD% and N%, NDF and ADF contents (Table 6.7). Similarly, site had significant effects on all quality parameters measured for the HPW fractions but did not affect N concentration or DMD of the pod wall. The V x S interactions were significant for all quality parameters measured for the pod wall fraction but not on the quality parameters measured for the haulm fraction or the HPW (Table 6.7). In general, HPW quality attributes for variety ECAB0081 (e.g. HPW DMD 64.5% and total N (1.25%) were higher than for other varieties in Trial 1 (Table 6.6). In Trial 2, H-Dume (54.9%) and Dinknesh (48.7%) were higher in DMD than the other varieties, but their total N concentration were lower than Anger, Loko

and Dimtu varieties (Table 6.6). Interestingly, these varieties also had higher seed and HPW yields (Table 6.2). However, in Trial 3 higher DMD, and comparable N concentrations of HPW were obtained from Nasir, Dinknesh, H-Dume and Aregene varieties. In Trial 4, Ibado and Nasir varieties were better in terms of HPW DMD (52.0% and 51.0%, respectively) and comparable to N concentration of the HPW compared with the other varieties (Table 6.7).

In Trials 2 and 4 the composition and DMD generally differed among the morphological fractions ($P< 0.0001$) (Table 6.8). Generally, the pod wall fraction had a lower total N (0.79 and 1.08%), but a higher DMD (66.0 and 61.6%) than these attributes in the haulm fraction in Trial 1 and 2, respectively (Table 6.8). The same trends were observed in Trials 3 and 4. When data were combined across Trials 3 and 4 (Table 6.8) site affected ($P<0.0001$) all HPW and morphological fractions quality parameters and there were also morphological fraction x site interactions.

Table 6.6 Composition and DMD of pod wall, haulm (stem+ little leaf) and HPW of common bean varieties harvested at seed maturity stage at Shalla (Trial 1) and Bako-Tibe (Trial 2) in 2013 (n=3)

| | Total N% | | | DMD% | | | NDF% | | | ADF% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trial 1 Variety | Pod wall | Haulm | HPW | Pod wall | Haulm | HPW | Pod wall | Haulm | HPW | Pod wall | Haulm | HPW |
| A-Melka | 0.75 | $0.68^{de}$ | $0.70^{cd}$ | $67.5^{bc}$ | $48.9^{de}$ | $53.5^{ef}$ | $56.4^{cd}$ | $74.9^{ab}$ | $70.4^{ab}$ | $41.6^{b}$ | $59.1^{a}$ | $54.8^{ab}$ |
| Awash-1 | 0.87 | $1.25^{ab}$ | $1.16^{a}$ | $62.4^{e}$ | $55.4^{c}$ | $57.1^{cd}$ | $60.7^{a}$ | $64.1^{d}$ | $63.2^{de}$ | $44.5^{a}$ | $51.0^{c}$ | $49.4^{de}$ |
| Deme | 0.82 | $1.01^{bc}$ | $0.96^{b}$ | $69.6^{ab}$ | $55.7^{bc}$ | $59.8^{bc}$ | $52.8^{e}$ | $65.0^{d}$ | $61.4^{ef}$ | $38.0^{c}$ | $50.8^{c}$ | $47.0^{e}$ |
| Dimtu | 0.62 | $0.61^{e}$ | $0.61^{d}$ | $65.7^{cd}$ | $46.6^{e}$ | $50.8^{f}$ | $58.2^{bcd}$ | $76.1^{a}$ | $72.1^{a}$ | $41.8^{b}$ | $59.7^{a}$ | $55.8^{a}$ |
| Dinknesh | 1.03 | $0.89^{cd}$ | $0.93^{b}$ | $66.3^{cd}$ | $48.5^{e}$ | $52.9^{ef}$ | $55.9^{d}$ | $73.0^{ab}$ | $68.8^{bc}$ | $42.3^{b}$ | $58.5^{a}$ | $54.5^{ab}$ |
| ECAB0056 | 0.76 | $1.02^{bc}$ | $0.95^{b}$ | $63.5^{de}$ | $53.3^{c}$ | $55.8^{de}$ | $58.5^{abc}$ | $68.1^{cd}$ | $65.7^{cd}$ | $42.6^{b}$ | $53.3^{bc}$ | $50.7^{cd}$ |
| ECAB0081 | 0.82 | $1.44^{a}$ | $1.25^{a}$ | $70.5^{a}$ | $62.2^{a}$ | $64.7^{a}$ | $52.1^{e}$ | $57.5^{e}$ | $55.9^{g}$ | $38.3^{c}$ | $45.6^{d}$ | $43.4^{f}$ |
| GLP2 | 0.69 | $1.47^{a}$ | $1.24^{a}$ | $63.4^{de}$ | $59.6^{ab}$ | $60.7^{b}$ | $58.7^{abc}$ | $58.2^{e}$ | $58.4^{fg}$ | $40.9^{b}$ | $44.7^{d}$ | $43.6^{f}$ |
| Nasir | 0.71 | $0.90^{cd}$ | $0.84^{bc}$ | $65.3^{cde}$ | $53.0^{cd}$ | $56.8^{cd}$ | $60.3^{ab}$ | $71.1^{bc}$ | $67.7^{bc}$ | $45.4^{a}$ | $56.4^{ab}$ | $52.9^{bc}$ |
| **Mean** | **0.79** | **1.03** | **0.96** | **66.0** | **53.7** | **56.9** | **57.1** | **67.5** | **64.8** | **41.7** | **53.2** | **50.2** |
| P>F | 0.232 | <0.0001 | <0.0001 | 0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| $LSD_{0.05}$ | 0.29 | 0.24 | 0.19 | 2.93 | 4.06 | 3.00 | 2.44 | 4.54 | 3.18 | 1.72 | 4.02 | 2.85 |
| CV(%) | 21.7 | 13.5 | 11.8 | 2.6 | 4.4 | 3.1 | 2.5 | 4.0 | 2.9 | 2.4 | 4.4 | 3.3 |
| Trial 2 Variety | | | | | | | | | | | | |
| Anger | $1.38^{ab}$ | $1.29^{ab}$ | $1.32^{a}$ | $57.3^{c}$ | $37.7^{bc}$ | $42.9^{cd}$ | $61.5^{ab}$ | $72.3^{b}$ | $69.4^{bc}$ | $45.0^{a}$ | $59.4^{b}$ | $55.6^{b}$ |
| Dimtu | $0.76^{c}$ | $1.39^{a}$ | $1.23^{ab}$ | $60.6^{b}$ | $41.5^{b}$ | $46.3^{bc}$ | $54.8^{c}$ | $69.0^{bc}$ | $65.4^{cd}$ | $39.5^{b}$ | $57.4^{b}$ | $53.0^{bc}$ |
| Dinknesh | $0.88^{c}$ | $1.14^{b}$ | $1.07^{b}$ | $60.5^{b}$ | $44.1^{b}$ | $48.7^{b}$ | $64.0^{a}$ | $70.7^{b}$ | $68.8^{bc}$ | $46.8^{a}$ | $57.0^{b}$ | $54.1^{b}$ |
| H-Dume | $0.73^{c}$ | $1.20^{ab}$ | $1.07^{b}$ | $61.0^{b}$ | $52.4^{a}$ | $54.9^{a}$ | $64.4^{a}$ | $64.0^{c}$ | $64.1^{d}$ | $46.9^{a}$ | $50.6^{c}$ | $49.5^{c}$ |
| Ibado | $1.08^{bc}$ | $0.78^{c}$ | $0.86^{c}$ | $62.9^{b}$ | $34.9^{c}$ | $41.7^{d}$ | $60.7^{b}$ | $78.2^{a}$ | $73.9^{a}$ | $44.9^{a}$ | $65.4^{a}$ | $60.4^{a}$ |
| Loko | $1.62^{a}$ | $1.25^{ab}$ | $1.32^{a}$ | $67.4^{a}$ | $39.8^{bc}$ | $45.5^{bcd}$ | $54.9^{c}$ | $74.4^{ab}$ | $70.4^{ab}$ | $41.1^{b}$ | $59.8^{b}$ | $56.0^{b}$ |
| **Mean** | **1.08** | **1.18** | **1.14** | **61.6** | **41.7** | **46.7** | **60.0** | **71.4** | **68.7** | **44.0** | **58.3** | **54.8** |
| P>F | 0.002 | 0.001 | 0.002 | 0.0001 | 0.0012 | 0.0006 | <0.0001 | 0.0025 | 0.0039 | 0.005 | 0.0014 | 0.0013 |
| $LSD_{0.05}$ | 0.41 | 0.22 | 0.21 | 2.77 | 6.45 | 4.60 | 3.30 | 5.54 | 4.28 | 3.81 | 5.15 | 3.82 |
| CV (%) | 21.2 | 10.4 | 10.2 | 2.5 | 8.7 | 5.5 | 3.1 | 4.4 | 3.5 | 4.9 | 5.0 | 3.9 |

*P<0.01 indicates highly significant genotypes mean; Means with no superscript letter with a column of each trial are not significantly different (P>0.05); HPW: Haulm + pod walls; LSD: Least significant difference (P=0.05); CV: Coefficient of variation; N: Nitrogen; DMD: Dry matter digestibility; NDF: Neutral detergent fibre; ADF: Acid detergent fibre.*

Table 6.7 Composition and DMD of pod wall, haulm (leaf +stem) and HPW of common bean varieties harvested at seed maturity stage at *Boricha* (Trial 3)*, Mandura* (Trial 4) (n=3) and across both sites (n=6) in 2013

| | Total N% | | | DMD% | | | NDF% | | | ADF% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trial 3 Variety | Pod wall | Haulm | HPW | Pod wall | Haulm | HPW | Pod wall | Haulm | HPW | Pod wall | Haulm | HPW |
| A-Melka | 0.86$^{bcd}$ | 0.75 | 0.78 | 61.2 | 40.1 | 44.6 | 61.8 | 80.1 | 76.2 | 47.6$^{ab}$ | 65.0$^{a}$ | 61.4 |
| Argene | 1.17$^{a}$ | 0.75 | 0.89 | 63.5 | 41.1 | 48.1 | 59.7 | 78.9 | 72.8 | 45.3$^{bc}$ | 63.4$^{ab}$ | 57.7 |
| Awash-1 | 1.00$^{abc}$ | 0.78 | 0.84 | 62.2 | 41.2 | 46.9 | 60.8 | 77.2 | 72.7 | 46.4$^{ab}$ | 61.3$^{c}$ | 57.3 |
| Dimtu | 0.66$^{d}$ | 0.70 | 0.69 | 60.6 | 41.0 | 46.0 | 62.3 | 79.1 | 74.8 | 47.0$^{ab}$ | 63.3$^{ab}$ | 59.1 |
| Dinknesh | 0.77$^{d}$ | 0.70 | 0.72 | 61.7 | 42.0 | 48.2 | 62.2 | 79.0 | 73.7 | 48.5$^{a}$ | 63.6$^{ab}$ | 58.9 |
| H-Dume | 1.05$^{ab}$ | 0.69 | 0.81 | 63.1 | 41.5 | 48.5 | 60.5 | 78.5 | 72.7 | 47.5$^{ab}$ | 62.7$^{bc}$ | 57.8 |
| Ibado | 0.75$^{d}$ | 0.67 | 0.69 | 62.2 | 41.2 | 46.7 | 60.3 | 79.5 | 74.5 | 43.6$^{c}$ | 62.0$^{bc}$ | 57.1 |
| Nasir | 0.82$^{cd}$ | 0.62 | 0.69 | 61.9 | 40.5 | 48.3 | 62.1 | 79.0 | 72.8 | 48.4$^{a}$ | 63.3$^{ab}$ | 57.9 |
| SARI | 0.81$^{cd}$ | 0.81 | 0.81 | 61.4 | 40.7 | 45.8 | 61.5 | 78.8 | 74.5 | 47.6$^{ab}$ | 63.4$^{ab}$ | 59.5 |
| **Mean** | **0.88** | **0.72** | **0.77** | **62.0** | **41.0** | **47.0** | **61.2** | **78.9** | **73.9** | **46.9** | **63.1** | **58.5** |
| P>F | 0.0015 | 0.1644 | 0.0972 | 0.1253 | 0.863 | 0.3435 | 0.2803 | 0.2925 | 0.2809 | 0.0104 | 0.0342 | 0.1283 |
| $LSD_{0.05}$ | 0.21 | 0.14 | 0.15 | 1.94 | 2.47 | 3.67 | 2.42 | 2.04 | 3.1714 | 2.43 | 1.83 | 2.93 |
| CV(%) | 13.6 | 11.0 | 11.6 | 1.81 | 3.5 | 4.5 | 2.3 | 1.5 | 2.5 | 3.0 | 1.7 | 2.9 |
| Trial 4 Variety | | | | | | | | | | | | |
| A-Melka | 1.00$^{b}$ | 0.93 | 0.95 | 64.6$^{a}$ | 43.6 | 49.1 | 57.3$^{e}$ | 75.0 | 70.3 | 43.5$^{e}$ | 59.7 | 55.4 |
| Argene | 1.17$^{a}$ | 1.09 | 1.11 | 64.0$^{ab}$ | 45.2 | 49.9 | 57.7$^{de}$ | 71.2 | 67.9 | 43.6$^{e}$ | 55.8 | 52.8 |
| Awash-1 | 0.92$^{bc}$ | 0.89 | 0.90 | 61.2$^{e}$ | 43.8 | 48.9 | 61.2$^{b}$ | 74.7 | 70.7 | 46.3$^{b}$ | 59.8 | 55.8 |
| Dimtu | 0.96$^{b}$ | 0.80 | 0.84 | 61.6$^{cde}$ | 39.5 | 46.3 | 59.6$^{bcd}$ | 76.1 | 71.0 | 44.1$^{cde}$ | 61.0 | 55.8 |
| Dinknesh | 0.95$^{bc}$ | 0.80 | 0.85 | 62.3$^{cd}$ | 38.4 | 45.7 | 58.9$^{cde}$ | 77.5 | 71.8 | 43.5$^{e}$ | 62.4 | 56.6 |
| H-Dume | 0.71$^{d}$ | 0.61 | 0.64 | 60.6$^{e}$ | 39.8 | 46.5 | 63.4$^{a}$ | 79.8 | 74.5 | 48.1$^{a}$ | 63.1 | 58.2 |
| Ibado | 0.69$^{d}$ | 0.89 | 0.82 | 62.8$^{bc}$ | 46.8 | 52.0 | 60.8$^{bc}$ | 75.0 | 70.4 | 43.9$^{de}$ | 59.6 | 54.5 |
| Nasir | 0.79$^{cd}$ | 0.89 | 0.86 | 62.3$^{cd}$ | 45.8 | 51.0 | 60.4$^{bc}$ | 73.9 | 69.6 | 45.5$^{bc}$ | 58.7 | 54.5 |
| SARI | 0.84$^{bcd}$ | 0.67 | 0.72 | 61.3$^{cde}$ | 43.9 | 49.4 | 60.3$^{bc}$ | 76.9 | 71.6 | 45.3$^{bcd}$ | 61.7 | 56.5 |
| **Mean** | **0.89** | **0.84** | **0.85** | **62.3** | **43.0** | **48.8** | **60.0** | **75.6** | **70.9** | **44.9** | **60.2** | **55.6** |
| P>F | 0.0002 | 0.3671 | 0.1722 | 0.0005 | 0.0853 | 0.0608 | 0.0002 | 0.4655 | 0.4432 | <.0001 | 0.2815 | 0.2894 |
| $LSD_{0.05}$ | 0.16 | 0.40 | 0.31 | 1.49 | 6.09 | 4.16 | 1.97 | 7.18 | 5.29 | 1.52 | 5.59 | 4.02 |
| CV(%) | 10.4 | 27.4 | 20.7 | 1.4 | 8.2 | 4.9 | 1.9 | 5.5 | 4.3 | 2.0 | 5.4 | 4.2 |
| Site | | | | | | | | | | | | |
| Boricha | 0.88 | 0.72$^{b}$ | 0.77$^{b}$ | 62.0 | 41.0$^{b}$ | 47.0$^{b}$ | 61.2$^{a}$ | 78.9$^{a}$ | 73.9$^{a}$ | 46.9$^{a}$ | 63.1$^{a}$ | 58.5$^{a}$ |
| Mandura | 0.89 | 0.84$^{a}$ | 0.85$^{a}$ | 62.3 | 43.0$^{a}$ | 48.8$^{a}$ | 60.0$^{b}$ | 75.6$^{b}$ | 70.9$^{b}$ | 44.9$^{b}$ | 60.2$^{b}$ | 55.6$^{b}$ |
| P>F | Effects across both Trials (3 and 4) (n=6) | | | | | | | | | | | |
| Variety (V) | <0.0001 | 0.336 | 0.024 | 0.025 | 0.326 | 0.22 | 0.003 | 0.515 | 0.378 | 0.0003 | 0.262 | 0.133 |
| Site (S) | 0.492 | 0.019 | 0.017 | 0.324 | 0.029 | 0.02 | 0.0005 | 0.001 | 0.0003 | <0.0001 | 0.0004 | <0.0001 |
| V x S | <0.0001 | 0.344 | 0.161 | 0.033 | 0.132 | 0.12 | 0.0006 | 4501 | 0.327 | 0.004 | 0.2300 | 0.323 |
| $LSD_{0.05}$ | 0.085 | 0.210 | 0.147 | 1.389 | 3.652 | 2.909 | 1.334 | 3.799 | 2.966 | 1.402 | 2.985 | 2.458 |

*P<0.05 and P<0.01 indicates significant and highly significant genotypes mean respectively; Means with no superscript letter with a column of each trial are not significantly different (P>0.05); HPW: Haulm + pod walls; LSD: Least significant difference (P=0.05); CV: Coefficient of variation; N: Nitrogen; DMD; Dry matter digestibility; NDF: Neutral detergent fibre; ADF: Acid detergent fibre.*

Table 6.8 Composition and DMD of common bean morphological fractions harvested at seed maturity stage at *Shalla* (Trial 1) *Bako-Tibe* (Trial 2), *Boricha* (Trial 3) and *Mandura* (Trial 4) in 2013

| Residue morphological fraction | Total N% | DMD% | NDF% | ADF% |
|---|---|---|---|---|
| Trial 1 (n=27) | | | | |
| Haulm (A) | 1.03[a] | 53.7[c] | 67.5[a] | 53.2[a] |
| Pod wall (B) | 0.79[c] | 66.0[a] | 57.1[c] | 41.7[c] |
| HPW(A+B) | 0.96[b] | 56.9[b] | 64.8[b] | 50.2[b] |
| P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| LSD (P=0.05) | 0.059 | 0.824 | 0.946 | 0.751 |
| CV % | 11.6 | 2.5 | 2.7 | 2.8 |
| Trial 2 n=18 | | | | |
| Haulm (A) | 1.18 | 41.7[c] | 71.4[a] | 58.3[a] |
| Pod wall (B) | 1.08 | 61.6[a] | 60.0[c] | 44.0[c] |
| HPW (A+B) | 1.14 | 46.7[b] | 68.7[b] | 54.8[b] |
| P>F | 0.0627 | <0.0001 | <0.0001 | <0.0001 |
| LSD (P=0.05) | 0.084 | 1.605 | 1.325 | 1.384 |
| CV % | 10.8 | 4.7 | 2.9 | 3.8 |
| Trial 3 (n=27) | | | | |
| Haulm (A) | 0.72[c] | 41.0[c] | 78.9[a] | 63.1[a] |
| Pod wall (B) | 0.88[a] | 62.0[a] | 61.2[c] | 46.9[c] |
| HPW(A+B) | 0.77[b] | 47.0[b] | 73.9[b] | 58.5[b] |
| P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| LSD(P=0.05) | 0.030 | 0.679 | 0.545 | 0.538 |
| CV % | 7.0 | 2.5 | 1.4 | 1.7 |
| Trial 4 (n=27) | | | | |
| Haulm (A) | 0.84 | 43.0[c] | 75.6[a] | 60.2[a] |
| Pod wall (B) | 0.89 | 62.3[a] | 60.0[c] | 44.9[c] |
| HPW(A+B) | 0.85 | 48.8[b] | 70.9[b] | 55.6[b] |
| P>F | 0.2059 | <0.0001 | <0.0001 | <0.0001 |
| LSD | 0.058 | 0.930 | 0.979 | 0.791 |
| CV % | 12.1 | 3.3 | 2.6 | 2.7 |
| Averaged across both Trials (3 and 4) (n=54) | | | | |
| Haulm (A) | 0.78[b] | 42.0[c] | 77.2[a] | 61.7[a] |
| Pod wall (B) | 0.88[a] | 62.1[a] | 60.6[c] | 45.9[c] |
| HPW (A+B) | 0.81[b] | 47.9[b] | 72.4[b] | 57.0[b] |
| LSD (P=0.05) | 0.040 | 0.760 | 0.770 | 0.633 |
| CV | 13.1 | 3.9 | 2.9 | 3.0 |
| Effects (P>F) | | | | |
| Morphological (M) fraction | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Site | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| M. fraction x site | 0.0343 | 0.0751 | 0.0201 | 0.2621 |

*P<0.05 and P<0.01 indicates significant and highly significant genotypes mean respectively; Means with no superscript letter with a column of each trial are not significantly different (P>0.05); LSD: Least significant difference (P=0.05); CV: Coefficient of variation; N: Nitrogen; DMD; Dry matter digestibility; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; HPW: Haulm + pod walls.*

### 6.3.4. Variation in yields of total N and digestible DM and PUI

HPW N and digestible DM yields ranged from 8.2- 24.5 kg/ha and 0.35-1.46 t/ha, respectively (Tables 6.4 and 6.5). There were higher yields, and a wider range, in HPW N (mean 30.0, range 12.0 - 42.0 kg/ha and mean 11.5, range 9.4-20.9 kg/ha) in Trial 1 (Table 6.4) and Trial 3 (Table 6.5), respectively. Similarly, there was a wider range in HPW DDM yield in Trial 1 (Table 6.4) and Trial 4 (Table 6.5).

There were generally varietal differences ($P<0.05$) in N and DDM yields of the HPW (Tables 6.4 and 6.5) although not in Trial 2 (Table 6.4). There were also varietal differences ($P<0.01$) in PUI in Trial 1 but not in the other trials. Varieties ECAB0081 and H-Dume in Trials 1 and 2, respectively had greater HPW N and DDM yields and PUI than the other varieties (Table 6.4). Similarly, varieties H-Dume, SARI, Nasir and Dinknesh in Trial 3 and Ibado, H-Dume, Dimtu and Dinknesh in Trial 4 had higher HPWN and DDM yields but not consistently higher PUI (Table 6.5). The lowest HPW DDM yielding varieties Loko in Trial 2 , Dimtu in Trial 3, and Awash-1 in Trial 4 also had highest PUI values. When data were combined across trials (Trials 3 and 4) (Table 6.5), site affected HPW N and DDM yields differed significantly between sites. Also there were V x S interactions on HPW N and DDM yields.

### 6.3.5. Relationships between seed and yield related attributes

Within each trial, as well as in the pooled data, there were positive relationships ($P<0.01$) between yields of seed and HPW (Figure 6.1). Similarly, there was a strong positive association ($r=0.93$; $P<0.0001$; $n=99$) between yield of seed and total biomass when data were combined across trials (data not shown). However, there was no general association

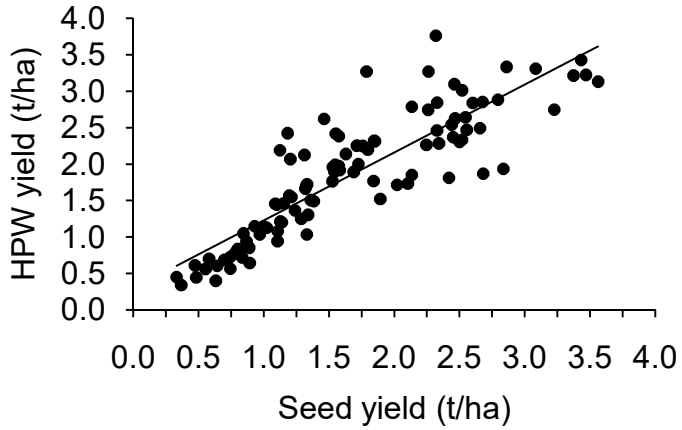


Figure 6.1 Relationship between the haulm + pod wall (HPW) yield (t/ha) (Y) and seed yield (t/ha) (X) in common bean varieties across four trials in 2013.

between seed yield and HI. These attributes were weakly related in Trial 3 (r=0.42; P=0.029; n=27) but not in the other trials.

The regression relationships were as follows:

Trial 1.Y= 1.009X - 0.109 (r=0.83; P<0.0001; n=27);

Trial 2. Y=0.965X - 0.031 (r= 0.93; P<0.0001; n=18):

Trial 3.Y=0.791X + 0.849 (r=0.60; P=0.001; n=27);

Trial 4. Y=1.231X - 0.014 (r=0.98; P<0.0001; n=27);

Pooled relationship: Y = 0.93X + 0.298 (r=0.87; P<0.0001; n=99).

### 6.3.6. Relationships between seed and HPW quality related attributes

There was a weak negative relationship between seed yield and HPW N content in Trial 4 and in the pooled data, but not in Trials 1-3 considered individually (Figure 6.2).

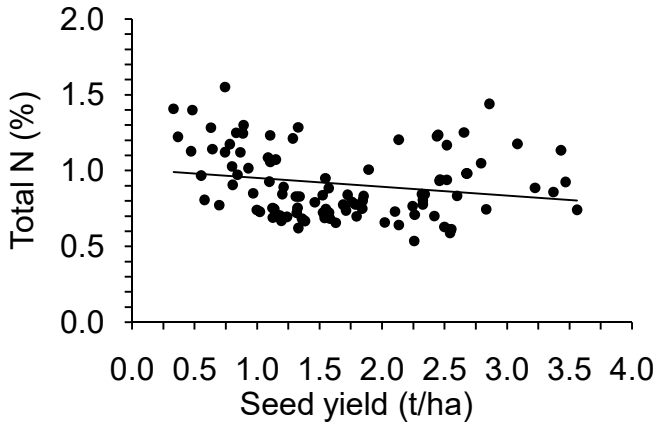


Figure 6.2 Relationship between the haulm + pod wall (HPW) N (%) concentration (Y) and seed yield (t/ha) (X) in common bean varieties across four trials in 2013.

The regression relationships were as follows:

Trial 1. Y = -0.01X + 0.985 (r= -0.02; P=0.91; n=27);

Trial 2. Y= -0.245X + 1.338 (r= -0.29; P=0.24; n=18);

Trial 3. Y= 0.009X + 0.752 (r=0.04; P=0.81; n=27);

Trial 4. Y = -0.232X + 1.153 (r= -0.64; P<0.001; n=27);

Pooled relationship: Y = -0.058X + 1.009 (r= -0.20; P=0.043; n=99).

There was a positive association between seed yield and HPW DMD when data were combined across trials (Figure 6.3) but there were no relationships in any of the trials when considered independently.

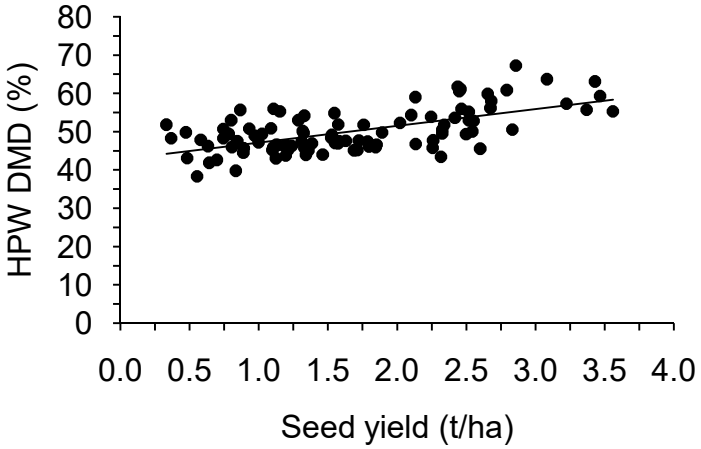


Figure 6.3 Relationship between the haulm + pod wall (HPW) DMD (%) (Y) and seed yield (t/ha) (X) in common bean varieties across four trials in 2013.

The regression relationships were as follows:

Trial 1. Y=3.32X + 48.18 (r= 0.37; P=0.054; n=27);

Trial 2. Y= 5.028X + 42.684 (r= 0.24; P=0.347; n=18);

Trial 3. Y= 1.059X + 45.273 (r= 0.25; P=0.2095; n=27);

Trial 4. Y= -1.497X + 50.741; (r= -0.23; P=0.242; n=27);

Pooled relationship: Y =4.363X+42.82 (r= 0.62; P<0.0001; n=99)

### 6.4. Discussion

Although seed is the primary product of common beans as discussed above, the quantity and quality of CR as livestock feed is also important in many smallholder crop-livestock systems. The present studies show that it is possible to select genotypes of common bean for higher yields of both seed and HPW (i.e. greater total biomass), and to do so with similar or increased HI. The large variation in these and haulm quality attributes among the varieties is important since it indicates that there is opportunity to select improved genotypes for improved yields of both seed and HPW, and HPW of higher nutritive value for ruminants, and to achieve substantial genotype gains. Furthermore this should be possible with the common bean genotypes already available in EA.

#### 6.4.1. Variation amongst varieties for yield and yield related attributes

The lack of differences among varieties observed at 1 of the 4 sites (Trial 3) is in agreement with Asfaw and Blair (2014) who also reported a general absence of differences in HI among varieties within environments. In this latter study HI ranged from 0.11-0.23 in drought stressed and 0.60-0.66 in non-drought stressed environments.

Generally the HI for food legumes varies greatly, both between species and among varieties within species (Batterham and Egan, 1987). Large genetic variation among common bean varieties in seed yield has been reported previously (Haile et al., 2012; Tadesse et al., 2014; Yoseph et al., 2014) and this variation was comparable with that observed in the present study within Trial 1 and 4. Considerable variation in seed yield among common bean genotypes within environments has also been reported by Gebeyehu and Assefa (2003) and Tsegaye et al. (2012). Araújo and Teixeira (2003) reported that common bean cultivars differed in seed yield (0.87-1.59 t/ha) and HI (range 0.47 - 0.66). The latter study and the present study observed that the highest seed yielding varieties did not consistently have high HI.

In the present study, the variation observed among varieties was generally higher for yield of HPW than of seed. This supports the hypothesis that there is substantial scope for rapidly increasing CR biomass from food legumes (Erskine et al., 2000). Also (Scully and Wallace, 1990) reported a common bean accession that had high growth rates and total biomass yield without reducing seed yield. These studies suggest that these improvement pathways are not competitive, and higher yields of multiple plant parts can be achieved by selection of improved varieties. This has major implications for on-farm feed resource availability and livestock productivity for legume CR.

The much lower yields of both of seed and HPW in Trial 2 than in Trials 1, 3 and 4 of the present study might be attributed to both environmental (site) effects and to the different varieties examined. Multi-environment trials of common bean (Gebeyehu and Assefa, 2003; Mekbib, 2002; Mekbib, 2003; Tsegaye et al., 2012) have often demonstrated genotype × environment interactions for seed yield. These results demonstrate the importance of environmental effects in the performance of the varieties, at least for the attributes examined in the present study. The genotype x site interactions in Trials 3 and 4 on leaf ($P<0.0001$) and stem ($P=0.04$) proportions (Table 6.3), LSR ($P<0.0001$) (Table 6.5), and yields of seed ($P<0.02$), HPW ($P<0.0001$), and total biomass ($P<0.0001$) (Table 6.3) indicated that the variation in the attributes is not independent of environment. The simultaneous selection for these attributes may have to be done in appropriate environments. In general, in the current study yield attributes (HPW, seed and total biomass) affected by the V x S interactions are most affected by environmental factors (i.e. site) (52-57%) (values not shown) and did not have stable performance across sites.

PUI has been used for ranking wheat varieties (Tolera et al., 2008) in areas where CR are an important feedstuffs for ruminants. The higher or comparable PUI of low yielding common bean varieties obtained in the current study suggested that ranking common bean varieties should combine an index for higher seed, HPW and digestible yields with equivalent or higher HI.

### 6.4.2. Variation amongst varieties for morphological fractions and residue quality attributes at harvest

The differences among varieties in LSR observed in the current study are in agreement with the findings of Asfaw and Blair (2014) also in common bean. Differences in natural leaf shedding at pod harvesting among varieties may partly account for the effect of variety on LSR (Larbi et al., 1999). At harvest maturity in common bean, the stem forms the largest fraction, the pod wall the next most important, and the leaf only a minority component in HPW; thus the nutritive value of common bean HPW is highly dependent upon the nutritional quality of the stem. The natural leaf loss prior to harvest at seed maturity can result in a high stem and pod wall residues with negligible amounts of leaf available for ruminant feed (Bhaid and Talaptra, 1965).

The total N concentrations of the common bean HPW discussed in the present study were within the range of the haulm values reported by other authors (López et al., 2005) in common bean. In general the characteristics of CR most likely to constrain their use as ruminant feeds, are their generally low N concentration and ME contents and their often low acceptability which make it difficult to achieve high voluntary intake by ruminants. N concentration of cereal residues (e.g. maize stover, Chapters 4 and 5) is often much lower than the threshold needed in ruminant diets even for low DMD diets and is often considered the most limiting factor in utilization of CR. It is well recognised that cattle require forage of 45-50% DMD for maintenance and 55-60% for moderate growth and/or lactation (McDowell, 1972). Hence, the substantial variation observed amongst the varieties in total N concentration and DMD of common bean CR is important. Selection of cultivars with higher total N and DMD can be expected to have considerable effects to improve low quality residue based diets and ruminant productivity. The HPW of some varieties in the present study met a minimum requirements of 1% N concentration and 50% DMD needed by ruminants for moderate growth. Examples were the varieties ECAB0081, GLP2 and Awash-1 in Trial 1 and variety H-Dume in Trial 2 (Table 6.6). These higher values could be partly attributed to the differences in the proportions of leaves,

stems and pod walls in the HPW and the higher LSR (Tables 6.2 and 6.4). López et al. (2005) also reported that leaf-rich common bean haulm had higher DMD than stem-rich haulm. The wide variation in HPW quality attributes in the present study suggests that there may be a selectable genetic component. The lower mean DMD of the HPW in Trial 2 than Trials 1 and 3 might be attributed to environment, the different varieties, and the proportions of the botanical fractions in the HPW. Regardless it emphasises the desirability of identifying and breeding common bean cultivars with higher DMD

As in the present study Araújo and Teixeira (2003) reported strong relationships between seed yield and total biomass yield among common bean cultivars. To some extent this can be expected since biomass yield includes seed yield. Scully and Wallace (1990) also observed a linear and positive relationship between total biomass (seed + HPW) and seed yield in common bean and suggested that varieties with larger biomass and better seed yield could be selected simultaneously. Positive relationships between seed yield and HI have also been reported (Araújo and Teixeira, 2003; Scully et al., 1991; Tar'an et al., 2002). Scully and Wallace (1990) suggested that most of this variation was related to total biomass while HI explained a minor variation in common bean yield. This suggests that biomass is the critical attribute for yield improvement in this crop.

The negative association between seed yield and HPW N concentration may be explained by the translocation of N to seed during crop maturity. Araújo and Teixeira (2003) reported a strong association between seed yield and seed N concentration in common bean cultivars. The general absence of any strong inverse relationships between total N or DMD with seed yields in the current study indicates that there is opportunity to select for better quality HPW without reducing seed yields.

As discussed above, fodder related attributes of the CR have not been considered as selection criteria for new varieties of common bean in EA. However, as Schiere et al. (2004) have pointed out it would be valuable for plant breeders can consider higher total biomass yield, at least equivalent HI, and higher LSR and stem quality as selection criteria to improve whole plant value rather than only for the value of higher seed yield. Similar arguments have been made in relation to plant breeding for lentil as another food legume (Kusmenoglu and Muehlbauer, 1998; Tullu et al., 2001).

## 6.5. Conclusion

The study showed the presence of considerable variability in seed and HPW yields and HPW nutritive value among widely grown varieties of common bean in EA. These results confirm the hypothesis that it should be possible to select common bean varieties/genotypes which yield higher total biomass and HPW, desirable HPW quality characteristics, and have similar or higher HI. The study also demonstrated that there are varieties such as ECAB0081 which were superior in all yield and quality related attributes and had comparable HI. This has obvious and important benefits to address the serious problems of feed shortages and utilization of low-quality cereal CR (maize stover) for ruminants in crop-livestock system of EA. However, three further aspects need consideration. First, it is important that consistency of such relationships should be investigated over a wide range of environments (sites and years) and with a diverse range of common bean genotypes. Second, because of the importance of LSR and the relatively high nutritive value of leaf it would be highly desirable to select genotypes which retain the leaf at seed maturity. Third, farmers need to be aware of the consequences of a delay in harvest after physiological maturity of the crop. Close collaboration among plant breeders, animal nutritionists and farmers is needed for most effective screening of new genotypes.

.

# Chapter 7 Variability in yield and the nutritive value for ruminants of common bean residues: Effects of variety and harvesting stages

## 7.1. Introduction

The role and importance of common bean (*Phaseolus vulgaris* L.) as a legume crop was discussed in Chapter 6. Although the majority of this crop is harvested at seed maturity as 'dry beans', smallholder farmers often early harvest some of the crop at green pod fill growth stage (also known as Eshet harvest) mainly for home consumption when food is scarce. These are termed as 'shell beans' when harvested at physiological maturity of seeds but before desiccation, or as 'green beans' or 'snap beans' when harvested before seed development (Khan et al., 2015; Yuste-Lisbona et al., 2014). The CR (haulms and pod walls) of common bean at Eshet harvest are of high nutritive value for ruminants compared with the CR at seed maturity (Heuzé et al., 2015) and are often used in some regions of Ethiopia with maize or sorghum stover for fattening animals in market oriented crop-livestock systems (Gebreyohannes and Hailemariam, 2011). However, little is known about the yield and nutritive value of the fresh early harvested common bean haulm for ruminants and how it is affected by variety and harvesting stage (Heuzé et al., 2015).

The yield and nutritive value of common bean CR at seed maturity stage (final-harvest) were conducted at two sites (*Boricha* and *Mandura*) in 2013 (Chapter 6). In addition, the variability in yield and quality as ruminant feeds of the common bean varieties harvested at immature green pod fill (early) crop growth stages at these sites were investigated and compared with the CR harvested at seed maturity. The relationships between the total N and DMD of morphological fractions and whole haulm DM yield at early harvest and seed yield at final harvest of common bean were examined.

## 7.2. Materials and Methods

The experimental sites, design, planting and management, sampling and measurements at harvest, and laboratory analyses were as described for the *Boricha* and *Mandura* trial sites (Table 6.1 and Appendix, Figure A7.1) except where stated otherwise..

At the 'final harvest' (Chapter 6), all pods were at mature colour. For the present study the 'early harvest' was planned for the R6 stage when 50% of pods have fully developed seeds (mid-seed fill) (Schwartz and Langham, 2016). This criterion was achieved at *Boricha* site (Trial 1). However, the harvest was unavoidably delayed at the *Mandura* site

(Trial 2) and ~80% of pods had fully developed seeds (just before physiological maturity). The 'final harvest' (Chapter 6) comprised the middle area 2m x 2m of the plot (Figure 7.1) while the 'early harvest' forage was sampled from 0.5m x 2m area as shown in Figure 7.1. The data were analysed as described in Chapter 6 except that the harvest stage was also examined as a main effect.

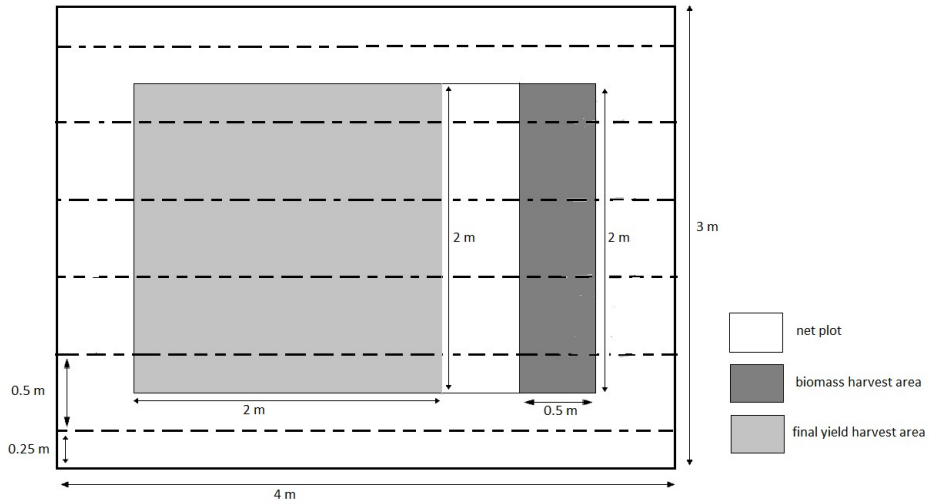


Figure 7.1 Scheme for biomass sampling and seed yield measurement in field plots with common bean varieties.

## 7.3. Results

### 7.3.1. Yields and characteristics of crop fractions at 'early harvest'

Seed, whole haulm (i.e. pod wall, leaf and stem) and total biomass yields at the 'early harvest' are presented in Table 7.1 and the results for the 'late harvest' in Chapter 6 Table 6.3. In either trial sites there were differences among varieties at 'early harvest' in total biomass (t/ha), but the seed and whole haulm yields differed among varieties ($P<0.05$) only in Trial 2. There was wider variation in yield responses among varieties in Trial 2 than in Trial 1 (Table 7.1). Seed yields ranged from 0.83-1.53 t/ha and 0.31-1.57 t/ha, and whole haulm yields ranging from 2.06-3.17 t/ha and 1.19-2.93 t/ha, in Trials 1 and 2, respectively. At early harvest the highest yielding varieties were Nasir, Dinknesh, H-Dume and SARI in Trial 1, and H-Dume, Ibado, Dimtu and Dinkinesh in Trial 2. The lowest yielding varieties in Trial 1 were Ibado and Dimtu, and in Trial 2 Argene and A-Melka.

In both trials the stem formed the largest component of the whole haulm (50-55%) (Table 7.1). In Trial 1 the leaf proportion ($P=0.048$) and LSR ($P=0.027$) varied, and the stem proportion tended to vary ($P=0.052$), among varieties. However, the pod wall proportions

and residue to seed ratio (R:S) (did not vary. Conversely, in Trial 2 the stem (P<0.01) and pod wall (P<0.0001) proportions and R:S (P<0.0001) varied among varieties whereas the leaf fraction and the LSR did not (Table 7.1). Among varieties, the LSR ranged from 44.7-61.9% and 34.7-42.8% while the residue to seed ratio ranged from 2.09-3.26 and 1.87-3.86 in Trials 1 and 2, respectively.

Table 7.1 Yield and whole haulm morphological fractions (% w/w) of common bean varieties harvested at the "early maturity" in 2013 (n=3). The results for the corresponding "final maturity" harvest are given in Chapter 6 Table 6.3

| | Early harvest yields (t/ha) | | | Whole haulm fractions (%) | | | | R:S ratio |
|---|---|---|---|---|---|---|---|---|
| Trial 1 Variety | Seed | Whole haulm | Total biomass | Leaf | Stem | Pod wall | LSR (%) | |
| A-Melka | 1.26 | 2.95 | 4.21$^{a}$ | 23.9$^{bc}$ | 57.7 | 18.3 | 41.6$^{d}$ | 2.58 |
| Argene | 0.85 | 2.74 | 3.59$^{ab}$ | 27.5$^{a}$ | 45.2 | 27.3 | 61.0$^{a}$ | 3.26 |
| Awash-1 | 1.13 | 2.75 | 3.87$^{ab}$ | 25.1$^{bc}$ | 52.9 | 22.0 | 47.6$^{bcd}$ | 2.52 |
| Dimtu | 0.82 | 2.06 | 2.88$^{b}$ | 24.7$^{bc}$ | 52.7 | 22.7 | 47.0$^{bcd}$ | 2.52 |
| Dinknesh | 1.43 | 3.16 | 4.58$^{a}$ | 26.1$^{ab}$ | 48.1 | 25.8 | 55.9$^{ab}$ | 2.50 |
| H-Dume | 1.40 | 3.17 | 4.57$^{a}$ | 25.1$^{bc}$ | 47.1 | 27.8 | 53.4$^{abc}$ | 2.31 |
| Ibado | 0.83 | 2.06 | 2.88$^{b}$ | 23.3$^{c}$ | 52.8 | 23.8 | 44.7$^{cd}$ | 2.53 |
| Nasir | 1.53 | 3.15 | 4.69$^{a}$ | 24.8$^{bc}$ | 43.6 | 31.6 | 56.9$^{ab}$ | 2.09 |
| SARI | 1.35 | 3.15 | 4.50$^{a}$ | 26.0$^{ab}$ | 51.3 | 22.7 | 51.0$^{abcd}$ | 2.37 |
| **Mean** | **1.18** | **2.80** | **3.98** | **25.2** | **50.2** | **24.7** | **51.0** | **2.52** |
| P>F | 0.118 | 0.062 | 0.031 | 0.048 | 0.052 | 0.125 | 0.027 | 0.660 |
| $LSD_{0.05}$ | 0.60 | 0.87 | 1.25 | 2.29 | 8.40 | 8.42 | 10.80 | 1.11 |
| CV % | 29.6 | 18.0 | 18.2 | 5.3 | 9.7 | 19.7 | 12.3 | 25.5 |
| Trial 2 Variety | | | | | | | | |
| A-Melka | 0.65$^{d}$ | 1.79$^{c}$ | 2.43$^{c}$ | 21.4 | 57.7$^{ab}$ | 20.9$^{b}$ | 37.2 | 2.76$^{b}$ |
| Argene | 0.31$^{e}$ | 1.19$^{d}$ | 1.50$^{d}$ | 20.7 | 59.2$^{a}$ | 20.2$^{b}$ | 35.0 | 3.86$^{a}$ |
| Awash-1 | 0.87$^{cd}$ | 1.88$^{c}$ | 2.75$^{c}$ | 20.2 | 58.1$^{ab}$ | 21.8$^{b}$ | 34.7 | 2.19$^{c}$ |
| Dimtu | 1.24$^{b}$ | 2.57$^{b}$ | 3.80$^{b}$ | 20.6 | 54.4$^{bc}$ | 25.1$^{a}$ | 38.0 | 2.12$^{cd}$ |
| Dinknesh | 1.21$^{b}$ | 2.52$^{b}$ | 3.73$^{b}$ | 22.1 | 51.8$^{c}$ | 26.1$^{a}$ | 42.8 | 2.13$^{cd}$ |
| H-Dume | 1.57$^{a}$ | 2.93$^{a}$ | 4.50$^{a}$ | 20.7 | 52.7$^{c}$ | 26.6$^{a}$ | 39.5 | 1.87$^{d}$ |
| Ibado | 1.26$^{b}$ | 2.68$^{ab}$ | 3.94$^{ab}$ | 21.4 | 53.4$^{c}$ | 25.2$^{a}$ | 40.3 | 2.14$^{cd}$ |
| Nasir | 1.07$^{bc}$ | 2.35$^{b}$ | 3.42$^{b}$ | 21.0 | 52.1$^{c}$ | 26.9$^{a}$ | 40.5 | 2.21$^{c}$ |
| SARI | 1.09$^{bc}$ | 2.40$^{b}$ | 3.49$^{b}$ | 21.2 | 52.6$^{c}$ | 26.3$^{a}$ | 40.2 | 2.20$^{c}$ |
| **Mean** | **1.03** | **2.26** | **3.28** | **21.0** | **54.7** | **24.3** | **38.7** | **2.39** |
| P>F | <0.0001 | <0.0001 | <0.0001 | 0.9312 | 0.0025 | <0.0001 | 0.406 | <0.0001 |
| $LSD_{0.05}$ | 0.25 | 0.34 | 0.57 | 2.95 | 3.79 | 2.34 | 7.66 | 0.30 |
| CV % | 14.3 | 8.6 | 10.1 | 8.1 | 4.0 | 5.6 | 11.4 | 7.3 |

*P<0.05 and P<0.01 indicates significant and highly significant varieties mean respectively; Means with no superscript letters are not significantly different (P>0.05); LSR: Leaf to stem ratio; LSD: R:S: Residue to seed ratio; Least significant difference (P=0.05); CV: Coefficient of variation.*

### 7.3.2. Haulm quality characteristics of crop fractions at 'early harvest'

In general, the leaf fraction had higher N and DMD but lower NDF and ADF concentrations than the respective stem and pod wall fractions at early harvest. The pod wall was intermediate between leaf and stem (Table 7.2). N concentration in the fractions and the whole haulm varied ($P<0.05$) among varieties in both trials (Table 7.2). N concentration of the whole haulm ranged from 1.7-2.5% (mean 2.0%) in Trial 1 and 1.3-1.7 (mean 1.5%) in Trial 2. In Trial 2 DMD of whole haulm, leaf and stem differed among varieties ($P<0.05$) and for whole haulm ranged from 60.2-64.2%. However, in Trial 1 there was no difference ($P>0.05$) among varieties in the DMD of the fractions and the whole haulm ranged from 66.2-68.9% (Table 7.2). There were differences in pod wall DMD and N, NDF and ADF concentrations among varieties. The variation in DMD of the whole haulm was consistent with the variation in pod wall, stem and leaf fractions, and the contributions of these fractions to the whole haulm.

Composition and DMD differed among the botanical fractions ($P< 0.0001$) in both trials (Table 7.3). On average, leaf had the highest N content, followed by pod wall, whole haulm and then stem in Trial 1. In Trial 2 leaf also had the highest N content, followed by whole haulm, pod wall and stem. DMD of the leaf (72.4 and 73.4%) was highest, followed by pod wall (71.7 and 67.3%), whole haulm (67.6 and 62.2%) and then stem (63.4 and 55.7%) in Trial 1 and 2, respectively (Table 7.3).

Table 7.2 Composition and DMD of pod wall, leaf, stem and whole plant residue of common bean varieties harvested at “early maturity” in 2013 (n=3). The corresponding results for the “final maturity” harvest are given in Chapter 6 Table 6.7

| Trial 1 | Total N% | | | | DMD% | | | | NDF% | | | | ADF% | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variety | Pod wall | Leaf | Stem | Whole | Pod wall | Leaf | Stem | Whole | Pod wall | Leaf | Stem | Whole | Pod wall | Leaf | Stem | Whole |
| A-Melka | 2.13$^{bc}$ | 3.25$^{b}$ | 1.40$^{bc}$ | 1.98$^{bcd}$ | 75.0$^{ab}$ | 73.5 | 61.4 | 66.7 | 46.7$^{ab}$ | 36.4$^{abc}$ | 58.2$^{a}$ | 51.1$^{a}$ | 34.9 | 29.0 | 45.5$^{a}$ | 39.8$^{a}$ |
| Argene | 2.82$^{a}$ | 3.65$^{a}$ | 1.66$^{a}$ | 2.53$^{a}$ | 69.5$^{bcd}$ | 72.0 | 65.3 | 68.3 | 49.7$^{a}$ | 33.0$^{d}$ | 51.8$^{c}$ | 46.1$^{d}$ | 38.1 | 28.7 | 39.9$^{c}$ | 36.4$^{de}$ |
| Awash-1 | 2.33$^{b}$ | 3.07$^{bc}$ | 1.47$^{ab}$ | 2.07$^{bc}$ | 68.7$^{cd}$ | 73.2 | 63.0 | 66.7 | 52.4$^{a}$ | 34.2$^{cd}$ | 56.2$^{ab}$ | 49.9$^{abc}$ | 39.9 | 29.4 | 43.5$^{ab}$ | 39.2$^{ab}$ |
| Dimtu | 2.30$^{b}$ | 3.07$^{bc}$ | 1.14$^{d}$ | 1.88$^{cde}$ | 77.9$^{a}$ | 73.2 | 62.8 | 68.8 | 40.0$^{b}$ | 36.9$^{ab}$ | 55.4$^{ab}$ | 47.4$^{cd}$ | 28.1 | 29.3 | 39.8$^{c}$ | 34.6$^{e}$ |
| Dinknesh | 2.84$^{a}$ | 3.14$^{bc}$ | 1.33$^{bcd}$ | 2.20$^{b}$ | 73.9$^{abc}$ | 69.2 | 62.1 | 67.0 | 39.3$^{d}$ | 37.3$^{a}$ | 55.9$^{ab}$ | 46.8$^{d}$ | 29.7 | 32.3 | 42.5$^{ab}$ | 36.5$^{cde}$ |
| H-Dume | 1.69$^{de}$ | 3.07$^{bc}$ | 1.18$^{cd}$ | 1.80$^{cde}$ | 69.1$^{bcd}$ | 71.9 | 63.6 | 67.4 | 52.3$^{a}$ | 36.5$^{abc}$ | 56.4$^{ab}$ | 50.1$^{abc}$ | 39.1 | 31.5 | 42.7$^{ab}$ | 38.7$^{abcd}$ |
| Ibado | 1.39$^{e}$ | 3.02$^{bc}$ | 1.30$^{bcd}$ | 1.71$^{e}$ | 67.7$^{d}$ | 72.6 | 63.1 | 66.2 | 53.8$^{a}$ | 34.6$^{bcd}$ | 55.9$^{ab}$ | 50.8$^{ab}$ | 37.5 | 30.1 | 42.0$^{bc}$ | 38.5$^{abcd}$ |
| Nasir | 1.85$^{cd}$ | 3.04$^{bc}$ | 1.21$^{cd}$ | 1.87$^{cde}$ | 70.8$^{bcd}$ | 73.7 | 63.1 | 68.2 | 50.8$^{a}$ | 35.6$^{abc}$ | 57.3$^{ab}$ | 49.9$^{abc}$ | 38.9 | 30.1 | 44.1$^{ab}$ | 39.0$^{abc}$ |
| SARI | 2.25$^{b}$ | 2.82$^{c}$ | 1.49$^{ab}$ | 2.01$^{bcd}$ | 72.4$^{abcd}$ | 72.4 | 65.7 | 68.9 | 46.8$^{ab}$ | 36.5$^{abc}$ | 54.2$^{bc}$ | 48.0$^{bcd}$ | 35.2 | 29.5 | 41.7$^{bc}$ | 37.1$^{bcd}$ |
| **Mean** | **2.20** | **3.12** | **1.35** | **2.00** | **71.7** | **72.4** | **63.4** | **67.6** | **48.0** | **35.7** | **55.7** | **48.9** | **35.7** | **30.0** | **42.4** | **37.8** |
| P>F | 0.0001 | 0.018 | 0.008 | 0.0001 | 0.030 | 0.347 | 0.099 | 0.314 | 0.035 | 0.019 | 0.039 | 0.021 | 0.083 | 0.227 | 0.011 | 0.008 |
| $LSD_{0.05}$ | 0.36 | 0.37 | 0.25 | 0.25 | 5.90 | 3.71 | 2.87 | 2.64 | 9.43 | 2.37 | 3.30 | 3.05 | 8.54 | 2.92 | 2.84 | 2.53 |
| CV (%) | 9.4 | 6.8 | 10.6 | 7.1 | 4.8 | 3.0 | 2.6 | 2.3 | 11.3 | 3.8 | 3.4 | 3.6 | 13.8 | 5.6 | 3.9 | 3.9 |
| Trial 2 Variety | | | | | | | | | | | | | | | | |
| A-Melka | 1.51$^{ab}$ | 3.12$^{b}$ | 1.08$^{a}$ | 1.60$^{abc}$ | 71.5$^{a}$ | 72.6$^{a}$ | 51.4$^{d}$ | 60.2$^{d}$ | 47.6$^{e}$ | 39.7 | 67.6$^{a}$ | 57.4$^{a}$ | 34.3$^{e}$ | 31.0$^{bc}$ | 53.7$^{a}$ | 44.8$^{a}$ |
| Argene | 1.42$^{ab}$ | 3.03$^{b}$ | 1.09$^{a}$ | 1.55$^{bc}$ | 68.1$^{bc}$ | 73.2$^{a}$ | 58.0$^{a}$ | 63.2$^{abc}$ | 53.4$^{bcd}$ | 37.1 | 59.8$^{cd}$ | 53.8$^{bcd}$ | 40.1$^{abc}$ | 30.8$^{bc}$ | 45.3$^{de}$ | 41.2$^{b}$ |
| Awash-1 | 1.44$^{ab}$ | 3.49$^{a}$ | 1.15$^{a}$ | 1.68$^{ab}$ | 66.5$^{bcd}$ | 72.2$^{ab}$ | 55.3$^{abc}$ | 61.1$^{cd}$ | 53.9$^{abc}$ | 37.9 | 63.8$^{b}$ | 56.4$^{a}$ | 39.4$^{bcd}$ | 32.2$^{abc}$ | 50.7$^{b}$ | 44.5$^{a}$ |
| Dimtu | 1.51$^{ab}$ | 3.41$^{a}$ | 1.01$^{ab}$ | 1.63$^{abc}$ | 69.4$^{ab}$ | 75.0$^{a}$ | 57.6$^{ab}$ | 64.1$^{ab}$ | 49.0$^{cde}$ | 37.9 | 59.7$^{d}$ | 52.6$^{cd}$ | 35.3$^{de}$ | 28.3$^{c}$ | 44.3$^{e}$ | 38.8$^{c}$ |
| Dinknesh | 1.57$^{a}$ | 3.45$^{a}$ | 1.09$^{a}$ | 1.74$^{a}$ | 69.4$^{ab}$ | 74.9$^{a}$ | 57.1$^{ab}$ | 64.2$^{a}$ | 48.6$^{de}$ | 36.9 | 59.3$^{d}$ | 51.6$^{d}$ | 35.3$^{de}$ | 28.5$^{c}$ | 44.5$^{e}$ | 38.6$^{c}$ |
| H-Dume | 0.96$^{c}$ | 2.59$^{c}$ | 0.86$^{c}$ | 1.25$^{e}$ | 63.8$^{d}$ | 76.6$^{a}$ | 55.0$^{bc}$ | 61.8$^{bcd}$ | 58.8$^{a}$ | 34.6 | 63.4$^{b}$ | 56.2$^{ab}$ | 44.2$^{a}$ | 28.3$^{c}$ | 48.7$^{bc}$ | 43.2$^{ab}$ |
| Ibado | 0.99$^{c}$ | 3.04$^{b}$ | 1.09$^{a}$ | 1.48$^{cd}$ | 64.2$^{d}$ | 67.9$^{b}$ | 57.2$^{ab}$ | 61.2$^{cd}$ | 57.0$^{ab}$ | 43.0 | 62.4$^{bc}$ | 57.0$^{a}$ | 40.8$^{abc}$ | 35.7$^{a}$ | 47.6$^{cd}$ | 43.4$^{ab}$ |
| Nasir | 1.09$^{c}$ | 2.87$^{b}$ | 0.88$^{bc}$ | 1.35$^{de}$ | 64.9$^{cd}$ | 73.1$^{a}$ | 54.2$^{c}$ | 61.0$^{cd}$ | 56.6$^{ab}$ | 39.6 | 64.2$^{b}$ | 57.0$^{a}$ | 42.5$^{ab}$ | 33.0$^{ab}$ | 49.7$^{bc}$ | 44.3$^{a}$ |
| SARI | 1.34$^{b}$ | 2.86$^{b}$ | 1.06$^{a}$ | 1.51$^{bcd}$ | 68.0$^{bc}$ | 75.2$^{a}$ | 55.7$^{abc}$ | 63.1$^{abc}$ | 49.9$^{cde}$ | 39.1 | 64.0$^{b}$ | 55.0$^{abc}$ | 36.3$^{cde}$ | 29.7$^{bc}$ | 50.8$^{b}$ | 42.5$^{ab}$ |
| **Mean** | **1.31** | **3.09** | **1.03** | **1.53** | **67.3** | **73.4** | **55.7** | **62.2** | **52.7** | **38.4** | **62.7** | **55.2** | **38.7** | **30.8** | **48.4** | **42.4** |
| P>F | <0.0001 | <0.0001 | 0.008 | 0.0004 | 0.0016 | 0.044 | 0.0029 | 0.0143 | 0.001 | 0.091 | <0.0001 | 0.0012 | 0.002 | 0.039 | <0.0001 | <0.0001 |
| $LSD_{0.05}$ | 0.18 | 0.26 | 0.15 | 0.17 | 3.35 | 4.60 | 2.77 | 2.33 | 5.14 | 4.76 | 2.61 | 2.59 | 4.55 | 4.47 | 2.53 | 2.23 |
| CV (%) | 7.7 | 4.8 | 8.3 | 6.5 | 2.9 | 3.6 | 2.9 | 2.1 | 5.6 | 7.2 | 2.4 | 2.7 | 6.8 | 8.4 | 3.0 | 3.0 |

*P<0.05 and P<0.01indicates significant and highly significant genotypes mean respectively; Means with no superscript letter are not significantly different (P>0.05); LSD: Least significant difference (P=0.05); CV: Coefficient of variation; N: Nitrogen; DMD; Dry matter digestibility; NDF: Neutral detergent fibre; ADF: Acid detergent fibre.*

Table 7.3 Composition and DMD of common bean morphological fractions harvested at "early maturity" in 2013 (n=27)

| Morphological fraction | Total N% | DMD% | NDF% | ADF% |
|---|---|---|---|---|
| **Trial 1** | | | | |
| Pod wall (A) | 2.18[b] | 71.7[a] | 48.0[b] | 35.7[c] |
| Leaf (B) | 3.12[a] | 72.4[a] | 35.7[c] | 30.0[d] |
| Stem (C) | 1.35[d] | 63.4[d] | 55.7[a] | 42.4[a] |
| Whole (A+B+C) | 2.01[c] | 67.6[b] | 48.9[b] | 37.8[b] |
| P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| LSD (P=0.05) | 0.091 | 1.165 | 1.588 | 1.444 |
| CV % | 7.9 | 3.2 | 6.2 | 7.2 |
| **Trial 2** | | | | |
| Pod wall (A) | 1.31[d] | 67.3[b] | 52.7[c] | 38.7[c] |
| Leaf(B) | 3.09[a] | 73.4[a] | 38.4[d] | 30.8[d] |
| Stem (C) | 1.03[e] | 55.7[e] | 62.7[a] | 48.4[a] |
| Whole (A+B+C) | 1.53[c] | 62.2[c] | 55.2[b] | 42.4[b] |
| P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| LSD (P=0.05) | 0.067 | 1.017 | 1.165 | 1.124 |
| CV % | 7.2 | 2.9 | 4.1 | 5.1 |

*P<0.001 indicates highly significant genotypes mean; N: Nitrogen; DMD: Dry matter digestibility; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; LSD: Least significant difference; CV: Coefficient of variation.*

### 7.3.3. Haulm nutrient yields at 'early harvest'

In both trials at "early harvest", on average across varieties the N yield was greatest in leaf (18.4 kg/ha), followed by stem (15.9 kg/ha), and then by pod wall (11.1 kg/ha) (Table 7.4). However, the DDM yield (t/ha) was greatest in stem, followed by similar proportions in leaf and pod wall. Morphological fractions generally varied among varieties (P<0.05) in terms of N and DDM yields/ha. In Trial 1 Dinknesh, SARI, Nasir and H-Dume varieties gave the highest haulm N and DDM yields/ha, while in Trial 2 Dinknesh, Dimtu and Ibado were higher in haulm N yield/ha, but H-Dume, Ibado, Dimtu and Dinknesh provided the highest haulm DDM yield/ha (Table 7.4).

Table 7.4 Yields of haulm N and DDM of common bean varieties harvested at "early maturity" in 2013 (n=3). The corresponding results for the "final maturity" harvest are given in Chapter 6 Table 6.5

| | Early harvest N yield (kg/ha) | | | | Early harvest DDM yield (t/ha) | | | |
|---|---|---|---|---|---|---|---|---|
| Trial 1 Variety | Pod wall | Leaf | Stem | Whole haulm | Pod wall | Leaf | Stem | Whole haulm |
| A-Melka | 11.4$^{de}$ | 23.2$^{ab}$ | 24.0 | 58.6$^{ab}$ | 0.40$^{cd}$ | 0.52 | 1.05 | 1.97 |
| Argene | 20.5$^{ab}$ | 28.1$^{a}$ | 21.8 | 70.3$^{a}$ | 0.50$^{bc}$ | 0.55 | 0.82 | 1.87 |
| Awash-1 | 13.8$^{cd}$ | 21.2$^{abc}$ | 21.8 | 56.8$^{ab}$ | 0.41$^{cd}$ | 0.51 | 0.93 | 1.84 |
| Dimtu | 10.8$^{de}$ | 15.7$^{c}$ | 12.4 | 38.8$^{bc}$ | 0.36$^{cd}$ | 0.37 | 0.68 | 1.42 |
| Dinknesh | 23.4$^{a}$ | 26.0$^{a}$ | 20.5 | 69.9$^{a}$ | 0.60$^{ab}$ | 0.57 | 0.95 | 2.12 |
| H-Dume | 14.7$^{bcd}$ | 24.4$^{a}$ | 17.9 | 57.1$^{ab}$ | 0.60$^{ab}$ | 0.58 | 0.96 | 2.14 |
| Ibado | 6.5$^{e}$ | 14.5$^{c}$ | 14.3 | 35.3$^{bc}$ | 0.32$^{d}$ | 0.35 | 0.69 | 1.36 |
| Nasir | 18.4$^{abc}$ | 23.8$^{ab}$ | 16.7 | 58.9$^{ab}$ | 0.70$^{a}$ | 0.58 | 0.87 | 2.15 |
| SARI | 15.4$^{bcd}$ | 23.0$^{ab}$ | 24.9 | 63.2$^{a}$ | 0.50$^{bc}$ | 0.59 | 1.08 | 2.17 |
| **Mean** | **15.0** | **22.2** | **19.3** | **56.5** | **0.49** | **0.51** | **0.89** | **1.89** |
| P>F | 0.0013 | 0.0496 | 0.183 | 0.026 | 0.0008 | 0.0853 | 0.329 | 0.066 |
| LSD | 6.45 | 8.33 | 10.01 | 20.8 | 0.15 | 0.18 | 0.38 | 0.61 |
| CV % | **24.9** | 21.7 | 29.9 | 21.3 | 17.7 | 20.8 | 24.6 | 18.5 |
| Trial 2 Variety | | | | | | | | |
| A-Melka | 5.6$^{e}$ | 11.9$^{e}$ | 11.2$^{cd}$ | 28.7$^{d}$ | 0.27$^{c}$ | 0.28$^{c}$ | 0.53$^{e}$ | 1.07$^{c}$ |
| Argene | 3.4$^{f}$ | 7.4$^{f}$ | 7.6$^{e}$ | 18.3$^{e}$ | 0.16$^{d}$ | 0.18$^{d}$ | 0.41$^{f}$ | 0.75$^{d}$ |
| Awash-1 | 5.9$^{de}$ | 13.3$^{de}$ | 12.5$^{bc}$ | 31.7$^{cd}$ | 0.27$^{c}$ | 0.27$^{c}$ | 0.60$^{de}$ | 1.15$^{c}$ |
| Dimtu | 9.7$^{ab}$ | 18.1$^{ab}$ | 14.1$^{ab}$ | 41.9$^{a}$ | 0.45$^{ab}$ | 0.40$^{ab}$ | 0.80$^{ab}$ | 1.64$^{ab}$ |
| Dinknesh | 10.3$^{a}$ | 19.0$^{a}$ | 14.0$^{ab}$ | 43.4$^{a}$ | 0.46$^{ab}$ | 0.41$^{ab}$ | 0.75$^{bc}$ | 1.62$^{ab}$ |
| H-Dume | 7.6$^{cd}$ | 15.7$^{bcd}$ | 13.3$^{b}$ | 36.5$^{bc}$ | 0.50$^{a}$ | 0.46$^{a}$ | 0.85$^{a}$ | 1.81$^{a}$ |
| Ibado | 6.6$^{de}$ | 17.5$^{abc}$ | 15.5$^{a}$ | 39.7$^{ab}$ | 0.43$^{ab}$ | 0.39$^{b}$ | 0.82$^{ab}$ | 1.64$^{ab}$ |
| Nasir | 6.9$^{cde}$ | 14.1$^{de}$ | 10.7$^{d}$ | 31.7$^{cd}$ | 0.41$^{b}$ | 0.36$^{b}$ | 0.66$^{cd}$ | 1.44$^{b}$ |
| SARI | 8.4$^{bc}$ | 14.6$^{cde}$ | 13.4$^{b}$ | 36.3$^{bc}$ | 0.43$^{ab}$ | 0.38$^{b}$ | 0.70$^{c}$ | 1.51$^{b}$ |
| **Mean** | **7.2** | **14.6** | **12.5** | **34.2** | **0.375** | **0.349** | **0.680** | **1.40** |
| P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| LSD | 1.70 | 2.99 | 1.71 | 5.00 | 0.08 | 0.07 | 0.10 | 0.22 |
| CV % | 13.7 | 11.8 | 7.9 | 8.4 | 12.6 | 11.1 | 8.3 | 8.9 |

*P<0.05 and P<0.01 indicates significant and highly significant* varieties *mean respectively; Means with no superscript letters are not significantly different (P>0.05); N: Nitrogen; DDM: Digestible dry matter; LSD: Least significant difference (P=0.05); CV: Coefficient of variation.*

### 7.3.4. Effect of crop growth stage at harvest on seed and haulm DM yields

Crop growth stage at harvest affected (P<0.05 and P<0.01) the yields and proportions of the haulm fractions at both sites with the exception of stem DM yield in Trial 1 (Table 7.5). As the plant matured from early to final harvest, the seed yield increased from 1.18 to 1.67 t/ha (by 42%) in Trial 1, and 1.03 to 1.32 t/ha (28%) in Trial 2, while leaf yield decreased from 0.71 to 0.15 t/ha (373%) in Trial 1, and 0.47 to 0.10 t/ha (370%) in Trial 2. There were tendencies for pod wall DM yields to decrease by 11 to 12% in both trials, while stem yield decreased by 21% in Trial 2 but not in Trial 1. Whole haulm yield decreased (P<0.0001) with later harvest, by 29% and 40% in Trial 1 and 2, respectively. Total biomass yields

decreased (P<0.001) by 12% with later harvest in Trial 2 but not in Trial 1. With later harvest the leaf proportion decreased more than two-fold, while stem and pod wall proportions increased. In general, as the plant matured from early to final harvest, the change in leaf proportion was large compared to the change in stem and pod wall fractions. Moreover, the change in yields and the proportions of leaf and stem fractions were wider in Trial 1 than Trial 2 as the plant matured.

Table 7.5 Seed and residue yields and morphological proportions (%) of common bean residue harvested at early and final (seed) maturity crop growth stages in 2013 (n = 27)

| | | Yields (t/ha) | | | | | | Haulm proportion (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Trial no. | H-stage | Seed | Leaf | Stem | Pod wall | Whole haulm | Total biomass | Leaf | Stem | Pod wall |
| 1 | Early | 1.18$^{b}$ | 0.71$^{a}$ | 1.41 | 0.68$^{a}$ | 2.80$^{a}$ | 3.98 | 25.2$^{a}$ | 50.2$^{b}$ | 24.7$^{b}$ |
| | Final | 1.67$^{a}$ | 0.15$^{b}$ | 1.41 | 0.61$^{b}$ | 2.17$^{b}$ | 3.84 | 6.9$^{b}$ | 64.5$^{a}$ | 28.6$^{a}$ |
| | P>F | <0.0001 | <0.0001 | 0.99 | 0.03 | <0.0001 | 0.50 | <0.0001 | <0.0001 | <0.013 |
| | LSD | 0.22 | 0.06 | 0.20 | 0.06 | 0.27 | 0.41 | 0.59 | 2.90 | 3.09 |
| | CV | 28.1 | 26.1 | 25.8 | 18.0 | 19.6 | 18.8 | 6.7 | 9.2 | 21.0 |
| 2 | Early | 1.03$^{b}$ | 0.47$^{a}$ | 1.22$^{a}$ | 0.56$^{a}$ | 2.26$^{a}$ | 3.28$^{a}$ | 21.0$^{a}$ | 54.7$^{b}$ | 24.3$^{b}$ |
| | Final | 1.32$^{a}$ | 0.10$^{b}$ | 1.01$^{b}$ | 0.50$^{b}$ | 1.61$^{b}$ | 2.94$^{b}$ | 6.8$^{b}$ | 63.3$^{a}$ | 29.9$^{a}$ |
| | P>F | <0.0001 | <0.0001 | <0.0001 | 0.002 | <0.0001 | 0.0004 | <0.0001 | <0.0001 | <0.0001 |
| | LSD | 0.08 | 0.02 | 0.06 | 0.04 | 0.10 | 0.18 | 0.66 | 1.03 | 0.82 |
| | CV | 12.9 | 13.0 | 9.0 | 13.6 | 9.4 | 10.4 | 8.6 | 3.2 | 5.5 |

*P<0.05 and P<0.05 indicates significant and highly significant varieties mean respectively; H-stage: Harvesting stage; LSD: Least significant difference at P=0.05; CV: Coefficient of variation.*

### 7.3.5. Effect of crop growth stage at harvest on haulm quality and nutrient yields

Composition and DMD, and DDM and total N yields of morphological fractions were affected by maturity in both trials (P<0.05 and P<0.01) (Table 7.6). Total N concentration, DMD, and yields of DDM and N decreased (P<0.0001), while NDF and ADF content increased (P<0.0001). These changes in nutritive value were much greater in Trial 1 than in Trial 2.

Table 7.6 Composition, DMD, and nutrient yields of common bean residue harvested at early and final (seed) maturity crop growth stages in 2013 (n = 27)

| Trial 1 | Harvesting stage | Total N (%) | DMD (%) | NDF (%) | ADF (%) | DDMY (t/ha) | NY (kg/ha) |
|---|---|---|---|---|---|---|---|
| Pod wall | Early | 2.18[a] | 71.7[a] | 48.0[b] | 35.7[b] | 0.49[a] | 15.0[a] |
| | Final | 0.88[b] | 62.0[b] | 61.2[a] | 46.9[a] | 0.38[b] | 5.4[b] |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | LSD | 0.09 | 1.38 | 2.22 | 2.04 | 0.04 | 1.50 |
| | CV | 10.9 | 3.7 | 7.4 | 8.9 | 18.5 | 26.5 |
| Haulm | Early | 1.95[a] | 66.4[a] | 49.0[b] | 38.3[b] | 1.41[a] | 41.6[a] |
| | Final | 0.72[b] | 41.0[b] | 78.9[a] | 63.1[a] | 0.64[b] | 11.3[b] |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | LSD | 0.08 | 0.85 | 0.86 | 0.81 | 0.13 | 4.40 |
| | CV | 10.7 | 2.9 | 2.4 | 2.9 | 22.9 | 30.2 |
| Whole haulm | Early | 2.01[a] | 67.6[a] | 48.9[b] | 37.8[b] | 1.89[a] | 56.5[a] |
| | Final | 0.77[b] | 47.0[b] | 73.9[a] | 58.5[a] | 1.02[b] | 16.7[b] |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | LSD | 0.09 | 1.03 | 1.06 | 1.04 | 0.14 | 5.12 |
| | CV | 11.4 | 3.28 | 3.2 | 3.9 | 18.0 | 25.3 |
| Trial 2 | | | | | | | |
| Pod wall | Early | 1.31[a] | 67.3[a] | 52.7[b] | 38.7[b] | 0.38[a] | 7.2[a] |
| | Final | 0.89[b] | 62.3[b] | 60.7[a] | 44.9[a] | 0.31[b] | 4.2[b] |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | LSD | 0.06 | 0.82 | 1.25 | 1.10 | 0.03 | 0.46 |
| | CV | 10.0 | 2.30 | 4.0 | 4.7 | 13.6 | 14.5 |
| Haulm | Early | 1.61[a] | 60.6[a] | 56.0[b] | 43.5[b] | 1.03[a] | 27.1[a] |
| | Final | 0.84[b] | 43.0[b] | 75.6[a] | 60.2[a] | 0.48[b] | 9.0[b] |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | LSD | 0.10 | 1.77 | 1.82 | 1.62 | 0.04 | 1.21 |
| | CV | 15.4 | 6.2 | 5.1 | 5.7 | 10.8 | 12.1 |
| Whole haulm | Early | 1.53[a] | 62.2[a] | 55.2[b] | 42.4[b] | 1.40a | 34.2[a] |
| | Final | 0.85[b] | 48.8[b] | 70.9[a] | 55.6[a] | 0.78b | 13.1[b] |
| | P>F | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| | LSD | 0.08 | 1.35 | 1.42 | 1.25 | 0.06 | 1.36 |
| | CV | 12.5 | 4.4 | 4.1 | 4.7 | 9.8 | 10.4 |

*P<0.01indicates highly significant varieties mean; N: Nitrogen; DMD: Dry matter digestibility; NDF: Neutral detergent fibre; ADF: Acid detergent fibre; DDMY: Digestible DM yield; NY: Nitrogen yield; LSD: Least significant difference at P=0.05; CV: Coefficient of variation.*

### 7.3.6. Relationships between yield and yield related attributes and haulm quality parameters

Yield and quality parameters were often correlated among the varieties at 'early harvest' (Table 7.7). There were strong and positive correlations between seed yield (final harvest) and whole haulm yield (r=0.60, P<0.001 in Trial 1; r=0.98, P<0.001 in Trial 2) (Table 7.7), and also between seed and total biomass yield (r=0.82, P<0.001 in Trial 1; r=0.99,

P<0.001 in Trial 2) (data not shown). Also yields of leaves, stems and pod walls at early harvest were correlated with final harvest seed yield in both trials (Table 7.7).

There was no association (P>0.05) between whole haulm total N content and DMD (Table 7.7). NDF and ADF contents were negatively correlated with DMD of whole haulm (r= -0.65; P<0.01, and r= -0.68; P<0.01 in Trial 1, and r= -0.95; P<0.01 and r= -0.92; P<0.01 in Trial 2, respectively). There were negative correlations between total N and NDF contents of the whole haulm (r= -0.64; P<0.01 and r= -0.42; P<0.05 in Trial 1 and Trial 2, respectively), but the total N and ADF contents were not related. Quality parameters (N, DMD, NDF and ADF) were generally not related (P>0.05) to the yield attributes measured in either trial. However, LSR was positively correlated with DMD (r=0.47; P<0.05) and total N (r=0.56; P<0.01) and negatively correlated with NDF (r= -0.51; P<0.01), but was unrelated to ADF (r= -0.31; P>0.05) in Trial 1 and all these were unrelated (P>0.05) in Trial 2.

Table 7.7 Pearson correlation matrix among variates between yield and quality attributes measured in common bean varieties harvested at early crop growth stage in 2013 (n=27)

| | | DMD (%) | | | | Total N (%) | | | | Dry matter yield (t/ha) | | | | LSR (%) | SY (t/ha) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variates | | Pod walls | Leaves | Stems | Whole | Pod walls | Leaves | Stems | Whole | Pod walls | Leaves | Stems | Whole | Haulm | Final harvest |
| *Trial 1* | | | | | | | | | | | | | | | |
| DMD (%) | Pod walls | 1 | | | | | | | | | | | | | |
| | Leaves | -0.09 | 1 | | | | | | | | | | | | |
| | Stems | -0.19 | 0.22 | 1 | | | | | | | | | | | |
| | Whole | 0.41* | 0.45* | 0.66*** | 1 | | | | | | | | | | |
| Total N (%) | Pod walls | 0.31 | -0.20 | 0.08 | 0.27 | 1 | | | | | | | | | |
| | Leaves | -0.09 | -0.07 | -0.25 | -0.20 | 0.42* | 1 | | | | | | | | |
| | Stems | -0.13 | 0.12 | 0.37 | 0.16 | 0.49** | 0.43* | 1 | | | | | | | |
| | Whole | 0.03 | -0.05 | 0.18 | 0.24 | 0.86*** | 0.69*** | 0.75*** | 1 | | | | | | |
| DMY (t/ha) | Pod walls | -0.18 | -0.06 | 0.19 | 0.27 | 0.15 | 0.07 | 0.03 | 0.24 | 1 | | | | | |
| | Leaves | 0.10 | 0.00 | 0.22 | 0.24 | 0.30 | 0.09 | 0.45* | 0.38 | 0.59*** | 1 | | | | |
| | Stems | 0.22 | -0.01 | 0.04 | -0.01 | 0.09 | -0.05 | 0.35 | 0.08 | 0.19 | 0.85*** | 1 | | | |
| | Whole | 0.11 | -0.02 | 0.14 | 0.15 | 0.19 | 0.02 | 0.35 | 0.23 | 0.58*** | 0.98*** | 0.90*** | 1 | | |
| LSR (%) | Haulm | -0.14 | 0.01 | 0.31 | 0.47* | 0.44* | 0.27 | 0.15 | 0.56** | 0.67*** | 0.22 | -0.31 | 0.08 | 1 | |
| SY (t/ha) | Final harvest | 0.16 | 0.13 | -0.09 | 0.25 | 0.21 | 0.02 | 0.08 | 0.22 | 0.63*** | 0.61*** | 0.40* | 0.60*** | 0.38* | 1 |
| *Trial 2* | | | | | | | | | | | | | | | |
| DMD (%) | Pod walls | 1 | | | | | | | | | | | | | |
| | Leaves | 0.10 | 1 | | | | | | | | | | | | |
| | Stems | 0.11 | -0.04 | 1 | | | | | | | | | | | |
| | Whole | 0.44* | 0.40* | 0.82*** | 1 | | | | | | | | | | |
| Total N (%) | Pod walls | 0.88*** | 0.09 | 0.21 | 0.48* | 1 | | | | | | | | | |
| | Leaves | 0.36 | -0.29 | 0.08 | 0.08 | 0.60*** | 1 | | | | | | | | |
| | Stems | 0.32 | -0.35 | 0.08 | 0.03 | 0.41* | 0.64*** | 1 | | | | | | | |
| | Whole | 0.55** | -0.24 | 0.13 | 0.23 | 0.73*** | 0.89*** | 0.84*** | 1 | | | | | | |
| DMY (t/ha) | Pod walls | -0.43* | 0.20 | 0.09 | 0.12 | -0.47* | -0.27 | -0.48* | -0.40* | 1 | | | | | |
| | Leaves | -0.41* | 0.09 | 0.05 | 0.07 | -0.44* | -0.16 | -0.35 | -0.27 | 0.96*** | 1 | | | | |
| | Stems | -0.38 | 0.15 | 0.03 | 0.02 | -0.42* | -0.20 | -0.45* | -0.39* | 0.94*** | 0.92*** | 1 | | | |
| | Whole | -0.41* | 0.16 | 0.06 | 0.06 | -0.45* | -0.22 | -0.45* | -0.38 | 0.98*** | 0.97*** | 0.98*** | 1 | | |
| LSR (%) | Haulm | -0.19 | -0.08 | 0.02 | 0.12 | -0.20 | -0.01 | 0.08 | 0.15 | 0.42* | 0.56** | 0.20 | 0.35 | 1 | |
| SY (t/ha) | Final harvest | -0.40* | 0.17 | 0.08 | 0.08 | -0.41* | -0.18 | -0.43* | -0.34 | 0.96*** | 0.95*** | 0.98*** | 0.98*** | 0.32 | 1 |

** Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level; ***Correlation is significant at the 0.001 level. N: Nitrogen; DMD: Dry matter digestibility; DMY: Dry matter yield: LSR: Leaf to stem ratio; SY:* Seed yield.

## 7.4. Discussion

### 7.4.1. Variation in yield and haulm morphological characteristics and quality attributes among varieties

Total biomass yield varied among the varieties in both trials. The general absence of differences in seed and whole haulm yields among varieties in Trial 1 was associated with a much larger error variance than in Trial 2. However, this may have been associated with the different harvest stages as well as the different environments. Furthermore, stem forms the majority of the whole haulm and there was lesser variability among varieties in stem proportion in Trial 1 than in Trial 2. Araújo and Teixeira (2008) similarly reported that common bean cultivars differed in shoot mass at early crop growth stages. The LSR varied among varieties in Trial 1 (P=0.02) but not in Trial 2 (P=0.40). Varietal differences in LSR were reported by Asfaw and Blair (2014) in common bean harvested at the mid-pod filling crop growth stage. Differences among cultivars in leaf shedding at pod harvest (Larbi et al., 1999) and differences in crop growth stage at harvest between two trials may largely account for the effect of varieties on whole haulm yield in Trial 2 and LSR in Trial 1. Varieties Nasir, Dinknesh, H-Dume and SARI in Trial 1, and H-Dume and Ibado in Trial 2, had the highest seed, haulm and total biomass yields. These varieties were consistently the best across the two stages of harvest (Chapter 6, Table 6.3).

Haulm yield and quality parameters are important in evaluation of feed for ruminants since they determine animal output when haulm is fed as the sole diet (Prasad et al., 2010). The haulm quality differed among the varieties within each of the present trials. Differences in haulm quality might relate to variations among varieties in the LSR and the accumulation and lignification of cell wall contents.

N concentration of the whole haulm varied in Trial 1 (1.71-2.53%, mean 2.0%) and Trial 2 (1.25-1.74%, mean 1.53%) (Table 7.2) and were substantially greater than the minimum requirement (1.2 % N) necessary in the diet for adequate digestive activities of rumen microbes (Ørskov, 1991). The higher N concentration of the whole haulm in Trial 1 than in Trial 2 was associated with the later harvest in Trial 2. The leaf had higher N and DMD, but lower NDF and ADF concentrations, than the stem and pod wall fractions. This was in accord with other reports (Larbi et al., 1999; Njie and Reed, 1995; Pieltain et al., 1996) in common bean and groundnut. The N concentration of leaf and stem fractions in the early

harvest in the present study were similar to those reported by Pieltain et al. (1996). Although, the N content of pod wall of the current study was higher than that reported by these authors, this might be due to the differences in harvest time and varieties. Early harvest N concentration ranged from 1.53-2.0% in the whole haulms in the current study and these were higher than for the whole common bean haulm N values (1.07%) reported by López et al. (2005), but in later study the harvest was at seed maturity. The high N concentrations showed that haulm harvested at early crop growth stage could effectively provide supplemental N for ruminants offered low quality cereal straw based basal diets.

### 7.4.2. Variation in haulm nutrient yields

The lack of significant variation among varieties in stem N yield (kg/ha) in Trial 1 was associated with no discernible variation in stem yield (t/ha) (data not shown) and only small variation among varieties in stem N (range 0.52 percentage units). This contrasted with substantial variation in pod wall N (range 1.45 percentage units), leaf N (range 0.83 percentage units) and whole haulm N (range 0.82 percentage units) in Trial 2 (Table 7.4). The large range among cultivars in N yield (35.3-70.3 kg/ha in Trial 1 and 18.3-43.4 kg N/ha in Trial 2) and in DDM yield (1.36-2.17 t/ha in Trial 1 and 0.75-1.81 t/ha in Trial 2) suggested that use of the most appropriate varieties can double the N and DDM yields without compromising seed yield. The highest haulm N and DDM yielding varieties observed in both trials of the current study were also consistently the best when harvested at seed maturity (Chapter 6 Table 6.5). Although, choice of genotypes clearly depends on environmental factor site these results do indicate the improvement possible if the most appropriate genotypes can be identified for a specific environment.

### 7.4.3. Effect of crop growth stage at harvest on seed and haulm yields, morphological proportions and haulm quality

In general, there were higher yields of whole haulm and total biomass, but much lower yield of seed, at the earlier harvest than the final harvest. The earlier harvest material was of much higher nutritive values for ruminants for use as a supplement to N deficient cereal CR for the lactating or fattening animals. As the plant matured from early to final harvest the increase in seed yield, by 42% and 28% in Trial 1 and 2, respectively, was within the range reported by Borreani et al. (2006) in field pea as the plant matured from the end of flowering to beginning of ripening and where the contribution of the seed to the DM yield

was increased from 0 to 48%. Seeds attain maximum dry weight when they reach physiological maturity (Shaheb et al., 2015; Shaw and Loomis, 1950; Tekrony and Egli, 1997). In the current study leaf, pod wall and whole haulm yield generally decreased as the plant matured from early to final harvest. The yield decreases of the leaf and pod wall fractions with plant at maturity explain the decrease in whole haulm and total biomass yields in both trials (Table 7.5). The proportion of leaves in forage declines as the plant matures and the extent is more pronounced in food legumes than cereals (Batterham and Egan, 1987; Suttie, 2000).

Advancing maturity is well known to affect the composition and reduce the digestibility of forages (Albayrak et al., 2013; Amodu et al., 2001; Makkar et al., 1996; Thomson et al., 1990) and is usually associated with the reduction in LSR and lignifications. In this context Wilson and Kennedy (1996) concluded that it is the single most important factor impacting on the cell wall concentration and composition of forages during the plant maturation process. The differences observed between leaf-rich and stem-rich straws of legumes in general, and common bean in particular, confirm the importance of morphological composition of the legume CR to its nutritive value (López et al., 2005).

### 7.4.4. Relationships between yield, yield related attributes and haulm quality parameters

The strong positive correlations between whole haulm and seed yield in this study are in accord with the reports in common bean of Araújo and Teixeira (2008) that grain yield was correlated with shoot mass at pod filling crop growth stages. This suggests that haulm (harvested at early/pod filling crop growth stages) and seed yield characteristics may be combined in breeding programs for common bean varieties, and also that seed yield could be predicted from haulm measurements during the pod filling crop growth stage. The lack of a relationship between LSR with seed yield (r= 0.32) in Trial 2 and the weak relationship in Trial 1 of the current study, are in accord with the report of (Asfaw and Blair, 2014) also in common bean.

Negative correlations between fibre (NDF and ADF) contents and DMD were expected since higher fibre content is usually associated with reduced digestibility. No association existed between whole haulm total N content and DMD in either trial of the current study.

Larbi et al. (2010) also reported that the lack of relationship between CP and OMD in narbon vetch and in grass pea.

The lack of association between the haulm quality parameters and most yield related attributes suggested that it should be possible to select common bean varieties with higher seed yield for human food and also for higher green forage yields and better forage quality for ruminants when harvested at early crop growth stages.

### 7.5. Conclusion

There were differences among common bean varieties harvested at early seed maturity stage in leaf, stem, pod wall and whole haulm yields and quality. It can be concluded that whole haulm DMD harvested at early seed maturity depends on both stem digestibility and LSR. With crop maturity, the extent of leaf yield loss was greater than for other fractions. Early harvested whole CR had much higher nutritive values for ruminants than the final harvest CR, and should be valuable particularly as a supplement to N deficient cereal CR (e.g. maize stover) in ruminant diets. The current study also suggested that there is a need to evaluate common bean varieties in a number of sites and years and at various crop growth stages (flowering, pod filling and maturity). It is also recommended that plant breeders should if possible select genotypes with low leaf loss at crop maturity.

# Chapter 8 Agronomic practices and production of crop residues for ruminants: Farmers' perceptions and rationale for current practice in crop–livestock systems in Ethiopia

## 8.1. Introduction

Crop–livestock systems in SSA are socially, economically and technologically diverse due to the variety of agro-ecological conditions, population densities and economic opportunities (Cecchi et al., 2010; Williams et al., 2000). The Ethiopian highland crop-livestock systems are dominated by rain-fed low input/low output subsistence smallholder farms (Ayele and Bosire, 2011). Livestock are an integral part of these systems and crop residues (CR), especially straws and stovers, are an important feed resource for these livestock (Valbuena et al., 2012). Furthermore, the importance of CR is increasing in many regions due to decreasing access to grazing lands as cropping is expanded to meet increasing demands for human food (Delgado et al., 1999; Koralagama et al., 2008; Mekasha et al., 2014; Suttie, 2000). As by-products, CR provide fodder at low cost (Williams et al., 1997) and are particularly important during the dry season (Powell et al., 1996; Rufino et al., 2011; Zingore et al., 2011).

Various crop management practices have been recommended to improve the yield and quality of CR (Reddy et al., 2003). However, it is likely farmers will modify such recommended management practices to suit their own circumstances and needs. There is a paucity of information on farmers' perceptions and rationale for their management of maize and grain legume crops, and their use of agronomic practices such as improved varieties, seed rates and harvest practices, and the implications for CR yield and quality. Such perceptions are important to the introduction of sustainable farming techniques at the farm level (Wossink et al., 1997).

The present study was designed to: (1) explore farmer crop management practices in relation to CR yield and quality from maize and grain legume crops, (2) compare selected crop management practices recommended by researchers with those used by farmers in relation to yield and quality of CR, and (3) investigate the effects of crop management and socio-economic factors on production of grain and stover in smallholder maize-legume-livestock systems.

## 8.2. Methodology

### 8.2.1. Site descriptions

The study was conducted in three weredas/districts (Akaki, Shalla and Misrak-Badawacho) (Appendix, Figure A8.1) selected to represent contrasting crop-livestock systems with different challenges and opportunities for improved maize-legume and livestock integration. Shalla and Misrak-Badawacho (M-B) districts represented maize-common bean and livestock systems while Akaki district represented small cereals-chickpea and maize-livestock systems. These districts represented a gradient of agro-ecology (moisture availability) and productivity, increasing from a semi-arid extensive production system in Shalla to a sub-humid and semi-intensive production in M-B, and mid/highland and semi-intensive production in Akaki district.

Shalla district is part of West-Arsi zone in Oromia region, located in the Central Rift Valley, Ethiopia at 1500-2300 masl (a detailed description is given in Chapter 6). M-B district is part of Hadiya Zone of Southern Nations Nationalities and Peoples Regional State (SNNPRS), and is located 345 km south of Addis Ababa. The district is located between $7^0$ 9''- $8^0$15'N latitude and $37^0$ 5' - $40^0$ 00'E longitude (Kebede, 2016), is 1500-2500 masl and with annual rainfall of 801mm-1400mm (mean 1000 mm). There is a short rainy season from March to May and a main rainy season from June to October (Abera et al., 2016; Lijalem et al., 2016). The dominant soil types are sandy loam and clay loam (village level survey, 2014). Major crops are maize, teff and common bean followed by *ensete* (*Ensete ventricosum*) (false banana), coffee, spices, sugarcane and fruits.

Akaki district is located in *Finfine zuria* special zone of Oromia Regional State in central Ethiopia located between $8^0$33'-$8^0$57'N latitude and $38^0$43'-$38^0$50'E longitude. It lies 30km southeast of Addis Ababa at 2100-3000 masl and with mean annual rainfall of 1133 mm (800-1200 mm). The dominant soil type is a black vertisol (Abera and Kebede, 2013; Dadi et al., 2005). The main cropping season is from June to January and the dry season from February to May. The major rain-fed crops in main season are teff, chickpea, wheat, grass pea, lentil, fenugreek, maize and faba bean while the major irrigated crops are potato, cabbages, beet root/red beet, carrot, onion and maize. Cattle, sheep, goats and equines are the predominant livestock species across the three districts.

### 8.2.2. Survey approach and sampling techniques

The survey was based on focus group discussions at the village level followed by a household (HH) level survey in selected sites which used a multi-stage stratified random sampling technique. During stage 1, districts were selected purposively based on secondary data available in each district and discussions with experts. Participatory rural appraisal tools such as semi-structured interviews and focus group discussions (FGD) were used to understand the overall context of each crop-livestock system (village level survey). In stage 2, in consultation with local experts from district agricultural offices, all *kebeles* (the lowest administrative unit in the governmental structure) known for maize-legumes-livestock production were listed and sample *kebeles* (lowest administrative units in wereda/district) were then selected purposively. From each district, 4 *kebeles* were selected based on varying distance to agricultural and livestock markets. This was assumed to influence their crop management practices in relation to CR yield and quality and the degree of crop-livestock integration. Two *kebeles* from near to market (NEAR) and another two *kebeles* relatively far from market (FAR) were selected to ensure good representations. In the last stage, HH lists of the selected *kebeles* were obtained from the district offices and HH were then selected using a simple random sampling technique. The HH level survey used a structured questionnaire. The farm HH head was taken as the basic sample unit while the list of HH in the *kebeles* was taken as a sampling frame.

#### 8.2.2.1. Village level survey data collection

The village level survey was intended to develop an understanding of local knowledge on key aspects of the crop-livestock system through FGD on the types of crops grown, production seasons, crop agronomic and harvest practices in relation to CR yield and quality, and livestock management and perceptions. Two *kebeles* (one NEAR and one FAR) were selected in each district for the village level survey. Qualitative and quantitative information on group level perceptions and experiences was collected from the 6 *kebeles* over the three study districts (Table 8.1). Experienced farmers (both male and female) and local stakeholders, including agriculture officials with good local knowledge of crop and livestock production practices were interviewed. The discussion focused on check-lists developed with farmers. Key informant interviews and personal observations were also used to obtain a general understanding of the intended objectives of the farmers and an understanding of the crop-livestock system.

#### 8.2.2.2. Household (HH) level survey data collection

Four *kebeles* (two NEAR and two FAR) within each district (a total of 12 *kebeles*) were included in the HH level survey. There were 50 randomly selected respondents in each *kebele* resulting in a total of 200 HH per district and 600 HH across districts. The survey was approved by the School of Agriculture and Food Science, the University of Queensland Human Ethics committee (Approval ID: SAFS/H15/14).

Data were collected on: (i) the general socio-economic characteristics of the HH, (ii) the type of crops they had grown in 2014, (iii) crop agronomic practices (mainly input use such as variety, seed rate and harvest procedure) in relation to CR yield and quality,(iv) the volume of harvest of both grain and CR, (v) livestock production practices and (vi) farmers' perceptions and rationale for crop agronomic practices, harvest procedure, CR use and livestock production in the context of the crop-livestock system. Estimates of GY were consistent among farmers but reported CR yields were not. CR yield was therefore estimated from GY data by established conversion factors (Kossila, 1988; Lal, 2005; Tolera, 2007). The survey instrument was digitized using the Census and Survey Processing System (CSPro) software package for data collection while interviewing HH.

Table 8.1 Descriptions and number of HH that participated in the village level survey in 2014

| District | *Kebele* | Access to main market | Village | Village Altitude, (masl) | GPS co-ordinate | | Number of participant HH |
|---|---|---|---|---|---|---|---|
| | | | | | Latitude (N) | Longitude (E) | |
| Shalla | Awara Gama | NEAR | Awara Haro | 1696 | 7.281 | 38.447 | 10 |
| | Korbeti | FAR | Urji Dalecha | 1772 | 7.238 | 38.379 | 9 |
| M-B | Amburse Anjulo | NEAR | Gola-3 | 1944 | 7.139 | 37.978 | 8 |
| | Mehal Jarso | FAR | Mender-9 | 1932 | 7.126 | 37.899 | 8 |
| Akaki | Hechu | NEAR | Andode | 2087 | 8.848 | 38.768 | 9 |
| | Abu Lugna | FAR | Zoni-Tokofa | 1920 | 8.678 | 38.773 | 10 |
| Total | | | | | | | 54 |

*masl: Meters above sea level. GPS: Global Positioning System; N: North; E: East; HH: Household. Source: Village level survey (2014).*

### 8.2.3. Data analysis

Data were analysed using both descriptive and inferential procedures. The quantitative and qualitative data collected through the questionnaire were subjected to statistical analyses using IBM (2011) and with the Statistical Package for Social Sciences software (SPSS). Descriptive statistics and cross tabulations were employed to summarize data. Qualitative data were also presented in the form of a synthesis narrative. Multiple regression analyses were used to investigate cause and effect relationships between maize CR yield and intuitively and theoretically relevant explanatory variables. The explanatory variables for CR yield were grouped into socio-economic factors, crop management practices and infrastructural variables. Details of the explanatory variables used in the regression analysis along with their measurements are given in Table 8.2.

## 8.3. Results

### 8.3.1. Household socio-demographic characteristics

From the HH survey 7.9% of HH were female headed, and ranged from 6.4-9.3% across districts (Table 8.3). The mean family size was 7.1 (SD=2.9) with Shalla having the highest (8.1, SD=3.2) followed by M-B (7.6, SD=2.4) and Akaki (5.6, SD = 2.4). More than 83% and 66% of farmers had family sizes between 3-10 persons per HH and ≤35 years of age, respectively.

About 33% of the surveyed farmers were illiterate (no schooling) and nearly 45% had up to $6^{th}$ grade of school education. The proportion of farmers that engaged in on-farm and off-farm activities was higher in Akaki (65.0% and 9.8%) and M-B (60.0% and 9.6%) than in Shalla district (53% and 4.9%) respectively (Table 8.3).

Resource endowment, land sizes and livestock ownership were also analysed. The mean total owned land of the HH in 2014 cropping season ranged from 0-8.5 ha, with mean of 1.6 ha (SD = 1.3) per HH. The mean total owned land was higher in Shalla and Akaki than in M-B district (Table 8.4).

Table 8.2 Variables and their descriptions used for the linear regression model

| Variables | Description |
|---|---|
| *Scio-economic* | |
| Education | Formal and informal education received by the head of the household (years of schooling); |
| Maize farming experience | Number of years the farm family has been engaged in maize cultivation (measured in years); |
| Family size | Members in a farm family who share food from a single source (in number) |
| On farm activities | Whether the farm family work within the farm completely for sustaining livelihood; Yes=1; No=0 |
| Off farm activities | Whether the farm family earns wages from working in others' farms; Yes=1; No=0 |
| Farm land size | Size of the homestead owned and total cultivable land (ha) |
| Livestock holding | Number of owned total livestock with the farm family (in TLU) |
| Number of oxen | Number of owned oxen (castrated/uncastrated adult male cattle) with the farm family used for ploughing |
| *Crop management* | |
| Variety type | Adopter of improved maize varieties; Yes=1; No=0 |
| Seed rate | Total amount of maize seed used in cultivation plot (kg) |
| Fertilizer | Total amount of inorganic fertilizer used in maize cultivation plot (kg) |
| Pesticides | Total amount of active ingredient of plant protection chemicals used in maize cultivation plot (kg) |
| Labour | Total family and hired labour used for all operations related to maize cultivation (person-days) |
| *Infrastructural variables* | |
| Access to credit | Whether the farmer received credit for the last 5 years; Yes=1; No=0 |
| Distance to inputs market | Physical distance of farms to input market (travel time) |
| Distance to output market | Physical distance of farms to output market (travel time) |
| *Dependent variable* | |
| Crop residue yield | Total maize CR production (tonnes) |

Table 8.3 Socio-economic characteristics of sample households (%) in 2014

| Variables | District | | | Total |
|---|---|---|---|---|
| | Akaki | Shalla | M-B | |
| *Sex* | | | | |
| Male | 93.7 | 90.7 | 91.9 | 92.1 |
| Female | 6.4 | 9.3 | 8.2 | 7.9 |
| *Family Size* | | | | |
| <3 | 9.0 | 3.0 | 1.0 | 4.3 |
| 3-6 | 58.2 | 29.0 | 33.7 | 40.3 |
| 7-10 | 28.9 | 46.5 | 55.3 | 43.5 |
| >10 | 4.0 | 21.5 | 10.1 | 11.9 |
| *Age (Years)* | | | | |
| <18 | 45.0 | 61.0 | 55.0 | 53.7 |
| 18-35, | 35.0 | 27.0 | 30.0 | 30.7 |
| 36-50, | 13.0 | 9.2 | 12.0 | 11.4 |
| >50 | 7.2 | 2.5 | 3.7 | 4.5 |
| *Education (Years)* | | | | |
| Illiterate (0) | 32.0 | 41.0 | 26.0 | 33.0 |
| Up to 6 | 48.0 | 44.0 | 44.0 | 45.3 |
| 7-12 | 19.0 | 14.0 | 27.0 | 20.0 |
| >12 | 1.3 | 0.67 | 3.2 | 1.7 |
| Engaged in on-farm activity | | | | |
| No | 35.0 | 47.0 | 40.0 | 40.7 |
| Yes | 65.0 | 53.0 | 60.0 | 59.3 |
| Engaged in off-farm activity | | | | |
| No | 81.2 | 95.1 | 90.4 | 88.9 |
| Yes | 9.8 | 4.9 | 9.6 | 8.1 |
| Sample size | 201 | 200 | 199 | 600 |

*Source: HH level survey (2014).*

Table 8.4 Land holding of sample households (hectare) in the three districts in 2014

| | District | | | | | | Total | |
|---|---|---|---|---|---|---|---|---|
| | Akaki | | Shalla | M-B | | | | |
| Land category | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Total owned land | 1.9 | 1.4 | 2.1 | 1.4 | 0.9 | 0.6 | 1.6 | 1.3 |
| Total operated land | 2.8 | 2.2 | 2.5 | 1.5 | 1.2 | 2.7 | 2.1 | 2.3 |
| Total owned land 5 years ago | 1.9 | 1.4 | 2.1 | 1.3 | 0.9 | 0.6 | 1.6 | 1.3 |

*Total owned land = (Own land used + Rented/shared out land + Borrowed/Gifted out land in 2014); Total operated land = (Own land used + Rented/shared in land + Borrowed/Gifted in land in 2014); SD: Standard deviation. Source: HH level survey (2014).*

Cattle were the most widely kept ruminant followed by sheep and goats (Table 8.5). Cattle were kept by > 99% of farmers in 2014 and the number of local cattle owned by HH averaged 7.2 head (SD=4.8) per HH, with more in Shalla 9.7 (SD=6.3) than in M-B 4.8

(SD=2.2) district. There were few improved breed cattle (0.26 head/HH). The number of trained local oxen for ploughing per HH were about 2.0 head (SD=1.3) ranging from 1.2 head (SD=0.6) in M-B to 2.5 head (SD=1.5) in Akaki district.

Sheep were more common in Akaki and M-B than in Shalla district but goats were more common in Shalla (Table 8.5). More farmers (95.5%) in Shalla kept goats rather than sheep (18%) but the converse was true in M-B (33.2 versus 83.9% of HH) and Akaki (31.8 versus 78.6% of HH) districts. The proportion of farmers keeping equines (donkey, horses and mules) in Akaki district (94.0%) was higher than in Shalla (86.0%) and M-B (64.8%) districts.

Table 8.5 Livestock owned (TLU[#]) by the sample households in 2014

| Species | District | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Akaki | | Shalla | | M-B | | Total | |
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Local cattle | 7.00 | 3.60 | 9.70 | 6.30 | 4.80 | 2.20 | 7.20 | 4.80 |
| Improved cattle* | 0.12 | 0.44 | 0.07 | 0.34 | 0.58 | 1.30 | 0.26 | 0.84 |
| Sheep | 3.80 | 4.00 | 0.68 | 1.70 | 2.20 | 1.40 | 2.20 | 2.90 |
| Goats | 1.50 | 2.70 | 5.80 | 4.00 | 0.88 | 1.40 | 2.70 | 3.60 |
| Donkeys | 1.60 | 1.30 | 1.50 | 1.20 | 0.70 | 0.60 | 1.30 | 1.20 |
| Horses | 0.18 | 0.41 | 0.01 | 0.10 | 0.04 | 0.18 | 0.08 | 0.28 |
| Mules | 0.09 | 0.30 | 0.01 | 0.07 | 0.01 | 0.07 | 0.03 | 0.19 |

**Improved cattle are exotic breeds (Bos Taurus e.g. Holstein Friesian) and/or cross breed (Zebu x Bos taurus). [#]TLU (Tropical livestock unit- commonly an animal of 250 kg live-weight in Tropical Africa) conversion factors: Cattle=0.7, Sheep=0.1, Goats=0.1, Donkeys=0.5, Horses=0.8, and mules=0.7 (Jahnke, 1982). Source: HH level survey (2014).*

The surveyed farmers had on average 17.8, 17.6 and 20.3 years of experience with maize, legume and livestock production, respectively, across the three districts (Table 8.6). Although, maize farming experience in Akaki (14.0 years) and the legume farming experience (11.7 years) in Shalla district were lowest among the districts.

Table 8.6 Farming experiences (in years) of sample households in 2014

| Experience | District | | | | | | Total | |
|---|---|---|---|---|---|---|---|---|
| | Akaki | | Shalla | | M-B | | | |
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Maize cropping | 14.0 | 13.5 | 18.6 | 9.9 | 20.9 | 10.4 | 17.8 | 11.7 |
| Legume cropping | 21.4 | 12.3 | 11.7 | 5.1 | 19.8 | 10.2 | 17.6 | 10.6 |
| Livestock production | 22.6 | 12.4 | 17.9 | 10.0 | 20.3 | 10.6 | 20.3 | 11.2 |

*Source: HH level survey (2014).*

### 8.3.2. Cropping seasons and type of crops grown in the study areas

Based on the FGD, generally there are two cropping seasons in Shalla and M-B districts known as Belg (short) season and Meher (main) season. The short season is generally from mid-January to May but in some localities of Shalla district this season is from mid-March to mid-June. The main season cropping season is from mid-April to October in Shalla and from June to October in M-B district. In addition to the main season about 48 and 95% of the HH in Shalla and M-B districts cultivate in the short season, respectively. There is one main rain-fed cropping season in Akaki district from June to January and only 11% of the interviewed HH also cultivate in the short-rain season. There is also irrigation cropping in some localities of the NEAR villages in Akaki district mostly for vegetable production. Based on HH survey 2014 data the most HH (89.5% and 85%) in Shalla district grew maize and common bean respectively in the main season. However, in M-B districts most HH (54% and 42%) cultivate maize and common bean crops, respectively in the short-rain season. About 37% of the HH in shalla district also grew common bean in the 2014 short-rain season (Table 8.7).

Table 8.7 Proportion (%) of farmers growing cereal and grain legume crops in 2014

| Crop | Main season | | | | Short season | | | |
|---|---|---|---|---|---|---|---|---|
| | Akaki | Shalla | M-B | Total | Akaki | Shalla | M-B | Total |
| Maize | 39.8 | 89.5 | 14.6 | 48.0 | 0.5 | 5.5 | 53.8 | 19.8 |
| Sorghum | 0.0 | 2.5 | 3.0 | 1.8 | 0.0 | 0.0 | 0.5 | 0.2 |
| Teff | 91.0 | 14.5 | 77.9 | 61.2 | 0.0 | 10.0 | 12.6 | 7.5 |
| Wheat | 77.6 | 0.5 | 0.0 | 26.2 | 0.0 | 0.0 | 0.5 | 0.2 |
| Common bean | 0.5 | 85.0 | 23.6 | 36.3 | 0.0 | 37.0 | 41.7 | 26.2 |
| Chickpea | 85.1 | 0.0 | 6.5 | 30.7 | 1.0 | 0.0 | 1.0 | 0.7 |
| Faba bean | 5.5 | 0.0 | 0.0 | 1.8 | 0.0 | 0.0 | 0.0 | 0.0 |
| Lentil | 28.9 | 0.0 | 0.0 | 9.7 | 0.0 | 0.0 | 0.0 | 0.0 |

*Source: HH level survey (2014).*

In Akaki district teff is grown by most farmers (91%) in main season, followed by wheat (78%) and maize (40%). Among grain legumes chickpea is the most important crop (85% of HH) followed by lentil (29%) in 2014 main season in Akaki.

### 8.3.3. Adoption of improved varieties, and farmers' perceptions and rationale

Based on the HH survey almost all farmers (> 98%) in M-B and Shalla used improved maize varieties, but in Akaki district only 31% (Table 8.8). The major improved maize varieties grown by farmers in Shalla district were BH-543, Limu, BH-540, Javi (Pioneer-3253), Melkasa-2, MH-130 and Shone in Shalla district and Javi (Pioneer-3253), BH-540, Limu and Shone varieties in M-B district. The other introduced maize varieties in Shalla district were MH-138, MH-145, MH-146 and Abaraya but they were not popular.

There was also high adoption of improved common bean varieties in Shalla (94.5%) and in M-B (79.9%), but low adoption (0.5%) in Akaki district. The improved common bean varieties often used were Nasir, Dinkinesh, Red Wolayita, Ibado, Deme, Mexican, Awash-I and Awash-Melka in Shalla district, and Nassir, Red Wolaita and Ibado in M-B district. In contrast, the highest adoption of chickpea varieties was in Akaki (80.1%) while adoption was low in Shalla (0%) and M-B (7.5%) districts (Table 8.8). The improved chickpea varieties in Akaki district were Arerti and Shallo.

Table 8.8 Proportion (%) of farmers that have adopted improved varieties of main cereal and legume crops in 2014

| | District | | | |
|---|---|---|---|---|
| Crop | Akaki | Shalla | M-B | Total |
| Maize | 31.3 | 98.5 | 100 | 76.5 |
| Teff | 86.1 | 19.5 | 91.5 | 65.7 |
| Common bean | 0.5 | 94.5 | 79.9 | 58.2 |
| Chickpea | 80.1 | 0.0 | 7.5 | 29.3 |

*Source: HH level survey (2014).*

A very high proportion of farmers (> 88% in each of the districts) perceived that CR yield and quality were important and influenced decisions in accepting or rejecting new crop varieties (Table 8.9).

Table 8.9 Proportion (%) of farmers that perceived CR quantity/quality is essential to accept or reject new crop varieties in 2014

| | District | | | |
|---|---|---|---|---|
| Perception | Akaki | Shalla | M-B | Total |
| Strongly agree | 22.4 | 16.0 | 14.1 | 17.5 |
| Agree | 66.2 | 75.0 | 77.9 | 73.0 |
| Neither agree nor disagree | 9.0 | 9.0 | 7.0 | 8.3 |
| Disagree | 2.5 | 0.0 | 1.0 | 1.2 |
| Total | 100 | 100 | 100 | 100 |

*Source: HH level survey (2014).*

### 8.3.4. Seed rate used, and farmers' perceptions and rationale

Based on the HH survey wide ranges of seed rates were used for maize, common bean and chickpea by farmers (Table 8.10). A higher maize mean seed rate was used in Akaki (mean 53 kg/ha) than Shalla (26 kg/ha) and M-B district (26 kg/ha) but the range was wider in Shalla (13-72 kg/ha) than in M-B district (24-36 kg/ha) (Table 8.10).

Farmers were asked about their perceptions of the important factors affecting the amount of seed used for the major cereals and grain legumes grown. About 93.5, 86.7 and 86.2% responded that they adjust the recommended seed rate depending up on the type of variety, environment and crop management factors respectively (Table 8.11).

Table 8.10 Mean and standard deviation (SD) of seed rate (kg/ha) of maize and major grain legume crops in 2014

| | District | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Akaki | | Shalla | | M-B | | Total | |
| Crop | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Maize | 53.0 | 29.0 | 26.0 | 4.10 | 26.0 | 2.70 | 33.0 | 20.0 |
| Common bean | 112.0 | - | 98.0 | 9.80 | 105.0 | 12.0 | 99.0 | 11.0 |
| Chickpea | 113.0 | 14.0 | - | - | 104.0 | 6.2 | 113.0 | 14.0 |

*Source: HH level survey (2014).*

Table 8.11 Sample farmers (%) opinion on factors affecting seed rate of maize and/or grain legumes in 2014

| | District | | | |
|---|---|---|---|---|
| Perceptions | Akaki | Shalla | M-B | Total |
| Seed rate depends on the type of variety | | | | |
| Strongly agree | 18.9 | 19.5 | 17.1 | 18.5 |
| Agree | 68.7 | 76.5 | 79.9 | 75.0 |
| Neither agree nor disagree | 5.0 | 2.5 | 0.5 | 2.7 |
| Disagree | 6.5 | 1.5 | 2.5 | 3.5 |
| Not applicable | 1.0 | 0.0 | 0.0 | 0.3 |
| Total | 100 | 100 | 100 | 100 |
| Seed rate depends on environment | | | | |
| Strongly agree | 10.4 | 16.5 | 17.1 | 14.7 |
| Agree | 71.1 | 71.0 | 73.9 | 72.0 |
| Neither agree nor disagree | 10.4 | 11.5 | 7.0 | 9.7 |
| Disagree | 7.0 | 1.0 | 2.0 | 3.3 |
| Not applicable | 1.0 | 0.0 | 0.0 | 0.3 |
| Total | 100 | 100 | 100 | 100 |
| Seed rate depends on crop management | | | | |
| Strongly agree | 10.9 | 15.5 | 13.1 | 13.2 |
| Agree | 65.2 | 74.0 | 79.9 | 73.0 |
| Neither agree nor disagree | 12.4 | 9.0 | 5.5 | 9.0 |
| Disagree | 11.4 | 1.0 | 1.5 | 4.7 |
| Not applicable | 0.0 | 0.5 | 0.0 | 0.2 |
| Total | 100 | 100 | 100 | 100 |

*Source: HH level survey (2014).*

#### 8.3.4.1. The relationship between seed rate used and grain and residue yields

About 91.2% and 84.5% of the HH across the three districts perceived that maize grain yield will decrease if the seed rate used is lower or higher, respectively, than that recommended (Table 8.12). Similarly, 91.3% and 95.0% of the HH across the three districts perceived that grain legume seed yield will decrease if the seed rate used is lower and higher than the recommended rates, respectively (Table 8.12).

Table 8.12 The proportion (%) of farmers' who perceived that there are relationships between seed rate used and yield of maize and grain legumes in 2014

| Perceptions | District | | | Total |
|---|---|---|---|---|
| | Akaki | Shalla | M-B | |
| If lower seed rate used than the recommended-maize grain yield | | | | |
| No change | 1.5 | 1.0 | 2.0 | 1.5 |
| Increase | 5.0 | 9.5 | 7.5 | 7.3 |
| Decrease | 93.5 | 89.5 | 90.5 | 91.2 |
| Total | 100 | 100 | 100 | 100 |
| If higher seed rate used than the recommended-maize grain yield | | | | |
| No change | 15.4 | 6.0 | 12.6 | 11.3 |
| Increase | 8.0 | 1.5 | 3.0 | 4.2 |
| Decrease | 76.6 | 92.5 | 84.4 | 84.5 |
| Total | 100 | 100 | 100 | 100 |
| If lower seed rate used than the recommended-legume seed yield | | | | |
| No change | 0.0 | 2.5 | 0.0 | 0.8 |
| Increase | 6.5 | 10.0 | 7.0 | 7.8 |
| Decrease | 93.5 | 87.5 | 93.0 | 91.3 |
| Total | 100 | 100 | 100 | 100 |
| If higher seed rate used than the recommended-legume seed yield | | | | |
| No change | 1.5 | 1.0 | 0.0 | 0.8 |
| Increase | 8.0 | 0.0 | 4.5 | 4.2 |
| Decrease | 90.5 | 99.0 | 95.5 | 95.0 |
| Total | 100 | 100 | 100 | 100 |

*Source: HH level survey (2014).*

About 93% of farmers across districts perceived that using a lower seed rate than that recommended will decrease CR yields of both maize and grain legumes (Table 8.13). Also, 77.5% and 72.0% perceived that a higher seed rate will increase the CR yields of maize and grain legumes, and 19.7% and 25.3% perceived that the CR yields of maize and grain legumes will decrease if higher seed rate used than that recommended (Table 8.13).

Table 8.13 Proportion (%) of sample farmers' who perceived that there are relationships between seed rate used and the yields of maize and grain legume residue produced in 2014

| | District | | | |
|---|---|---|---|---|
| Perceptions | Akaki | Shalla | M-B | Total |
| If lower seed rate used than the recommended-maize residue yield | | | | |
| No change | 1.5 | 3.0 | 0.0 | 1.5 |
| Increase | 3.0 | 8.0 | 4.5 | 5.2 |
| Decrease | 95.5 | 89.0 | 95.5 | 93.3 |
| Total | 100 | 100 | 100 | 100 |
| If higher seed rate used than the recommended-maize residue yield | | | | |
| No change | 4.0 | 2.5 | 2.0 | 2.8 |
| Increase | 76.1 | 79.0 | 77.4 | 77.5 |
| Decrease | 19.9 | 18.5 | 20.6 | 19.7 |
| Total | 100 | 100 | 100 | 100 |
| If lower seed rate used than the recommended-legume residue yield | | | | |
| No change | 1.0 | 3.0 | 0.0 | 1.3 |
| Increase | 3.0 | 9.0 | 5.0 | 5.7 |
| Decrease | 96.0 | 88.0 | 95.0 | 93.0 |
| Total | 100 | 100 | 100 | 100 |
| If higher seed rate used than the recommended-legume residue yield | | | | |
| No change | 4.0 | 1.5 | 2.5 | 2.7 |
| Increase | 71.1 | 72.5 | 72.4 | 72.0 |
| Decrease | 24.9 | 26.0 | 25.1 | 25.3 |
| Total | 100 | 100 | 100 | 100 |

*Source: HH level survey (2014).*

#### 8.3.4.2. The relationship between seed rate used and residue quality as feedstuffs

About 62.2% and 58.7% of the HH across districts perceived that using a lower seed rate than that recommended will decrease the quality of CR of maize and grain legumes respectively while 30.7% and 32.7% of them perceived CR quality of maize and grain legumes, respectively, will increase (Table 8.14). If a higher seed rate is used than that recommended, 55.3% and 51.8% of the HH thought that maize and grain legumes CR quality will increase, respectively, and 36.0% and 35.0% perceived that maize and grain legumes CR quality will decrease, respectively (Table 8.14).

Table 8.14 The proportion (%) of farmers' who perceived that there are relationships between the seed rate used and maize and grain legume residue quality in 2014

| | District | | | |
|---|---|---|---|---|
| Perceptions | Akaki | Shalla | M-B | Total |
| If lower seed rate used than the recommended-maize residue quality | | | | |
| No change | 8.5 | 7.0 | 6.0 | 7.2 |
| Increase | 25.9 | 34.0 | 32.2 | 30.7 |
| Decrease | 65.7 | 59.0 | 61.8 | 62.2 |
| Total | 100 | 100 | 100 | 100 |
| If higher seed rate used than the recommended-maize residue quality | | | | |
| No change | 8.5 | 2.5 | 15.1 | 8.7 |
| Increase | 56.2 | 63.0 | 46.7 | 55.3 |
| Decrease | 35.3 | 34.5 | 38.2 | 36.0 |
| Total | 100 | 100 | 100 | 100 |
| If lower seed rate used than the recommended-legume residue quality | | | | |
| No change | 9.5 | 8.5 | 8.0 | 8.7 |
| Increase | 24.4 | 35.5 | 38.2 | 32.7 |
| Decrease | 66.2 | 56.0 | 53.8 | 58.7 |
| Total | 100 | 100 | 100 | 100 |
| If higher seed rate used than the recommended-legume residue quality | | | | |
| No change | 10.0 | 6.5 | 23.1 | 13.2 |
| Increase | 54.2 | 58.5 | 42.7 | 51.8 |
| Decrease | 35.8 | 35.0 | 34.2 | 35.0 |
| Total | 100 | 100 | 100 | 100 |

*Source: HH level survey (2014).*

### 8.3.5. Maize pre-harvest practices and farmers' perceptions/rationale

In the present context, the term crop pre-harvest practice refers to crop thinning, leaf stripping, partial harvest or total harvest of the crop during vegetative growth as fodder for livestock. This was usually practiced in maize and sorghum crops but also occasionally in other crops. Maize thinning (when it was at the knee-height at about 50 cm) stage of crop growth and during weeding (*Shilshalo* time) and leaf stripping were often practiced by some farmers to use the fodder for livestock in the study districts. Farmers in M-B district practiced leaf stripping of the bottom part of maize plants below the first ear.

About 17, 52 and 26.6% of farmers in Akaki, Shalla and M-B districts, respectively, pre-harvested maize for fodder in the main season. About 5.5% and 32.7% of the farmers in Shalla and M-B districts, respectively and no farmers in Akaki practiced pre-harvesting of maize for fodder in 2014 short season (Table 8.15).

Based on the FGD, cutting the maize stover just above the uppermost ear a few weeks earlier than grain harvest maturity and use of this as fodder for livestock is also a common practice in Shalla and M-B districts. This is usually called ‘de-tasseling”. In this practice the entire plots of maize may be harvested in this manner. Up to 90 % of farmers in Shalla and 50-70% of farmers in M-B district used this practice in 2014.

Table 8.15 Proportion (%) of sample farmers’ practicing various pre-harvest practices in maize for fodder at early crop growth stage in 2014

| Pre-harvest | Main season | | | | Short season | | | |
|---|---|---|---|---|---|---|---|---|
| Practices | Akaki | Shalla | M-B | Total | Akaki | Shalla | M-B | Total |
| Leaf stripping | 7.0 | 21.0 | 7.5 | 11.8 | 0.0 | 1.5 | 16.6 | 6.0 |
| Thinning | 8.0 | 25.5 | 17.6 | 17.0 | 0.0 | 3.0 | 12.6 | 5.2 |
| Partial harvest | 1.0 | 5.5 | 1.5 | 2.7 | 0.0 | 0.5 | 2.5 | 1.0 |
| Total harvest | 1.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.5 | 1.0 | 0.5 |

*Source: HH level survey (2014).*

### 8.3.6. Early-harvest practices, and farmers’ perceptions and rationale in relation to residue availability and use

A common practice is to harvest maize and/or grain legumes early at [(Kernel milk stage (R3) to dough stage (R4) in maize (Nielsen, 2016)), (from R6 to R7 stage in common bean (Schwartz and Langham, 2016) and at leaf colour change and before leaf shatter in chickpea]. This is locally known as *Eshet* for home consumption and/or sale. In both Shalla and M-B districts, the major crops harvested at *Eshet* are maize and common bean and this was done by about 20 and 15% of farmers respectively (Table 8.16). In Akaki district the major crops harvested at *Eshet* were Kabuli chickpea (ca 14 % of farmers), maize (ca 9 %) and Desi chickpea (ca 4%) (Table 8.16).

Farmers (35.3%) in Shalla harvested up to 25% of their maize and/or common bean plots in 2014 (Table 8.16) mainly for home consumption (32.2% of the farmers) followed by both for sale and home consumption (2.1%) and sale only (1.2%). The green residue was mainly used as livestock fodder (35.3% of the farmers) (Table 8.16). In Akaki and M-B districts, about 28.9% and 36.6% of farmers respectively used from <5% to all (100%) of their maize and/or grain legume plots for *Eshet* in 2014 and mainly for home consumption (20.3 and 30.3% of farmers) followed by both for sale and home consumption (5.9% and 4.0%) and for sale only (1.9 and 2.3%) respectively (Table 8.16).

The green residue from maize and common bean in M-B district (36.5% of the farmers) and from maize and/or grain legumes (15.8%) in Akaki district were mainly used as good quality feedstuffs which are especially suitable for lactating cows and fattening. However, 12.1% of the interviewed farmers in Akaki district wasted the green residue from chickpea during 2014 (Table 8.16).

Table 8.16 The proportion (%) of farmers' practiced early harvest practices in various crops for *Eshet* in 2014

| | District | | | |
|---|---|---|---|---|
| Crops for *Eshet* | Akaki | Shalla | M-B | Total |
| Maize | 8.7 | 20.5 | 20.6 | 16.6 |
| Haricot bean | 0.1 | 14.8 | 14.6 | 9.8 |
| Kabuli Chickpea | 13.8 | 0.1 | 1.1 | 5.0 |
| Desi Chickpea | 4.4 | 0.0 | 0.1 | 1.5 |
| Faba bean | 0.5 | 0.0 | 0.0 | 0.2 |
| Other crops | 0.8 | 0.1 | 0.2 | 0.4 |
| Proportion harvested per plot | | | | |
| <5% | 8.2 | 11.9 | 8.4 | 9.5 |
| 5-10% | 5.3 | 17.7 | 10.7 | 11.2 |
| 11-25% | 5.3 | 4.7 | 6.0 | 5.3 |
| 26-50% | 4.0 | 0.4 | 5.2 | 3.2 |
| 51-75% | 1.7 | 0.1 | 3.8 | 1.9 |
| Whole plot | 3.9 | 0.7 | 2.3 | 2.3 |
| Purpose of early harvest | | | | |
| For sale | 1.9 | 1.2 | 2.3 | 1.8 |
| For home consumption | 20.3 | 32.2 | 30.3 | 27.6 |
| Both for sale and home consumption | 5.9 | 2.1 | 4.0 | 4.0 |
| Gift | 0.2 | 0.0 | 0.0 | 0.1 |
| Green fodder utilization practices | | | | |
| Livestock feed | 15.8 | 35.3 | 36.5 | 29.2 |
| Return to the farm plot | 0.2 | 0.1 | 0.0 | 0.1 |
| Sale as green fodder | 0.1 | 0.0 | 0.0 | 0.0 |
| Waste | 12.1 | 0.1 | 0.1 | 4.1 |

*Source: HH level survey (2014).*

FGD indicated that choice of maize varieties for *Eshet* is important even though all common bean varieties can be harvested at *Eshet.* The harvest was mainly used for home consumption. The variety of chickpea is important and most of the *Eshet* is produced for sale in Akaki district. Green chickpea vegetable production in NEAR villages is from September to January in black soils (Vertisols) using residual moisture, and/or from August to October in light soils during the main season. Up to 30% of the farmers reported growing chickpea during the latter season specifically for sale as *Eshet* and farmers may

uproot and sell their entire chickpea crop. However, in FAR villages chickpea production was only from July to October. Some farmers (ca. 10 % of HH) uproot 25 % of their chickpea plot and sell as vegetables.

### 8.3.7. Maize and grain legumes maturity stage at harvest and farmers' perceptions

Survey data (Table 8.17) indicated that common bean and chickpea were usually harvested in a timely manner at seed maturity but maize was often harvested after grain maturity. The majority of interviewed farmers (93.5%) in M-B district harvested the maize plot in a timely fashion at maturity, but most (81.7 and 52.2%) in Shalla and Akaki districts, respectively did not harvest maize timely in 2014 (Table 8.18). Farmers intentionally left the maize plant for 1-4 weeks after maturity for the grain to dry completely before harvest during the main season in Shalla. In contrast, farmers in some *kebelles* of Shalla district reported that during the short rain season the maize was harvested immediately at maturity. For instance about 5.1% of the farmers in Shalla district harvested the maize plant during the 3-4 weeks after the grain maturity of the crop (Table 8.18).

Table 8.17 The proportion (%) of farmers' who harvested the crop timely at grain maturity in maize and grain legume crops in 2014

| | District | | | |
|---|---|---|---|---|
| Crops | Akaki | Shalla | M-B | Total |
| Maize | 48.8 | 18.3 | 93.5 | 53.5 |
| Common bean | 0.5 | 93.0 | 80.4 | 57.8 |
| Kabuli Chickpea | 68.2 | 0.0 | 7.0 | 25.2 |
| Desi Chickpea | 18.9 | 0.0 | 1.0 | 6.7 |

*Source: HH level survey (2014).*

Table 8.18 Proportion (%) of sample farmers practicing delayed harvest after grain maturity in maize crop in 2014

| | | District | | | |
|---|---|---|---|---|---|
| Crop | How long the crop stayed in the field? | Akaki | Shalla | M-B | Total |
| Maize | Up to 1 week | 14.6 | 4.1 | 2.0 | 6.9 |
| | 1 to 2 weeks | 30.5 | 23.9 | 2.5 | 19.0 |
| | 2 to 3 weeks | 6.1 | 48.2 | 1.0 | 18.4 |
| | 3 to 4 weeks | 0.0 | 5.1 | 0.0 | 1.7 |
| | > 4 weeks | 0.0 | 0.5 | 0.0 | 0.2 |

*Source: HH level survey (2014).*

In Akaki district, depending on labour availability, chickpea may be left in the field for 1-4 weeks before harvest. Common bean is usually harvested in a timely manner to avoid shattering and rain damage regardless of the cropping sequence.

Table 8.19 Farmers' perceptions (%) on the influence of crop maturity at harvest on CR yield and quality in 2014

| | District | | | |
|---|---|---|---|---|
| Perceptions | Akaki | Shalla | M-B | Total |
| Crop maturity stage at harvest affect CR yield and/or quality | | | | |
| Strongly agree | 27.4 | 23.5 | 22.6 | 24.5 |
| Agree | 70.1 | 73.5 | 76.9 | 73.5 |
| Neither agree nor disagree | 0.5 | 1.0 | 0.5 | 0.7 |
| Disagree | 0.5 | 2.0 | 0.0 | 0.8 |
| Strongly disagree | 1.0 | 0.0 | 0.0 | 0.3 |
| Not applicable | 0.5 | 0.0 | 0.0 | 0.2 |
| Total | 100 | 100 | 100 | 100 |

*Source: HH level survey (2014).*

Table 8.20 Farmers' perceptions (%) on the relationships between maize and grain legume maturity stage at harvest and grain yield and quality in 2014

| | District | | | |
|---|---|---|---|---|
| Perceptions | Akaki | Shalla | M-B | Total |
| If crop harvested after maturity-maize grain yield | | | | |
| No change | 66.2 | 57.5 | 68.3 | 64.0 |
| Increase | 11.4 | 35.0 | 18.6 | 21.7 |
| Decrease | 22.4 | 7.5 | 13.1 | 14.3 |
| Total | 100 | 100 | 100 | 100 |
| If crop harvested after maturity-maize grain quality | | | | |
| No change | 47.3 | 20.0 | 39.2 | 35.5 |
| Increase | 29.4 | 73.5 | 51.8 | 51.5 |
| Decrease | 23.4 | 6.5 | 9.0 | 13.0 |
| Total | 100 | 100 | 100 | 100 |
| If crop harvested after maturity-legume seed yield | | | | |
| No change | 2.0 | 0.5 | 0.5 | 1.0 |
| Increase | 4.5 | 2.0 | 2.5 | 3.0 |
| Decrease | 93.5 | 97.5 | 97.0 | 96.0 |
| Total | 100 | 100 | 100 | 100 |
| If crop harvested after maturity-legume seed quality | | | | |
| No change | 4.0 | 3.5 | 1.5 | 3.0 |
| Increase | 6.5 | 3.0 | 3.5 | 4.3 |
| Decrease | 89.6 | 93.5 | 95.0 | 92.7 |
| Total | 100 | 100 | 100 | 100 |

*Source: HH level survey (2014).*

Farmers were asked for their perceptions of the importance of crop maturity at harvest on CR yield and/or quality (Table 8.19) and whether delaying harvest after maturity affected maize GY and quality (Table 8.20) and residue yield and quality (Table 8.21). The majority of famers (98%) perceived that crop maturity at harvest does critically affect CR yield and quality (Table 8.19).

Table 8.21 Farmers' perceptions (%) on the relationships between maize and grain legume maturity stage at harvest and residue yield and quality in 2014

| Perceptions | District | | | Total |
|---|---|---|---|---|
| | Akaki | Shalla | M-B | |
| If crop harvested after maturity-maize residue yield | | | | |
| No change | 7.5 | 5.0 | 4.5 | 5.7 |
| Increase | 5.5 | 3.0 | 3.5 | 4.0 |
| Decrease | 87.1 | 92.0 | 92.0 | 90.3 |
| Total | 100 | 100 | 100 | 100 |
| If crop harvested after maturity-maize residue quality | | | | |
| No change | 8.5 | 3.5 | 2.5 | 4.8 |
| Increase | 5.5 | 8.0 | 4.5 | 6.0 |
| Decrease | 86.1 | 88.5 | 93.0 | 89.2 |
| Total | 100 | 100 | 100 | 100 |
| If crop harvested after maturity-legume residue yield | | | | |
| No change | 5.5 | 3.0 | 4.0 | 4.2 |
| Increase | 5.0 | 2.0 | 3.0 | 3.3 |
| Decrease | 89.6 | 95.0 | 93.0 | 92.5 |
| Total | 100 | 100 | 100 | 100 |
| If crop harvested after maturity-legume residue quality | | | | |
| No change | 6.5 | 5.0 | 2.5 | 4.7 |
| Increase | 4.5 | 7.0 | 4.5 | 5.3 |
| Decrease | 89.1 | 88.0 | 93.0 | 90.0 |
| Total | 100 | 100 | 100 | 100 |

*Source: HH level survey (2014).*

### 8.3.8. Crop cutting height at harvest and CR management practices

During FGD farmers were asked about the practices of crop cutting height at harvest. Farmers in Shalla district usually cut maize, teff and finger millet just above the ground but uproot common bean at final harvest. In M-B district maize and common bean are usually uprooted at or after seed maturity for final harvest. In Akaki district chickpea harvested at the *Eshet* stage is usually uprooted but when harvested at seed maturity the plant is more often cut just above the ground (mainly Arerti variety). In this district other crops are usually cut just above the ground. High cutting height of maize (2 internodes below the first ear) was reported in the FAR village in Akaki. The HH level survey data showed that in contrast to other districts, about 84% of farmers in M-B district uproot maize at or after maturity at harvest. About 23.9, 66.0 and 91.9% of farmers practiced low cutting height while 16.9, 32.5 and 8.0% practiced higher cutting height of maize in Akaki, Shalla and M-B districts respectively (Table 8.22).

Table 8.22 Proportion (%) of sample farmers' practicing cutting at different height at harvest in 2014

| Crop | Cutting height at harvest | District | | | Total |
|---|---|---|---|---|---|
| | | Akaki | Shalla | M-B | |
| Maize | Uprooting (low) | 1.5 | 0.5 | 83.9 | 28.5 |
| | Cut just above the ground (low) | 22.4 | 65.5 | 8.0 | 32.0 |
| | Cut 1 or 2 internodes below the ear | 13.4 | 29.0 | 8.0 | 16.8 |
| | Cut 3 internodes below the ear | 3.5 | 3.5 | 0.0 | 2.3 |
| Common been | Uprooting (low) | 0.5 | 91.0 | 79.9 | 57.0 |
| | Cut just above the ground (low) | 0.0 | 3.5 | 0.0 | 1.2 |

*Source: HH level survey (2014).*

### 8.3.9. Farmers' perceptions on CR management and use

About 93.0% of HH agreed that the incorporation of CR improves soil quality and this was evenly distributed across the three districts (Table 8.23). About 67.7% of the HH perceived that CR should be left on the field before the next tillage while 23.8% perceived that no CR should be left on the field. There was strong agreement (on average 94.8%) across the districts that CR are a vital feed source for livestock. About 76.1% perceived that it is better to feed CR to their livestock than leave it on the soil. Only a minority of farmers (27.3%) considered that the CR left in the field should be open for use by everybody in the village (Table 8.23).

### 8.3.10. Farmers' perceptions on livestock and crop-livestock integration

The majority of farmers (95.9%) perceived that manure from livestock is an essential input for crop production and also 99% considered that livestock are vital for cropping and transport. The majority of farmers (92.6%) did not have enough land to grow green fodder for their livestock and 91.8% considered that a shortage of feedstuffs was a major constraint to their farming (Table 8.24). Also the majority (99.2%) of farmers considered that a major constraint for keeping productive animals is effective and adequate livestock marketing (Table 8.24).

Table 8.23 Proportion (%) of farmers' perceived on crop residue management and use in 2014

| Perceptions | District | | | Total |
|---|---|---|---|---|
| | Akaki | Shalla | M-B | |
| Incorporation of CR improves soil quality | | | | |
| Strongly agree | 16.9 | 20.0 | 16.6 | 17.8 |
| Agree | 75.1 | 72.5 | 77.9 | 75.2 |
| Neither agree nor disagree | 5.5 | 6.5 | 4.5 | 5.5 |
| Disagree | 2.5 | 1.0 | 1.0 | 1.5 |
| Total | 100 | 100 | 100 | 100 |
| No CR should be left on field before next tillage | | | | |
| Strongly agree | 1.0 | 2.0 | 3.0 | 2.0 |
| Agree | 18.4 | 21.0 | 26.1 | 21.8 |
| Neither agree nor disagree | 10.0 | 9.5 | 6.0 | 8.5 |
| Disagree | 62.7 | 60.0 | 59.3 | 60.7 |
| Strongly disagree | 8.0 | 7.5 | 5.5 | 7.0 |
| Total | 100 | 100 | 100 | 100 |
| CR is a vital feed source for my livestock | | | | |
| Strongly agree | 48.8 | 37.0 | 37.2 | 41.0 |
| Agree | 46.3 | 58.0 | 57.3 | 53.8 |
| Neither agree nor disagree | 2.5 | 0.5 | 0.5 | 1.2 |
| Disagree | 2.0 | 3.5 | 3.5 | 3.0 |
| Strongly disagree | 0.0 | 0.0 | 0.5 | 0.2 |
| Not applicable | 0.5 | 1.0 | 1.0 | 0.8 |
| Total | 100 | 100 | 100 | 100 |
| Better to feed CR to my livestock than leave it on soil | | | | |
| Strongly agree | 23.9 | 13.0 | 10.6 | 15.8 |
| Agree | 56.2 | 58.5 | 66.3 | 60.3 |
| Neither agree nor disagree | 7.5 | 14.0 | 8.0 | 9.8 |
| Disagree | 11.4 | 13.0 | 14.6 | 13.0 |
| Strongly disagree | 0.5 | 0.5 | 0.0 | 0.3 |
| Not applicable | 0.5 | 1.0 | 0.5 | 0.7 |
| Total | 100 | 100 | 100 | 100 |
| CR in field should be open for use by everybody | | | | |
| Strongly agree | 3.5 | 6.0 | 0.5 | 3.3 |
| Agree | 15.9 | 30.5 | 25.6 | 24.0 |
| Neither agree nor disagree | 3.0 | 7.5 | 1.0 | 3.8 |
| Disagree | 56.2 | 44.0 | 56.3 | 52.2 |
| Strongly disagree | 21.4 | 12.0 | 16.6 | 16.7 |
| Total | 100 | 100 | 100 | 100 |

*Source: HH level survey (2014).*

Table 8.24 Farmers' perceptions (%) on various livestock issues in 2014

| Perceptions | District | | | Total |
|---|---|---|---|---|
| | Akaki | Shalla | M-B | |
| Manure is essential to improve my crop yields | | | | |
| Strongly agree | 31.8 | 30.5 | 22.1 | 28.2 |
| Agree | 57.7 | 69.0 | 76.4 | 67.7 |
| Neither agree nor disagree | 3.5 | 0.0 | 0.0 | 1.2 |
| Disagree | 4.5 | 0.0 | 0.5 | 1.7 |
| Strongly disagree | 0.0 | 0.0 | 0.5 | 0.2 |
| Not applicable | 2.5 | 0.5 | 0.5 | 1.2 |
| Total | 100 | 100 | 100 | 100 |
| I do not have enough land to grow green fodder | | | | |
| Strongly agree | 33.8 | 27.5 | 23.6 | 28.3 |
| Agree | 62.2 | 58.5 | 72.4 | 64.3 |
| Neither agree nor disagree | 1.0 | 7.5 | 2.5 | 3.7 |
| Disagree | 2.0 | 5.5 | 1.5 | 3.0 |
| Strongly disagree | 0.5 | 0.0 | 0.0 | 0.2 |
| Not applicable | 0.5 | 1.0 | 0.0 | 0.5 |
| Total | 100 | 100 | 100 | 100 |
| Livestock is vital for cropping activities and transportation of farm products | | | | |
| Strongly agree | 36.3 | 35.0 | 35.2 | 35.5 |
| Agree | 62.2 | 63.5 | 64.3 | 63.3 |
| Neither agree nor disagree | 0.5 | 0.5 | 0.0 | 0.3 |
| Disagree | 0.0 | 1.0 | 0.0 | 0.3 |
| Strongly disagree | 0.5 | 0.0 | 0.0 | 0.2 |
| Not applicable | 0.5 | 0.0 | 0.5 | 0.3 |
| Total | 100 | 100 | 100 | 100 |
| Feed shortage is a major constraint for my farm | | | | |
| Strongly agree | 29.9 | 24.0 | 29.6 | 27.8 |
| Agree | 61.7 | 64.0 | 66.3 | 64.0 |
| Neither agree nor disagree | 1.5 | 7.0 | 1.0 | 3.2 |
| Disagree | 5.5 | 4.5 | 2.5 | 4.2 |
| Strongly disagree | 1.0 | 0.5 | 0.0 | 0.5 |
| Not applicable | 0.5 | 0.0 | 0.5 | 0.3 |
| Total | 100 | 100 | 100 | 100 |
| Market problem is a major constraint for keeping productive animals | | | | |
| Strongly agree | 49.3 | 51.0 | 48.7 | 49.7 |
| Agree | 49.3 | 49.0 | 50.3 | 49.5 |
| Neither agree nor disagree | 0.5 | 0.0 | 0.5 | 0.3 |
| Not applicable | 1.0 | 0.0 | 0.5 | 0.5 |
| Total | 100 | 100 | 100 | 100 |

*Source: HH level survey (2014).*

### 8.3.11. Regressions of maize CR yield with possible explanatory variables.

The regression results (Table 8.25) showed that years of education of the HH head had positive relationships with CR yield (P<0.01). The number of HH members participating in on-farm activities tended to relate (P<0.10) positively to maize CR yield (in tonnes). Maize CR yield was positively related to livestock holding in Tropical Livestock Units (TLU) (P<0.01), adoption of improved maize varieties (P<0.01) and total maize seed used (kg) (P<0.01). The mean distance to output market was negatively related to CR yield (P<0.01). Farm land size (hectares) did not have any relationship (P>0.10) with CR yield (Table 8.25).

Table 8.25 Determinants of level of maize CR yield (tonnes/HH) - linear regression model

| Variables | Coefficient | Robust SE | t |
|---|---|---|---|
| Education of HH head in years | 0.118*** | 0.046 | 2.59 |
| Maize farming experience in years | -0.071 | 0.057 | -1.25 |
| Maize farming experience in years - squared | 0.001 | 0.001 | 0.84 |
| Family size | -0.014 | 0.090 | -0.15 |
| Number of HH participating in on-farm activities | 0.146* | 0.081 | 1.80 |
| Number of HH participating in off-farm activities | 0.057 | 0.244 | 0.23 |
| Farm land size | -0.030 | 0.070 | -0.42 |
| Livestock wealth in TLU | 0.457*** | 0.106 | 4.31 |
| Total number of oxen | -0.137 | 0.216 | -0.63 |
| Adopter of improved maize varieties (1=yes) | 1.565*** | 0.491 | 3.19 |
| Total maize seed used (kg) | 0.011** | 0.005 | 2.25 |
| Total fertilizer used for maize (kg) | 0.001 | 0.017 | 0.05 |
| Total pesticide used for maize (kg) | 15.571 | 13.785 | 1.13 |
| Total labour used for maize (man-days) | 0.049 | 0.031 | 1.61 |
| Access to credit for last 5 years (1=yes) | 0.005 | 0.372 | 0.01 |
| Mean distance to input market in travel time | 0.006 | 0.005 | 1.22 |
| Mean distance to output market in travel time | -0.010*** | 0.004 | -2.73 |
| Constant | 4.844*** | 1.009 | 4.80 |
| Number of observation | 440 | | |
| Log Likelihood | -1196.6 | | |

*Note: * P<0.1; ** P<0.05; *** P<0.01; SE: Standard error; TLU: Tropical livestock unit*
*Source: HH level survey (2014).*

## 8.4. Discussion

Chapters 3-7 have focused on the biophysical aspects of options for improving the yield and nutritive value of maize and common bean CR as feedstuff for ruminants. However, understanding the socio-economic factors and crop management practices in relation to

maize and CR yields is important to set those biophysical results in context and make realistic recommendation and enhance adoption.

### 8.4.1. Types of crops grown and adoption of improved varieties, and farmers perceptions

In general, the study area was characterised by cereal-dominated farming systems but the proportion of farmers who cultivate maize and grain legumes varied with season in 2014 (Table 8.7). There are clear and established reasons that the inclusion of grain legumes such as common bean or chickpea in crop rotation should improve and maintain soil fertility of cereal-dominated farming systems such as in the study area (Dakora and Keya, 1997; Fujita et al., 1992; Graham and Vance, 2003; Siddique et al., 2012).

The higher adoption rate of improved maize and common bean varieties observed in Shalla and M-B districts than Akaki district (Table 8.8) is likely mainly related to the variation in agro-ecological potential of the crops in the selected districts. Among cereal crops, Akaki district is known mainly for teff production and the adoption of improved teff varieties was 86%. Local contextual factors may also be involved in Shalla and M-B districts. In addition to the established government extension services, research, development and extension projects such as the SIMLESA have been actively involved in the Shalla and M-B districts for 4 years (2011-2014) and this may have contributed to the higher adoption of improved maize varieties in these districts than in Akaki. Abate et al. (2017) also reported that there were regional differences in adoption of improved maize varieties in SSA associated with the variations in the level of investment in maize research and development among the regions and countries within them.

In contrast to maize, a higher adoption rate of improved chickpea varieties was observed in Akaki than in Shalla and M-B districts. This may be explained by the agro-ecological potential of chickpea, access to information, improved seeds and relatively better access to a chickpea market in Akaki than in the other two districts (Table 8.7). Chickpea is an important cool-season food legume cultivated by smallholder farmers in areas such as Akaki (Dadi et al., 2005).

In the study districts, a large proportion of farmers perceived that CR quantity and quality were important to accept or reject new crop varieties (Table 8.9). Almost all of the maize in developing countries such as those in EA is produced for food in mixed crop-livestock

systems where stover is an important by-product as livestock feed (Erenstein et al., 2013). De Groote et al. (2013) observed that criteria for genotype choice of maize farmers in Ethiopia and Tanzania included grain taste, and nutritional quality, and stover biomass, and quality for animal feed, among other attributes. Dual-purpose varieties which (provide larger amounts and higher quality CR as well as grain) are attractive options to meet HH needs under current and likely future scenarios (Lenné et al., 2003). However, as is the situation globally, the potential of dual-purpose crop technologies for smallholder farmers in Ethiopia depends to a high degree on biophysical/agro-ecological and socio-economic factors (Blümmel et al., 2013b; De Groote et al., 2013; Franke et al., 2014; Notenbaert et al., 2013).

### 8.4.2. Maize seed rate used, and farmers perceptions for current practice

The seed rates used by farmers sometimes deviated from the recommended rates. For improved varieties of maize with a recommended rate of 25-30 kg/ha (Negasa et al., 1993), farmers used rates ranging from 13-72 kg/ha in Shalla district and up to 24-36 kg/ha in M-B district (Table 8.10). These differences between recommended and actual seed rates suggest a need for location specific recommendations for specific varieties of maize or the need to take account of the livestock feed issue when setting recommendations.

The FGD show that these wide ranges in seed rate are associated with many factors such as the type of variety (e.g. seed size, improved *versus* local variety), seed quality, environment/season (rainfall forecast/weather conditions, main versus short rain season, presence of soil insect pests, soil type e.g. soil fertility status), and crop management factors [method of sowing (row planting/broadcasting) and to some extent pre-harvest practices (such as thinning and leaf stripping in maize)]. Usually farmers used higher seed rates for local varieties of maize than for improved varieties but this was apparently mainly associated with the method of planting (i.e. local variety usually sown by broadcasting followed by thinning in some study areas). Also if the seed quality is poor (e.g. affected by weevils) farmers usually use a higher seed rate than the recommended rates. It is also likely that some farmers use lower rates of improved maize hybrid/variety seed (e.g. Shalla district, Table 8.10) associated with the higher cost per kg.

If moisture stress is forecast by farmers such as from their indigenous knowledge of the cropping seasons then farmers usually increase seed rate as a risk aversion strategy

(FGD results indicated that in moisture stress conditions seeds are more likely to abort before emergence) and/or use of short maturing varieties such as Melkasa-2. In Shalla district when farmers are aware of, or expect, the occurrence of insect pests in the soil they often increase the seed rate. Similarly Gebretsadik et al. (2014) reported that farmers prefer to use higher seeding rates in sorghum for adequate germination, better stand, and to reduce losses incurred by various stresses. In a previous study a wider range in maize seed rates were used by farmers (18-80 kg/ha) and the highest seed rate of 80 kg/ha was used in moisture stress areas to overcome seed emergence problems resulting from inadequate soil moisture (Negasa et al., 1993).

Seed rate may also be adjusted to deal with different soil types. Maize seed rates used by farmers in sandy medium fertile soils are usually higher than the recommended rate, but in good fertile black soils farmers usually follow the recommended practice. In farms using pre-harvest practices (Table 8.15) such as thinning at knee height of the maize growth stage the seed rate was often increased.

Average maize seed rate across the three districts was 33 (SD=20) kg/ha. This was higher than the average rate (20.5 kg/ha) used by farmers in Eastern India (Banerjee et al., 2014) and the average rate of 24.4 (SD=21.7) kg/ha used across North-eastern and North-western Ethiopia (Gebretsadik et al., 2014). These differences may be associated with varieties (improved versus local), growing environment, pre-harvest practices and farmers' perceptions. In general, a higher maize seed rate (53 kg/ha) was used in Akaki than the other two districts and this may be attributed to the high proportion of farmers (68.7%) using local varieties compared with the complete adoption of improved varieties in Shalla and M-B districts (Table 8.8). The wider maize seed rate range (13-72 kg/ha) used in Shalla than M-B district (24-36 kg/ha) is likely related mainly to more common pre-harvest of forage in Shalla (52%) than in the M-B (26.6%) district in the main season (Table 8.15). Maize is the main season crop in Shalla district (Table 8.7) and due the differences in moisture availability farmers often used higher seed rates of maize during the main season than in the short-rain season.

Farmers were aware of relationships between the seed rate and the yields of grain/seed and of residue, and the quality of residues as feedstuffs in maize and legumes and this in large part explained their seed rate choice. However, perceptions varied. It was also generally perceived that a higher seed rate of maize and legumes was associated with finer stems in the CR and improved quality and palatability of the CR.

### 8.4.3. Maize pre-harvest practices versus seed rate used and perceptions

Pre-harvest practices at early crop growth stage (Table 8.15) with use of the forage as feedstuffs were usually associated with seed rates higher than those recommended. Findings from other studies (Lukuyu et al., 2013) have shown that smallholder farmers in EA often deliberately change their maize management practices by planting at high density and systematically thinning the crop to obtain both fodder and grain. Gebreyohannes and Hailemariam (2011) reported that farmers in Hararghe, Ethiopia, used a high seed rate to enhance maize and sorghum biomass growth and then thinned excess seedlings for use as feedstuffs, and also defoliated maize and sorghum leaves after crop maturity. However, farmers in M-B district of the present study practiced leaf stripping at the bottom part of maize plants (below the top ear), most usually to intercrop common bean between maize rows at about silking growth stage of maize (R1) (Nielsen, 2016), and use of the fodder for livestock. Farmers reported time of defoliation is in accord with research (Asefa and Mekonnen, 1992) that partial defoliation of maize below the upper ear at high planting densities modifies the photosynthetic efficiency of leaves. They concluded that defoliation should be delayed until 30 days after 50% flowering. Also when leaves below the upper ear were removed, GY was increased by 11% at high plant density (13.3 plants/$m^2$) and the leaves above the upper-most ears are more important than the lower leaves at high plant densities for GY. Also it has been reported that Hararghe farmers usually de-tassel maize plants after maturity and feed the tops to livestock (Gebreyohannes and Hailemariam, 2011).

### 8.4.4. Early-harvest practices, and farmers perceptions in relation to residue availability and use

The crops harvested for Eshet at early crop growth stage in the study areas are usually maize, chickpea, common bean and faba bean for sale and/or home consumption (Table 8.16). Crops are also early-harvested by farmers to prepare the land for double cropping. For instance, in M-B district after harvesting maize for Eshet production the maize plot is often used for common bean in a double cropping system. Maize for Eshet production depends on the type of variety and the FGD indicated that this choice depended on whether the production was for sale or home consumption. In Akaki district farmers preferred improved varieties of faba bean due to their good pod yield. However they usually prefer local varieties of chickpea although yields may be low, especially during

adverse seasonal conditions (e.g. high rainfall during the crop growth stage). Improved chickpea varieties such as Arerti and Shasho are suitable for early harvest as a vegetable.

The utilization of the green fodder CR depends on the crop and purpose of harvest at this early stage. Maize and common bean CR are usually used for feeding livestock but this may not occur with some other grain legume crops. Chickpea at green pod stage (the entire plant) are usually sold and the seeds are consumed without any processing (Dadi et al., 2005) and consequently little chickpea CR from early harvest is available for livestock. According to farmers perceptions it is much more profitable to sell chickpea as a green vegetable than as seed harvested at maturity. FGD indicated that sale as the green vegetable can return US$ 3,300/ha while the return from harvesting at maturity is likely to be US$2100-2800/ha. Similar conclusions were reported by Dadi et al. (2005) and Rao et al. (2012). Since the green pods are perishable and cannot be transported long distances (Dadi et al., 2005), only farmers in districts close to urban markets can access this market option. In general early harvest of chickpea usually depends on its profitability and the extent of feed shortage. An appropriate technology to separate the green seed from the pod may be important so that green chickpea fodder retained on-farm could be used. Chickpea CR harvested at seed maturity can be available as a feedstuff for livestock.

### 8.4.5. Farmers perceptions on maturity stage at harvest in relation to grain and residue yields and quality

Delay in maize harvest after grain maturity was more common in Shalla than in the other study districts (Table 8.18). The majority of farmers perceived that delayed harvest of maize after maturity had either no effect or increased maize grain yield or quality. For instance, Shalla district farmers perceived that complete drying of maize plant in the field for several weeks after maturity is an essential practice for improved GY and quality but this had negative implications on stover yield and quality (Tolera et al., 1998). Farmers in some kebeles of Shalla district also reported that during the short rain season the maize was harvested just at physiological maturity because they needed to clear the land for common bean for the main season. If harvested at physiological maturity during the short-rain season farmers usually store the maize ear with the stalk around the homestead for further drying of the grain before threshing. For some farmers labour availability is also one of the reasons to leave maize in the field after physiological maturity of the crop.

Farmers in the M-B district want to clear maize for the next crop (e.g. teff) in the same plot so they often uproot the maize plants at physiological maturity and leave them in an upright position in prepared ditches for complete drying before grain storage. The major reason is to be able to double-crop. However, when maize is followed by chickpea the maize crop may be left in the field for 1-3 weeks after physiological maturity (Table 8.18) to conserve soil moisture for the next chickpea crop.

### 8.4.6. Crop cutting height at harvest and farmers perceptions

The height at which crops are harvested often varies with the crop, cropping system, crop maturity at harvest and individual farmer practices. In the M-B district farmers perceived that up-rooting both maize and common bean crops at early and final harvests would ease the land preparation for the next cropping activity. Also farmers in this district perceived that leaving CR causes difficulties for land ploughing and preparation. In Shalla district farmers reported that common bean at seed maturity is not suitable for manual harvest using a sickle. In Akaki district farmers also reported that it was inconvenient to harvest chickpea at the Eshet maturity stage by sickle and usually harvest by uprooting.

Higher cutting height of maize is usually practiced in Shalla (32.5%) and Akaki (16.9%) (Table 8.22). With higher cutting heights of maize the upper part of the maize stover is stored for later use as a feedstuff while the lower part is left in the field and used for aftermath grazing, fuel or mulching. The main reasons to cut at a low height are to meet the demand for CR as feed for livestock. A second reason is the need for maize stalk for fuel. Conversely land shortages and the need for timely preparation of the land for the next crop are the reasons to uproot maize and common bean crops for harvest in the M-B district.

### 8.4.7. Farmers' perceptions on CR use and crop-livestock integration

Farmers are aware that incorporation of CR improves soil quality but there are potential trade-offs in use of CR for various purposes. In mixed crop-livestock systems use of CR as livestock feed is one of the major interactions between crop and livestock production (Erenstein and Thorpe, 2010; Moritz, 2010). Several studies have quantified and evaluated CR trade-offs in mixed crop-livestock systems e.g. (Erenstein, 2002, 2003; Jaleta et al., 2013; Valbuena et al., 2012). In some areas such as M-B district double-cropping was associated with a land shortage (Table 8.4), and farmers perceived that there were also other factors affecting CR retention in the field. In this district the demand for CR generally

exceeded the supply. The majority of farmers perceived that CR is a vital feed source for livestock and that it is better to feed CR to livestock than leave it on the soil (Table 8.23). According to Baudron et al. (2014) modifying the supply-side of CR without altering the demand-side is unlikely to increase the quantity of CR retained in the fields, particularly in areas where farmers tend to maximize the number of livestock. If animal manure can be returned to the soil (Table 8.24) the CR can effectively used for both purposes. However, these often require transport of the manure from the homestead to the fields and this may be difficult due to distance and bulkiness. This manure application is usually on backyards and homesteads nearby.

Livestock are an integral component of crop-livestock systems. The majority of farmers (95.9%) in the current study perceived that manure from livestock is an essential input for crop production while livestock are vital for their cropping activities and transportation of farm products (Table 8.24). These integrated systems make efficient use of natural resources; animals often provide dung/manure that is used to fertilise crops, while CR are fed to livestock (Williams et al., 2000).

### 8.4.8. Socio-economic factors and crop management practices in relation to maize and CR yields

Socio-economic factors play an important role in determining crop yield by affecting crop management practices and availability and use of inputs (Somda et al., 2002). Empirical evidence has shown that HH characteristics play an important role in farm decision making (Adeoti, 2008; Lawal and Oluyole, 2008). The regression results of this study were presented in terms of the relationship among different socio-economic, crop management and institutional factors with maize CR yields measured in tonnes/HH during the 2014 main and short-rain season (Tables 8.25).

Formal education levels (i.e. years of school education) and farm experience are expected to influence knowledge, the willingness to adopt new ideas or practices and the farming system that could provide reliable information about the production systems in each area. This is useful in gathering local and indigenous knowledge and in implementing participatory technology development (Gebretsadik et al., 2014). A regression analysis in the present study showed that education has a positive influence ($P<0.01$) on CR (Table 8.25) produced per HH across growing seasons (Main and short-rain). Other studies have found a positive relationship between literacy and the ability to process information on

innovation in agriculture and maize GY (Akinola et al., 2010). In the present study about 33% of surveyed farmers were illiterate while about 45% and 20% of the surveyed farmers had up to 6 and 7-12 years of schooling respectively (Table 8.3).

A key indicator of economic status of farm HH is the type, quantity and quality of resources they own. Land, livestock and labour owned by farm HH constitute the major resources that can be used to generate income by smallholder farmers (Dadi et al., 2005). The number and composition of HH membership is an indicator of labour availability in a HH and subsequent ability to adopt labour-intensive technologies. Asset endowment is most important in overcoming resource constraints associated with most new technologies. Family size has direct implications for the availability of human labour available to the farming system (Gebretsadik et al., 2014). The higher mean family size (8.1) in Shalla than M-B (7.6) and Akaki (5.6) districts might well be associated with the cultural practice of polygamy by most HH in Shalla. In the present study, the number of HH members participating in on-farm activities was positively associated ($P<0.1$) with maize CR produced/HH across growing seasons (Table 8.25). Banerjee et al. (2014) also reported that family members engaged in on-farm activities was significantly correlated with overall maize GY yield produced across growing seasons.

Several studies in developing country contexts have documented the relationship between the land size owned by a farmer and farm productivity (Anand Vadivelu et al., 2006; Masterson, 2007; Thapa, 2007). However, the regressions in the current study indicated that farm land size (in hectare) had no significant effect on CR produced/HH across growing seasons in 2014. Several previous reports (Carter, 1984; Chand et al., 2011; Kimhi, 2006) indicated that an inverse relationship between farm size and productivity. Some previous studies have also suggested that large-scale farmers are more inclined to adopt new improved technologies than small-scale farmers (Abara and Singh, 1993; Akudugu et al., 2012; Feder et al., 1985). However, it should be remembered that the majority of farms in the present studied districts are small scale in the range 0.9-2.1 ha/HH with average farm size 1.6 ha (Table 8.4) and that the full technology package for improved productivity might not be used in such small farms.

Livestock ownership was common throughout the study area reflecting the prevalence of mixed crop-livestock systems. In spite of the important role that livestock play in the HH economy and capital accumulation, production of forage or pasture cultivation to supply feedstuffs was negligible. Livestock were primarily fed with CR, especially during the dry

season. Maize CR produced (tonnes/HH) had positive relationships with the HH livestock wealth in TLU ($P<0.01$) (Tables 8.25). The higher livestock numbers owned by farm HH contribute the income generated by smallholder farmers (Dadi et al., 2005) associated with more use of improved technologies relevant to yield. Investment in maize cultivation has a close relationship with income of the farm family where higher income provides farmers the ability to afford needed inputs and equipment for improved crop management (Sulo et al., 2012). De Groote et al. (2013) found that the area allocated to improved maize varieties increased with livestock ownership. This indicated that wealthier farmers may be better able to accept risk and are more likely to buy improved varieties of seed rather than using lower cost local varieties of seed.

Some crop management factors have been reported to affect maize GY (Subedi and Ma, 2009) and CR yield and quality (Reddy et al., 2003). The regression results showed that adoption of improved maize varieties in the present study had positive relationships ($P<0.01$) with maize CR produced (tonnes/HH) across growing seasons. Total maize seed used (in kg/HH) was positively related to maize CR ($P<0.05$) produced/HH across growing seasons. The regression results also showed that the amount of CR produced (tonnes/HH) decreases with the increase in mean distance to output markets ($P<0.01$).

### 8.5. Conclusion

There is substantial variation in agronomic practices relevant to CR yield and quality (e.g. choice of variety, seed rate used, harvest practices) which often differ from the recommended practices within and between the study districts. Farmers often modify the recommended agronomic practices depending on their own circumstances and needs. Farmers in the study district often preferred to grow dual-purpose varieties and often used seed rates lower or higher than the recommended rate. This mainly depended upon the type of variety, environment, pre-harvest practices for fodder and farmers perceptions. This suggests that there is a need for refined seeding rate recommendations specifically for environment, variety and the intended use of the crop.

The extent of early harvest of maize and grain legumes for Eshet was influenced by market access for sale of green maize ear or legume vegetables, the extent of HH demand for food during early crop growth stage and farmers perceptions on gross monetary value of green ear/vegetable compared to sale of the dry grain/seed harvested after maturity. This has implications for the availability of green fodder for livestock on the farm. In the

case of chickpea marketing as a green vegetable, the introduction of small-scale processing and packaging technologies would be valuable so that the high quality green CR is not wasted but made available on-farm as quality fodder for livestock and for soil improvement.

The regression models also showed that a number of factors influence maize CR yield. These are mainly socio-economic and crop management factors that affect maize residue production per HH. The probability of increasing maize CR yield (tonnes/HH) in the present study was associated with increases in education level of the HH head in years, the number of HH members participating in on-farm activities, livestock wealth, proportion of adopters of improved maize varieties, total maize seed used in tonnes/HH and mean distance to output market.

In conclusion, it is important that agronomic technology development and the associated recommendations should include evaluation of farmers perspectives and integrate socio-economic and biophysical factors to maximize whole plant value and improve whole farm productivity. These are essential components of the development of technology packages which respond to farmers' needs and are adapted to their farming systems and specific environments.

# Chapter 9 General discussion and conclusion

## 9.1. General discussion

### 9.1.1. Introduction

The role of livestock in supplying the increasing demands for high quality food by expanding populations and urbanization in developing countries is clear. However, the availability of forage for ruminants from grazing lands has been diminishing with the increased demand for more lands for crop cultivation and the feed base for livestock in SSA will continue to depend heavily on CR which are generally low quality feedstuffs even for ruminant animals.

Maize is the major cereal crop in EA and its stover is thus the most important CR feedstuff available for ruminants in ESA (Abate et al., 2015; Gebremedhin et al., 2007; Notenbaert et al., 2013; Romney et al., 2003; Thorne et al., 2002). However, because of the low N and high cell wall contents, and the low digestibility and voluntary intake (VI) of maize stover harvested after grain maturity, ruminants fed stover alone generally lose LW (Chapter 2, Table 2.5) and productivity is poor. Moreover, there are often competing demands for the CR available in crop-livestock system. In addition to use as a feedstuff, CR are needed for other purposes, most importantly for soil fertility (Blümmel et al., 2013b) and fuel (Abate et al., 2015) and other uses. In EA common bean is often included in maize-based crop-livestock systems and as a legume crop, CR is generally higher in quality as a feedstuff than maize stover and therefore may provide an opportunity to improve the quality of CR diets and thus animal performance and system sustainability.

The two of the most practical options for farmers to improve the quantity and fodder quality of CR produced are (i) through choice of genotype sown, to exploit genetic differences in quantity and/or quality of CR produced (Blümmel et al., 2013a; Sharma et al., 2010) and (ii) intensification of crop and CR management, to increase production and/or feed value of the CR (Reddy et al., 2003; Williams et al., 1997). Such options may utilize simple changes in crop management such as increasing plant density and higher cutting height of maize at harvest and harvesting either early or at seed maturity stages (e.g. with common bean). Each of these management options are already practiced by some farmers in the regions.

Studies in EA have reported the existence of genetic variation among maize genotypes in GY, SY and stover quality (i.e. dual purpose attributes) (Ertiro et al., 2013a; Tolera et al., 1999). However, the current recommendations for maize plant density have not been revised for three decades despite change in genotypes (improved) and management. Potentially there are synergies between higher density management and superior genotypes that can be easily exploited by farmers to maximize SY. The greater stress tolerance from interplant competition ("crowding stress") of modern maize hybrids (Morales-Ruiz et al., 2016; Raymond et al., 2009; Tokatlidis and Koutroubas, 2004) may offer opportunity to increase maize stover quantity without reducing GY and stover quality (Reddy et al., 2003).

Differences in maize stover quality and quantity associated with the practice of some farmers to high-cut maize at harvest (Chapter 8, Table 8.23) were investigated to determine the potential consequences. In most studies maize stover has been sampled immediately above ground level at grain maturity. Similarly, there is also little information on the extent of variation among common bean genotypes harvested at different crop growth stages (at seed maturity or Eshet stage that is often practiced by farmers, Table 8.17, Chapter 8). Availability of higher quality legume residues such as common bean haulm offers potential to use with low quality maize stover on the same farm to provide higher quality diets. Moreover, an understanding of farmers' choice (e.g. varieties, crop-management practices and harvest procedures) and their perceptions of GY and CR yield and quality and about current recommendations are important to inform changes in farming systems and enhance the adoption of interventions.

Crop management options that affect CR yield and quality include fertilization, plant density, selective harvesting and harvesting stage (Reddy et al., 2003). Apart from fertilization, the benefits of such practices/options for improved CR yield and quality were quantified in the current study in maize-legume-livestock production systems. Thus the present study: (1) investigated the effects of maize genotype (G), environment (site and years) (E) and management (M) as plant density (D) (G x E x M) on maize grain and stover yield, and stover quality attributes; (2) determined the effects of G and E on the yield and value as a ruminant feedstuff of the upper and lower parts of maize stover; (3) assessed the extent of genetic variation in seed and haulm yields, and haulm quality among existing popular common bean varieties harvested at seed maturity or at immature (R6-mid seed fill) crop growth stages. NIRS was used to facilitate laboratory analysis of

the attributes of feedstuff quality in large sample sets of CR and this required the development of improved and robust NIRS calibration equations. In addition smallholder farmers' perceptions and rationale, and the relationships among socio-economic and crop management factors with maize grain and residue yield in maize-legume-livestock systems were investigated.

### 9.1.2. Study approach

#### 9.1.2.1. Site selection and CR sampling, processing and measurements

An underlying principle of the research approach used in the experimental program was to collaborate with and leverage onto other research programs in EA and to maximise use of research resources. The work on maize reported in Chapters 4 and 5 during 2013 and 2014 was conducted in collaboration with the team of a large ACIAR-supported project on maize-legume crop-livestock system (SIMLESA: Sustainable Intensification of Maize-Legume cropping systems for food security in Eastern and Southern Africa) (http://aciar.gov.au/page/simlesa-program). The work on common bean reported in Chapters 5 and 6 during 2013 was conducted within N2Africa-supported project (http://www.n2africa.org/). These collaborations allowed experimentation on CR yields and quality across widely distributed sites in Ethiopia representing the most important maize and common bean cropping systems of the East African highlands. Also the project sites included as Chapter 8 survey sites were selected to meet the primary needs of both projects and again to represent the most important maize and grain legumes growing environments in EA (Appendix, Figures A4.1-A8.1). Planting and crop measurements during plant growth to harvest were done by the SIMLESA and N2Africa project teams with the involvement of the author, but the CR aspects were entirely the responsibility of the author. Furthermore, since it is recognised improper sampling is one of the largest sources of variation in forage analyses (Linn and Martin, 1991), CR measurements and sampling were done primarily by the author, with assistance the project teams only when necessary for timeliness. CR sampling and processing such as field and oven drying and procedures were uniform for all CR sub-samples.

#### 9.1.2.2. Crop residue quality attributes and methods used

Crop residue quality can be assessed using *in-vivo*, *in-situ* and *in-vitro* methods (López et al., 2000). *In-vivo* measurements best represent the animal response to diets. However,

such measurements are usually labour and time intensive and cannot be applied for large numbers of samples or when small quantities of forage are available (e.g. in plant breeding trials) (Adesogan et al., 2000; Beever and Mould, 2000; López et al., 2000). Laboratory (*in-vitro*) assays are required that are rapid, repeatable, and are directly correlated with animal performance (Adesogan et al., 2000; Casler and Van Santen, 2010; Weiss, 1993). In the present study, N, NDF and, ADF contents and DMD were estimated as important attributes of low quality forages and which commonly used to evaluate quality of forages as feedstuffs for ruminants (Paterson et al., 1994).

In low quality forages such as CR, N concentration is one of the most limiting factors for their utilization by ruminants and is almost universally included in routine feedstuff analyses. In the present study total N was determined using the Dumas combustion method (LECO combustion system N analyser), which may give slightly less accurate results but involves fewer analytical steps, uses smaller sample sizes and provide more rapid sample throughput than the Kjeldahl method. Dumas results can be slightly higher than for Kjeldahl as some additional N-containing compounds (e.g. nitrates) are measured (Adesogan et al., 2000).

Forage fibre composition generally is regarded as an important index of forage quality for ruminants, being correlated with intake and digestibility (Beever and Mould, 2000; Paterson et al., 1994). Evaluation of fibre composition is usually based on estimates of cell wall fractions as NDF comprising cellulose, hemicellulose and lignin and ADF comprising cellulose and lignin (Van Soest, 1967) which have long been considered among the useful indices of VI and digestibility of forages by ruminants, because the most important determinants of the rate and extent of digestion is the degree of lignification and cell wall content (Adesogan et al., 2000; Van Soest, 1965). The concentration of NDF has long been considered as laboratory variable most directly related to VI of ruminants (Casler, 2001; Casler and Vogel, 1999). Fibre fractions, especially ADF have been used extensively to predict forage digestibility (Givens et al., 1989, 1990; Givens et al., 1992; Moss and Givens, 1990). The detergent fibre system does, however, have limitations, particularly during estimation of ADF in feeds like distillery by-products which may contain significant amounts of heat-damaged protein and NDF in starch rich feeds where starch may be measured as NDF.. However, in low quality CR forages such limitations are not generally important (Beever and Mould, 2000).

Of the currently available *in-vitro* digestibility techniques, the rumen-fluid pepsin method of Tilley and Terry (1963) is one of the most useful for predicting digestibility *in-vivo* (Adesogan et al., 2000). This technique has been widely adopted by plant breeders to screen the nutritional value of new forage cultivars (Beever and Mould, 2000; Vogel and Sleper, 1994) and will likely continue to be used in breeding programs (Vogel et al., 1999). However, although the digestibility of forages is determined largely by structural factors, such as the degree of lignification, *in-vivo* digestibility is also influenced by factors such as physical processing, level of intake, diet protein concentration and other associative effects within mixed diets (Casler and Van Santen, 2010; McDonald et al., 2002). All of the factors that determine digestibility therefore have an impact on the ME the ruminant can derive from a specific feed (CSIRO, 2007; McDonald et al., 1988; Reynolds, 2000).

In the current study, the filter bag analysis systems were used for determining NDF and ADF contents (ANKOM Technology, Macedon, NY, USA) and in-vitro DMD (DAISY$^{II}$ incubator: ANKOM Technology, Macedon, Fairport, NY, USA) of the CR. Vogel et al. (1999) concluded that the filter bag analysis method provided results similar to the conventional laboratory methods and ranked the forage samples in the same relative order. The DAISY$^{II}$ incubator (ANKOM Technology, Macedon, Fairport, NY, USA) is an effective system for measuring DMD and provides results similar to the traditional methodology. This system is more labour efficient than traditional methods and provides advantage for analysis of forage, grain, and mixed samples (Holden, 1999). However, the method requires fistulated animals to obtain rumen fluid which may vary in composition and activity, long incubation periods and a constant electricity supply (Adesogan et al., 2000). The presence of metabolic faecal N *in-vivo* but not *in-vitro* residues, can cause lower protein digestibility *in-vivo* (Ibbotson et al., 1982). Also, the *in-vitro* indigestible residue may contain bacterial residues and other substances, which *in-vivo* would be digested post-ruminal digestive tract *in-vivo* (Adesogan et al., 2000). Generally, it is accepted that measurement of forage digestibility is not sufficient to enable prediction of animal performance with high precision (Beever and Mould, 2000).

#### 9.1.2.3. Application of NIRS and development of robust calibration equations

The use of NIRS for forage analyses is generally highly cost-effective and, reduces the need for wet chemistry to a small proportion of the total samples (e.g. as low as 10%) for validation purposes (Casler and Van Santen, 2010). Although the technique is secondary in nature, and involves complex statistical procedures, it requires no chemical reagents,

produces no pollutants, offers rapid, economical, non-destructive forage assessment, including for digestibility and energy value of CR and many attributes can be measured from a spectra of a feedstuff (Adesogan et al., 1998; De Boever et al., 1995). In the present study, NIRS analysis was utilized to analyse more than 2800 CR samples in duplicate for four attributes (Chapter 3). While calibration equations developed for tropical forage grasses and legumes in northern Australia were available, because of the specificity of NIRS calibrations to the training sets it was considered necessary to enlarge these calibration data sets with current samples and to thoroughly validate NIRS measurement of the CR.

Disadvantages of NIRS include the high capital cost of the equipment and the requirement for calibrations which depend on, large data sets (> 100 samples) which have to be updated frequently. Also there are, problems such as the transfer of errors in the wet chemistry analysis to prediction errors (Barber et al., 1989), and the need to validate the calibrations with independent data sets (Adesogan et al., 2000; Barber et al., 1989).

In the present study the laboratory analyses of CR reference samples (*ca*. n=470) selected from the experimental sample sets allowed expansion of the existing northern Australian NIRS calibrations. Broad-based robust forage NIRS calibrations representing the range of variation were successfully developed for analyses of four important attributes of the CR from maize, common bean, chickpea, faba bean and soybean crops in EA. Total N, DMD, NDF and ADF calibrations were developed with SEC= 0.145, 3.04, 2.49 and 1.74 percentage units and coefficient of determination ($R^2$) = 0.98, 0.93, 0.97 and 0.97 percentage units, respectively (Table 3.3). These observations are in accord with the concept that fewer samples are needed to expand an existing calibration than to develop a new calibration (Shenk and Westerhaus, 1994). As NIRS technologies, statistical methods, and software have improved, open population calibration methods (development of a broad calibration set) have replaced closed population methods in many breeding programs (Casler and Van Santen, 2010). The outcome of this study (Chapter 3) was a modified broad-based NIRS calibration equations fit for the purpose of measurement of feed value attributes of CR for ruminants. Also the present study provided improved NIRS calibrations for tropical forages in northern Australia and elsewhere.

#### 9.1.2.4. Survey approaches in avoiding survey biases

Several measures were employed to avoid survey biases such as those which may be associated with the researcher and the, representativeness and randomness of the response (Chapter 8). The HH level survey instrument was developed and revised based on primary and secondary information gathered with the team of researchers including the author and local agricultural experts via focus group discussions. The author was highly experienced and familiar with the smallholder crop-livestock systems of the study areas and took maximum care to avoid researcher views when questions were framed and the results interpreted. What, how and why types of questions including triangulation were included in the survey instrument so as to avoid the response biases. The interviewed farmers were selected randomly and questionnaire pre-tests and the HH survey was conducted by several well trained enumerators under close supervisions including the author.

### 9.1.3. Options to increase the quantity and quality of maize stover available as a ruminant feedstuffs

#### 9.1.3.1. Maize genotype choice

One of the most practical options for smallholder farmers to increase both stover yield and quality is by selection of improved dual-purpose genotypes providing that there are useful differences among genotypes and GY is not reduced (Blümmel et al., 2007). The regression results (Chapter 8) also confirmed that maize CR produced (tonnes/HH) increased ($P<0.01$) with the adoption of improved maize varieties. However, in the present study (Chapter 4) yield and stover quality attributes were influenced more by environmental effects (year and site) than by the G or G x E and M effects (Tables 4.2 and 4.5, Chapter 4). This is in accord with other multi-environmental trials which have commonly shown that the environmental effects on GY are larger than the G or G x E effects (Badu-Apraku et al., 2012; Beyene et al., 2013; DeLacy et al., 1996; Makumbi et al., 2015). For factors under farmer control, there was substantial variation among genotypes ($P<0.01$) for yields (t/ha) of TB, grain and stover (Tables 4.3 and 4.4, Chapter 4). Variation due to G was larger than that due to the G x E or G x D effects in both genotype group (Table 4.2) which is similar to previous observations for GY reported by Beyene et al. (2011a) in EA. The existence of G x E in multi-environmental trials, complicate the selection of superior cultivars and the best testing sites for identifying superior and stable genotypes (Badu-Apraku et al., 2012).

Commonly used maize genotypes showed considerable differences in stover digestibility (Table 4.6, Chapter 4). Although, these differences in digestibility between genotypes were numerically small they would be expected to have substantial implications for livestock productivity. In India, Kristjanson and Zerbini (1999) proposed that a one-percentage unit increase in digestibility in sorghum or pearl millet stover would increase milk output by 6 to 8%. Also, small increases of 3-4 percentage units in forage digestibility were associated with 17-24% increases in average daily gains and beef production per hectare in eastern Nebraska (Vogel and Sleper, 1994). Some bio-econometric models have indicated that breeding for stover quality might not be profitable (Thornton and Herrero, 2001), but in this study the benefits of increasing stover biomass were not explored because of its low nutritional value and perceived abundance at harvest time (De Groote et al., 2013).

ME content is an estimate of feed quality that is closer to the net energy (NE) actually available to the animal, since the ME measurement takes account of energy losses in urine and combustible gas methane (McDonald et al., 2002). Following McDonald et al. (1988), net energy can be calculated from ME using an efficiency factor k, which depends on the ME content of a feed. For the maize stover genotypes with the highest (7.29 MJ/kg) and lowest (6.79 MJ/kg) stover ME content in the present study, the k for maintenance energy would be 0.64 and 0.63 and their NE would be 4.54 and 4.29 MJ/kg, respectively. Since, livestock with a LW of 250 kg (one tropical livestock unit) will have a NE requirement of 21.4 MJ/day for maintenance, an animal would need to consume 4.71 and 4.99 kg from the stover with high and low ME, respectively, to provide maintenance requirement. The highest maize stover DM intake reported in previous work was 1.9% of the animal LW (Chapter 2, Table 2.5) i.e. 4.75 kg/day for a 250 kg animal. Thus, animals at maximum likely VI of maize stover would be expected to ingest sufficient ME for maintenance or somewhat less than maintenance.

The variation in total N content of maize stover in the current study was small and was generally not significant. The largest variation was in the EM genotypes at Hawassa (range 0.73-0.84%). Low N content less than the minimum microbial requirement (1.0–1.2% DM) will often be the most limiting nutritional factor in the utilization of cereal straws as a ruminant feedstuff. Such N deficiency usually results in severely reduced feed intake (e.g. by 20-40%) (CSIRO, 2007; Van Soest, 1994). A 0.1% increase in feed N concentration can increase VI by more than 10%, and voluntary feed intake could double as feed N content increased from 0.4 to 1.2% (Van Soest, 1994). Voluntary feed intake is

usually the most important quality attributes of cereal CR and ruminant feedstuffs in circumstances where there is enough CR available to feed animals to their appetite (Blümmel et al., 2003). Extrapolation of these estimates to the current data suggests that choosing the G could increase VI by 10% compared with a G with the lowest N concentrations simply as a consequence of N availability alone (Table 4.6).

The study identified genotypes with positive characteristics for both GY and ruminant nutrition. Earlier studies have also suggested that by considering G x E, superior genotypes in GY could be selected for commercial release to farmers in Africa (Beyene et al., 2011b; Pixley and Bjarnason, 2002). In the current study, Hybrid TH13321 (EM genotype group) produced the higher DMD% (Tables 4.6 and 4.7) as well as the highest TBY, GY, SY (Tables 4.3 and 4.4), stover DDMY and PUI (Tables 4.9 and 4.10), and the highest ME yield (values not shown). Similarly among the MM group, the hybrids (BH-546 followed by BH-543) were best in terms of combining GY, SY and stover quality or DDMY, PUI (Tables 4.3, 4.4, 4.6, 4.7, 4.9 and 4.10) ME yield (values not shown) than the older genotype BH-540. These genotypes are more dual-purpose than those hybrids selected for grain-only, and demonstrate the potential for exploiting variability in maize to increase TB to produce both high grain and high stover yields and stover quality. Thus, genotype improvement could contribute to increase TBY, GY and SY and stover quality. Abate et al. (2017) reported that the BH-540 cultivar released in 1995 is currently due for replacement with the recently released higher-yielding cultivar BH546. .

#### 9.1.3.2. Plant density

Plant D had a major effect on both GY and SY. Increasing D from 5 to 7 plants/$m^2$ generally increased the mean yields (averaged across years, sites and genotypes) (Table 4.4) but, the increases varied with genotypes and E (sites and years). Similar results were also reported by Raymond et al. (2009) and Morales-Ruiz et al. (2016) in GY and TBY as D was increased from 5-9 plants/$m^2$ under rain-fed condition in North America. The partitioning of variance components indicated that the density aspect of M accounted much more of the total variation in TBY and SY than genotype effects. This suggested that management factors such as density provide an important simple and practical option in conjunction with genotype to increase SY. Farmers in EA clearly express their demand for and use dual-purpose maize genotypes as found in the survey in the present study (Chapter 8) and also by (De Groote et al., 2013) and this is due most obviously to the

scarcity of arable land for forage production. These dual-purpose maize genotypes provide increased amounts of fodder without compromising GY and help to meet the increased demands for livestock feed in mixed maize livestock systems in EA (De Groote et al., 2013). Combining the 'best' G and M options such as higher plant D could further increase SY in smallholder crop-livestock systems.

Increased SY was not always been associated with the increased GY across all genotypes and environments. Higher D increased both grain and stover yields of the EM genotypes and the stover yields of the MM genotypes in all environments. However, in the semi-arid E (Melkassa site) GY was not consistently improved for all the MM genotypes. This might be due to a lower tolerance for crowding of these genotypes due to moisture stress in these semi-arid environments reducing GY. Maize GY is sensitive to water stress from emergence to maturity and EM genotypes may undergo less water stress than MM genotypes in semi-arid environments (Larson and Clegg, 1999). Based on these observations and other studies (Amede, 1993; Larson and Clegg, 1999; Mokhtarpour et al., 2011; Norwood and Currie, 1996) it is concluded that planting density should not be increased, under higher stress conditions for at least some MM genotypes. Also the conventional maize plant density currently being used by farmers and breeders in Ethiopia should be increased, at least for some recent maize genotypes (e.g. TH13321 and BH-546) to improve grain and stover yields and to optimize whole plant value. This is mainly associated with the differences in crowding stress tolerance among the older versus recently released genotypes within each genotype group. Crowding stress or planting D is a major factor in determining the degree of competition between plants (Mokhtarpour et al., 2011). The timing of competitive stress may also be important for GY. Early competition during vegetative growth may have little effect, but plant competition between the vegetative stage and anthesis potentially has a large effect, on GY (Hashemi et al., 2005). The optimum plant population depends on a number of factors including most importantly water availability, soil fertility, hybrid maturity group, time of planting and row spacing (Sangoi, 2001). Since planting at high D improves SY disproportionately, this could explain why farmers tend to plant at higher than recommended densities as discussed further in Chapter 8.

The absence of significant effects on DMD and N content of the stover with increased plant D at most sites (Table 4.5, Chapter 4) suggested that it should be possible to improve SY using the popular maize genotypes through increased plant D without

adversely affecting the quality of the stover. However, the present understanding is not sufficient to make general management recommendations across G, environments and plant D. Overall, the low N content (<0.86%) of the whole stover (Chapter 4) is a concern and will often be a fundamental constraint to the nutritional value of the stover as a feedstuff. In circumstances where the animal is able to select and consume the parts of maize stover with highest nutritive value, the diet ingested is likely to be of higher nutritive value than the results reported above (Chapter 4). The results of the current study and their implications for recommendations and improved feeding systems need to consider and be interpreted with this in mind.

Other options exist for improving either the stover quality, e.g. through higher cutting height (Chapter 5) or better utilization of maize stover by ruminants through feeding N from an alternative source e.g. legume residues (Chapters 6 and 7).Combinations of more types of G with range of maize plant densities (and fertilizer levels (to evaluate the potential to improve overall yield and stover quality, and specifically stover N) and its overall economic feasibility need to be assessed and quantified in specific crop-livestock production systems. In many ruminant production systems deficiencies of N in low quality forages are addressed by feeding supplementary protein meals and/or non-protein N. Unfortunately protein meals are rarely available to EA smallholder farmers, and use of non-protein N is fraught with difficulties in supply and risks of urea toxicity.

#### 9.1.3.3. Higher cutting height in maize: Yield and quality of stover components

There are competing uses for maize stover in smallholder crop-livestock system and farmers' decisions on CR use are determined by their preferences, total crop production, availability of alternative resources and demand for CR (Valbuena et al., 2015). Cutting height at harvest directly affects the amount of stover available to be stored for later use. Also because digestibility and N concentration of the stover increases from the bottom to the top of the plant, the height of cutting can influence the stover feedstuff quality (Joshi et al., 1995).

The high cutting height of maize at two internodes below the lowest ear (Chapter 5) allowed harvest of the majority (60-70%) of the total stover (Table 5.2) and provided ruminant feed substantially higher in nutritive value than the entire stover. The survey result (Chapter 8, Table 8.22) indicated that about 16.9, 32.5 and 8.0% of farmers

practiced higher cutting height of maize in Akaki, Shalla and M-B districts, respectively. The present studies (Chapter 5) confirm that it is possible to improve the quality of maize stover as a feedstuff and still provide stover CR for other competing uses through manipulating harvest procedure and choice of maize genotype (Chapter 8, Table 8.23). The quality of the morphological fractions, husk, leaf blade and stalk (stem with leaf sheath and tassel) in the upper and lower components of the stover varied significantly (Chapter 5, Table 5.10). Grazing CR allows animals to select a higher-quality diet such as leaves, husks and the upper part of stalks before consuming lower-quality stalk material (Lardy et al., 2015; McGee et al., 2012; Powell, 1984). This has implications for how CR are conserved and fed, and also for the most appropriate sampling of the stover components for nutritive analyses (Reed and Goe, 1989). This is an important consideration when developing diets based on CR for ruminants (Lardy et al., 2015) and demonstrates that caution needs to be exercised when using mean values from the literature to formulate diets or predict animal performance.

Higher cutting height increased ($P<0.0001$) the mean DMD relative to the LCS fraction by 2.0 percentage units in EM genotypes and by 3.0 percentage units in MM genotypes (range 1.7-3.6 percentage units across all genotypes) across sites and years (Tables 5.9 and 5.10). This would have important implications for ruminants as discussed above. Moreover, the G with lowest (7.12 MJ/kg) ME content of HCT component of the stover (data not shown), can supply the maintenance requirement of a tropical livestock unit (McDonald et al., 1988).

The mean N concentration was significantly higher in the HCT by 0.05-0.09 percentage units than LCS (Tables 5.9 and 5.10), although since the concentrations were usually <0.98 % N in the HCT component of the whole stover would still be expected to be deficient in N for ruminants (CSIRO, 2007; Van Soest, 1994). The N concentration below 1-1.2% may constrain adequate ruminal microbial activity that would be associated with low microbial growth and reduced fibre degradation (Sampaio et al., 2010) and result in reduced voluntary feed intakes, digestibility and animal performance (Van Soest, 1994).

According to farmers own circumstances and needs, genotypes (e.g TH13321 and Bh-546) could be harvested at a high cut, and the upper stover used as fodder while the lower stover used for other purposes as described above.

Smallholder farmers with mixed crop–livestock farming need stover quantity and quality, but the relative importance and values of the HCT and HCB components of the stover are likely to vary among farmers. Although a change to a high cutting height at grain harvest will reduce the amount of maize stover available to be stored this will not necessarily cause or exacerbate a shortage of maize stover for ruminants. Grazing of the stover aftermath should allow use as a ruminant feedstuff of the more palatable components of the BCS. In addition, some maize stover is usually needed as fuel and for soil amelioration and there seems no reason why the BCS which is less suitable as a feedstuff cannot be used for these purposes. A further consideration is husk proportion, relatively thinner stem, and the 15-18% lower proportion of stem units (Table 5.3) in the HCT stover will all contribute to the higher feedstuff value of the HCT than of whole stover (LCS).

It is well known that ruminants will achieve much higher VI of CR, and particularly of thick-stemmed cereals such as maize, if they are able to preferentially select the leaf blade fractions as a high proportion of their diet (Fernandez-Rivera and Klopfenstein, 1989; Lardy et al., 2015; McGee et al., 2012; Powell, 1984). Thus, it would be expected that the VI of ruminants fed the HCT stover will increase not simply in proportion to the increase in diet digestibility or N content, but also due to a higher leaf blade content and thinner stem of the diet. Nevertheless, the low N concentration even of the HCT fraction (<0.98 % N) is likely to continue as a constraint to intake and productivity by ruminants and can only be addressed by providing other higher N feedstuffs (as forages e.g. legume residues or supplements) to provide the necessary additional diet N. The lack of resources of poor farmers in many of these smallholder crop-livestock systems means that concentrate use is limited. Thus, there has been increased interest in the use of high-quality legume residues as supplements to poorer-quality forages and this is the theme of Chapters 6 and 7.

There will be factors associated with G and farm management that can affect cutting height at harvest and eventually the profitability of the harvest procedure and which need to be considered. It would be desirable that a number of harvest procedures be evaluated with a diverse range of maize genotypes to better understand the consistency of such effects and in particular the G x E interaction effects. Also it would be desirable to conduct animal feeding studies with stover fractions obtained by various harvest procedures to provide the data to evaluate the advantages and disadvantages of modifying cutting height of maize at harvest and the overall profitability in maize based crop-livestock systems.

### 9.1.4. Options to increase the quantity and quality of common bean residues available as a ruminant feedstuffs

#### 9.1.4.1. Varietal choice at seed maturity

The ME and N contents of cereal CR such as maize stover are usually lower than needed in ruminant animal diets even for maintenance (Minson, 1990; Van Soest, 1994). However, legume forages, including legume CR at harvest may often contain higher ME and N and at least sufficient for moderate growth rate (Chapter 2, Table 2.5). One practical way to increase the availability of grain legume CR is to introduce higher yielding (total biomass) varieties providing that this does not reduce seed yield or quality. In the context of EA where common bean is established as the most important grain legume crop in maize-based crop-livestock systems, it will be important to further integrate this legume crop with maize CR where possible. The present study shows that there is substantial variation in haulm yield and quality attributes among popular common bean varieties that can increase productivity in maize based crop-livestock systems. Improved use of legume CR with maize stover based diet of ruminants is likely an option with greatest impact to improve the nutrition of ruminant livestock.

The range in quality attributes of common bean CR observed in the present study was large enough (Chapter 6, Tables 6.6 and 6.7) to be important for efficient utilization of locally available ruminant feedstuffs based on maize stover or other cereal CR. The significant G x site interactions determined for some yield and haulm quality attributes indicated that these attributes were most affected by environmental variables as site (52-57%) and varieties did not have stable performance across sites. This is in agreement with previous findings (Siddique et al., 1999) that there were substantial species x environment interactions in some cool season grain legumes (Field pea, Faba bean, Lentil, Lathyrus spp., Desi chickpea) for seed yield.

The strong and positive relationship (r=0.87) between seed and haulm yields observed in Chapter 6 is in accord with previous findings in lentil (Erskine, 1983; Tullu et al., 2001) and groundnut (Larbi et al., 1999; Nigam and Blummel, 2010; Omokanye et al., 2001). This suggests that legumes with good haulm yield can be selected without reducing seed yield. However the observation that seed yield and haulm N% were negatively correlated at one (Mandura site) of the four sites in the present study indicated that in common bean there

will sometimes be a penalty for high seed yield as a lower N concentration in the CR. The absence of, or positive correlation, of HPW DMD with seed yield (Figure 6.3) also indicated that high seed yield and high DMD are not mutually exclusive. Varieties could be identified (ECAB0081 and Nasir in Trial 1, and H-Dume and Dinknesh varieties in Trial 2), with superior yields of HPW, seed, total biomass, N and DDM and with comparable HI. Also, there are varieties (e.g. ECAB0081) which were superior in all yields and quality related attributes and with comparable HI. These results confirm the hypothesis that it is possible to select common bean varieties which yield larger total biomass/HPW with desirable HPW quality characteristics and similar or higher HI.

#### 9.1.4.2. The potential of early harvest CR in common bean varieties

Small holder farmers often harvest some of the common bean crop at green pod fill growth stages (i.e. early or Eshet harvest) and use the green bean. The surveys (Chapter 8, Table 8.17) indicated that about 15% of small farmers in Shalla and Misrak-Badawacho districts harvest a portion of their common bean plots early for Eshet when other food sources are not ready for harvest. The green common bean fodder left after early harvest is available as a high quality feedstuff to use with low quality roughage such cereal CR (maize stover) based diets. However, very little information is available on green haulm yield and quality of common bean varieties, or of other grain legume crop varieties, in EA to achieve better utilization of these locally available feedstuffs and for improved animal performance. There were large differences in seed and haulm yields and in TBY ($P<0.05$) among varieties of common bean (Chapter 7, Table 7.1) in the present study. Similar differences have been observed among common bean cultivars in Mexico (Rosales-Serna et al., 2004). Shoot biomass accumulation is considered an important for seed yield (Saxena et al., 1990; Yan and Wallace, 1995).

There was wider variation in yield responses among common bean varieties in Trial 2 than in Trial 1 (e.g. TBY range 3.0 t/ha and 1.8 t/ha, respectively). This suggests that the crop growth stage at harvest used in Trial 2 (~80 % of pods had fully developed seeds or just before physiological maturity) could be the preferred time for sampling rather than that used in the Trial 1 crop growth stage (R6 or mid seed fill) (Schwartz and Langham, 2016) to identify the varieties higher yielding for both seed and haulm. This may have been related to their relatively immature crop growth stage in Trial 1 compared to Trial 2 for effective and increased partitioning of crop biomass to the harvested product (Richards,

2000). Similarly, Rosales-Serna et al. (2004) reported that the differences in TBY among cultivars were greater as the plant approached physiological maturity, and also observed that yields of seed and TBY were associated.. The variation in whole haulm yield in the present study was largely dependent on the proportion and yield of the stem fraction since stem forms the largest component of the whole haulm (>50%) (Table 7.1). The large range among cultivars in N and in DDM yields (Table 7.4) suggested that use of the most appropriate varieties can double the N and DDM yields without compromising seed yield.

There were large differences in nutritive value of the morphological fractions (leaf, stem and pod wall) in whole haulm (Table 7.2). For example the N concentration of the whole haulm ranged from 1.7-2.5% (mean 2.0%) in Trial 1 and 1.3-1.7 (mean 1.5%) in Trial 2 while the DMD of whole haulm ranged from 66-69% in Trial 1 and 60-64% in Trial 2 (Table 7.2). Such haulm would have high nutritive value for ruminants and it could be used in combination with N deficient cereal (maize) stover (Chapters 4 and 5) to provide diet of moderate quality for ruminants. The variation in whole haulm DMD was well related to both stem digestibility and LSR (%) in the present study. The nutritive value of common bean CR depends on the proportions of stems, pod walls and leaves (Pieltain et al., 1996). At early harvest the N content of the morphological fractions decreased in the following order (in Trial 1): Leaf>pod wall>whole haulm>stem and (in Trial 2): Leaf>whole haulm>pod wall>stem. The DMD of the morphological fractions decreased in the following order (in Trial 1): Leaf=pod wall>whole haulm>stem and (in Trial 2): Leaf>pod wall>whole haulm> stem (Table 7.3).

Limitations of these studies (Chapters 6 and 7) were that only a limited number of common bean varieties were examined and data were obtained only at a few sites for one year. Given the potential importance for several reasons of grain legume food crops in EA is appears that research is both needed and justified to further examine diverse varieties (e.g. categorizing by growth habit) and in various environments (sites and years) representing EA farming system.

### 9.1.5. Effects of harvesting stage on yields of seed and haulm and haulm quality

It is clear that harvest of food legume crops at seed maturity substantially increased seed yield by 28-42% but reduced haulm yield by 29-40% and the nutritive value of the haulm with lower N (1.53 vs.0.85%) and DMD (62.2 vs. 48.8%). At crop maturity there was

extensive leaf yield loss which decreased haulm quality. Leaf loss (i.e. leaf shatter) is an important factor reducing the nutritive value of CR, and particularly of grain legume CR. If varieties that retain their leaf at crop physiological maturity can be identified and this attribute selected effectively, it could be included by plant breeders into varieties with a major impact in increasing the value of the CR. Similarly Gebremeskel et al. (2011) reported low mean LSR in faba bean varieties when harvested after physiological maturity of the crop. In common with grasses the nutritional quality of tropical legumes decreases with age (Adjei and Fianu, 1985; Lazier, 1981; Van Hiep et al., 2008) particularly as decreased N content and DMD and increased fibre contents. Wilson and Kennedy (1996) concluded that the plant maturation process is the greatest single factor that impacts the cell wall concentration and composition of forage grasses and legumes; with maturity the proportion of stem mass increases while that of leaf decreases. The strong and positive correlations between seed yield (final harvest) and whole haulm yield at early harvest in both Trial 1 and Trial 2 (Table 7.7, Chapter 7) suggested that haulm (harvested at early/pod filling crop growth stages) and seed yield characteristics may be combined in breeding programs for common bean varieties and that seed yield could be predicted through haulm measurements during the pod filling crop growth stage. Further studies on effects of harvesting stages in common bean just before physiological maturity (90-95% maturity), at full maturity and after maturity (usually practiced by farmers) on the seed and haulm yields and quality need are warranted. Moreover anti-nutritional constituents in legume residues and the availability of the N to the ruminants need to be considered.

### 9.1.6. Farmers practices and perceptions

The value and relevance of local knowledge for optimal management, including in smallholder crop-livestock systems has been subject to extensive debate (Agrawal, 1995; German, 2010; Long, 1990). Nevertheless, it is generally accepted that there must be effective and positive coexistence between the different forms of knowledge for sustainable development (Long, 1990; Saïdou, 2006). The survey (Chapter 8) did not attempt to validate local perception against the current recommendations based on scientific findings from the research system. Rather, the primary objective and emphasis of the survey was to understand local perceptions and practices and their importance in relation to the existing knowledge developed by scientists.

Farmers in the present (Chapter 8) and other studies in EA (Dione et al., 2015; Gebretsadik et al., 2014) have reported local practices and perception about the crop management practices in relation to GY, and/or CR quantity, quality and utilization practices and about the role of multipurpose fodder trees (Mekoya et al., 2008). In the present study farmers' generally followed established local agronomic practices (e.g. crop variety, seed rate, harvest procedure) and some of their perceptions differed from, and likely affected their decisions, in relation to CR yield and quality compared to the recommended practices. For instance, on average 77, 58 and 29% of farmers adopted improved varieties of maize, common bean and chickpea, respectively, and this varied widely among districts. This has implications for CR availability through choice of varieties both for grain and CR. More than 88% of farmers perceived that CR quantity and quality is an essential aspect of acceptance or rejection of a particular crop variety (Table 8.10). This suggests a need to include CR yields and quality as selection criteria in new variety development and release procedures in EA.

There was wide adoption of improved maize varieties in Shalla and Misrka-Badawacho districts (Table 8.9). However, there was also a wide range in seed rate was used (Table 8.11) associated with genotype, environment, seed prices and farmers pre-harvest practices and perceptions. Understanding farmers harvest practices (Tables 8.17-8.19) and their perceptions in the present study also helped to substantiate the present findings (Chapters 4-7). Moreover, the importance of understanding the biophysical and socio-economic determinants of crop productivity and CR utilization practices has been documented (Banerjee et al., 2014; Jaleta et al., 2015). Regression model in the present study showed that the probability of increasing yield of maize CR were associated with a number of socio-economic and crop management variables.

In the past, attempts have been made to select genotypes mainly based on grain yield without much consideration of farmers' and consumer preferences. Other studies show that maize stover (De Groote et al., 2013) and common bean haulm (Mekbib, 1997) are important elements of livestock feed in EA. When choosing a genotype farmers consider numerous criteria including characteristics of field, consumer, and feed including residue quality and quantity (De Groote et al., 2013; Mekbib, 1997). For instance, farmers use palatability, water content and stay-green of the stover as indicators for their quality, and use them to evaluate maize varieties (De Groote et al., 2013).

The present result indicated farmers' local knowledge and perceptions on genotype choice and crop M or harvest procedure need to be considered during the research inception process and thus intervention strategies have to be related to the farmers perspectives in order to hasten the adoption pathways of recommended technologies/practices and improve overall farm productivity. Joint farmer and scientist experimentation and development of new knowledge could minimize gaps between the approaches. This gives scope for alternative, combined approaches from the perspectives of farmers and scientists in various socio-economic settings. As a first step, understanding the maize and common bean production and harvest practices, problems and research priorities of farmers in various agro-ecological and socio-economic contexts is important for a tailored approach to mitigation interventions. Joint implementations e.g. genotype selection needed to explore the improvement of the stover yield and quality, in particular with the attributes that farmers appreciate to achieve both prompt and long-term adoption by farmers.

### 9.2. Conclusion

The quality and quantity of CR is an important issue in smallholder mixed farming systems in EA. Substantial options have been investigated and documented for:

(i) increased CR yield without reducing GY and stover quality as a ruminant feedstuff through manipulating plant density among maize genotypes in specific environments;
(ii) improved utilization of CR as ruminant feedstuffs through exploiting the variability among maize genotypes under high or low cutting height at harvest; and
(iii) exploiting the variability among common bean varieties and the potential of existing early harvest practices of common bean to provide high N and high DMD forage for more efficient utilization of the low quality maize stover based diet of ruminants in smallholder farmers in EA.

A greater proportion of all measures of yield variation were attributed to E than G and M effects in maize. However, M generally accounted for a greater proportion of TBY and SY variations than G effects. Increasing plant D of maize from 5 to 7 plants/$m^2$ generally increased the mean yields of grain by 5-17%, and stover by 19-44%, across both years but varied with G and E (sites and years).

It is proposed that the recommended low plant D (4.4 to 5.3 plants/$m^2$) in widespread use in EA since the 1980s regardless of G should be revised upwards, especially for the recently developed EM (e.g. TH13321) and MM (e.g. BH-546) genotypes to improve both SY and GY without reducing stover quality in selected environments. Integrating the existing popular and selected common bean genotypes both for seed and haulm yields and haulm quality in maize based crop-livestock system would further improve feed availability and feed utilization efficiency of the low quality (e.g. maize stover) based diet of ruminants.

Depending on the farming system, it is also important to indicate priorities for total crop yield, grain or CR yield and quality. Where CR are important as feedstuffs, selection of grain legume (e.g. common bean) genotypes with low leaf loss at crop maturity stage is recommended for plant breeders and CR yield should be included as additional selection criteria in maize and common bean breeding programs. Farmers should be made more aware of the consequences of a delay in harvest after physiological maturity of both maize and common bean crops. To understand the bases of genotype variations, study on maize stover histology is warranted. Investigation of more genotypes over a range of environments (sites and years) and crop management options and conducting ruminant feeding trials using CR from promising genotypes and M options (plant D and harvest procedure) with different combinations of whole stover and HCT) and grain legume CR such as common bean haulm are also important.

Understanding of farmers' local practices/knowledge and perceptions about aspects of crop management that could affect GY and CR yield and quality is vital to maximize whole plant value and the likelihood of farmers' adopting and maintaining these technologies. Current development approaches need to recognize the importance of involving farmers at all stages through participatory approaches to enhance adoption. In this study, this was accomplished by linking the biophysical research (Chapters 4-7) and socio-economic study (Chapter 8). Farmers, crop and animal scientists should work jointly to develop interventions for improved output from the whole farm, particularly for smallholder mixed farming systems in EA.

## Bibliography


Abakemal, D., Hussein, S., Derera, J., and Laing, M. (2013). Farmers' perceptions of maize production systems and breeding priorities, and their implications for the adoption of new varieties in selected areas of the highland agro-ecology of Ethiopia. *Journal of Agricultural Science* **5**, 159-172.

Abara, I. O., and Singh, S. (1993). Ethics and biases in technology adoption: The small-firm argument. *Technological Forecasting and Social Change* **43**, 289-300.

Abate, T., Fisher, M., Abdoulaye, T., Kassie, G. T., Lunduka, R., Marenya, P., and Asnake, W. (2017). Characteristics of maize cultivars in Africa: How modern are they and how many do smallholder farmers grow? *Agriculture and Food Security* **6**, 1-17.

Abate, T., Shiferaw, B., Menkir, A., Wegary, D., Kebede, Y., Tesfaye, K., Kassie, M., Bogale, G., Tadesse, B., and Keno, T. (2015). Factors that transformed maize productivity in Ethiopia. *Food Security* **7**, 965-981.

Abera, S., Alemu, D., and Zemedu, L. (2016). Determinants of Haricot Bean Market Participation in Misrak Badawacho District, Hadiya zone, Southern Nations Nationalities and Peoples Regional State, Ethiopia. *Ethiopian Journal of Agricultural Sciences* **26**, 69-81.

Abera, W., Labuschagne, M., and Maartens, H. (2006). Evaluation of maize genotypes using parametric and non-parametric stability estimates. *Cereal Research Communications* **34**, 925-931.

Abera, W., Van Rensburg, J., Labuschagne, M., and Maartens, H. (2004). Genotype-environment interactions and yield stability analyses of maize in Ethiopia. *South African Journal of Plant and Soil* **21**, 251-254.

Abera, Y., and Kebede, M. (2013). Assessment on the status of some micronutrients in Vertisols of the central highlands of Ethiopia. *International Research Journal of Agricultural Science and Soil Science* **3**, 169-173.

Abrams, S., Shenk, J., Westerhaus, M., and Barton, F. (1987). Determination of Forage Quality by near Infrared Reflectance Spectroscopy: Efficacy of Broad-Based Calibration Equations. *Journal of Dairy Science* **70**, 806-813.

Adeoti, A. I. (2008). Factors influencing irrigation technology adoption and its impact on household poverty in Ghana. *Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS)* **109**, 51-63.

Adesogan, A., Givens, D., and Owen, E. (2000). Measuring chemical composition and nutritive value in forages. In 'Field and laboratory methods for grassland and animal

production research'.(Eds L t'Mannetje, RM Jones) pp. 263–278. CABI Publishing: Warwickshire.

Adesogan, A., Owen, E., and Givens, D. (1998). Prediction of the in vivo digestibility of whole crop wheat from in vitro digestibility, chemical composition, in situ rumen degradability, in vitro gas production and near infrared reflectance spectroscopy. *Animal Feed Science and Technology* **74**, 259-272.

Adjei, M., and Fianu, F. (1985). The effect of cutting interval on the yield and nutritive value of some tropical legumes on the coastal grassland of Ghana. *Tropical Grasslands* **19**, 164-171.

Admassu, S., Nigussie, M., and Zelleke, H. (2008). Genotype-environment interaction and stability analysis for grain yield of maize (Zea mays L.) in Ethiopia. *Asian Journal of Plant Sciences* **7**, 163-169.

African Business Council, N. (2010). Livestock in Ethiopia and opportunity analyses for Dutch investment. *Netherlands: pp1-27*.

Agnew, R., Park, R., Mayne, C., and Laidlaw, A. (2004). Potential of near infrared spectroscopy to predict the voluntary intake of grazed grass. *Animal Feed Science and Technology* **115**, 169-178.

Agrawal, A. (1995). Dismantling the divide between indigenous and scientific knowledge. *Development and Change* **26**, 413-439.

Akin, D., Hanna, W., and Rigsby, L. (1986). Normal-12 and brown midrib-12 sorghum. I. Variations in tissue digestibility. *Agronomy Journal* **78**, 827-832.

Akinola, A. A., Alene, A. D., Adeyemo, R., Sanogo, D., Olanrewaju, A. S., Nwoke, C., and Nziguheba, G. (2010). Determinants of adoption and intensity of use of balance nutrient management systems technologies in the northern Guinea savanna of Nigeria. *Quarterly Journal of International Agriculture* **49**, 25-45.

Akudugu, M. A., Guo, E., and Dadzie, S. K. (2012). Adoption of modern agricultural production technologies by farm households in Ghana: What factors influence their decisions. *Journal of Biology, Agriculture and Healthcare* **2**, 1-13.

Albanell, E., Plaixats, J., Ferret, A., Bosch, L., and Casañas, F. (1995). Evaluation of near-infrared reflectance spectroscopy for predicting stover quality trait in semi-exotic populations of maize. *Journal of the Science of Food and Agriculture* **69**, 269-273.

Albayrak, S., Türk, M., and Bozkurt, Y. (2013). Effects of harvesting stages on forage yield and quality of crimson clover. *Scientific Papers-Series A, Agronomy* **56**, 174-176.

Alemu, T. (2016). Variability in food-feed traits in chickpea (Cicer arietinum) varieties, MSc thesis, Hawassa University, Hawassa, Ethiopia. 96pp.

Allen, M. S. (1996). Physical constraints on voluntary intake of forages by ruminants. *Journal of Animal Science* **74**, 3063-3075.

Allison, C. (1985). Factors affecting forage intake by range ruminants: a review. *Journal of Range Management* **38**, 305-311.

Alomar, D. D., Fuchslocher, R. R., Cuevas, J. J., Madrones, R. R., and Cuevas, E. E. (2009). Prediction of the composition of fresh pastures by near infrared reflectance or interactance-reflectance spectroscopy. *Chilean Journal of Agricultural Research* **69**, 198-206.

Amede, T. (1993). Quantitative and Physiological Traits in Maize (Zea Mays L.) Associated with Different Levels of Moisture, Plant Density and Leaf Defoliation in Ethiopia. *In* "First National Maize Workshop of Ethiopia " (B. Tolessa, Ransom, J. K, ed.), pp. 74-80. IAR, 5-7 May 1992, Addis Ababa, Ethiopia, .

Amodu, J., Kallah, M., Onifade, O., Omokanye, A., and Adeyinka, I. (2001). The effect of harvesting at different growth stages on yield and quality of three late-maturing pearl millet accessions in northern Nigeria. *Tropical Grasslands* **35**, 175-179.

Anand Vadivelu, G., Wani, S., Bhole, L., Pathak, P., and Pande, A. (2006). An Empirical Analysis of the Relationship between Land Size, Ownership, and Soybean Productivity-New Evidence from the Semi-Arid Tropical Region in Madhya Pradesh, India. Natural Resource Management Program Report no. 4. *SAT eJournal* **2**, 1-43.

Anandan, S., Khan, A., Ravi, D., Rao, M. S. B., Reddy, Y. R., and Blümmel, M. (2013). Identification of a superior dual purpose maize hybrid among widely grown hybrids in South Asia and value addition to its stover through feed supplementation and feed processing. *Field Crops Research* **153**, 52-57.

Anley, W., Zeleke, H., and Dessalegn, Y. (2013). Genotype X environment interaction of maize (Zea mays L.) across North Western Ethiopia. *Journal of Plant Breeding and Crop Science* **5**, 171-181.

Anonymous (1995a). "Acid detergent and neutral detergent fibre using ANKOM's fibre analyser F200. ," Ankom Technology Corporation, Fairport, NY.

Anonymous (1995b). "In vitro true digestibility using ANKOM's DAISYII. ," ANKOM Technology Corporation, Fairport, NY.

AOAC (2005). "Combustion method of analysis (997.09). Official methods of analysis, 18th edn. Association of Official Analytical Chemist (AOAC)," Washington D.C. USA.

Araújo, A. P., and Teixeira, M. G. (2003). Nitrogen and phosphorus harvest indices of common bean cultivars: Implications for yield quantity and quality. *Plant and Soil* **257**, 425-433.

Araújo, A. P., and Teixeira, M. G. (2008). Relationships between grain yield and accumulation of biomass, nitrogen and phosphorus in common bean cultivars. *Revista Brasileira de Ciência do Solo* **32**, 1977-1986.

ARC (1980). "The nutrient requirements of ruminant livestock: Technical review by an Agricultural Research Council working party," Great Britain.

Aredo, T. A., and Musimba, N. (2003a). Study on the chemical composition, intake and digestibility of maize stover, tef straw and haricot bean haulms in Adami Tulu District, Ethiopia. *Kasetsart Journal* **37**, 401-407.

Aredo, T. A., and Musimba, N. (2003b). Study on the chemical composition, intake and digestibility of maize stover, tef straw and haricot bean haulms in Adami Tulu District, Ethiopia. *Kasetsart Journal* **37**, 401-407.

Asefa, S., and Mekonnen, D. (1992). Leaf removal and planting density effects on grain yield and yield components of maize (Zea mays L.). *Ethiopian Journal of Agricultural Sciences* **13**, 1-8.

Asekova, S., Han, S.-I., Choi, H.-J., Park, S.-j., Shin, D.-H., Kwon, C.-H., Shannon, J. G., and LEE, J. D. (2016). Determination of forage quality by near-infrared reflectance spectroscopy in soybean. *Turkish Journal of Agriculture and Forestry* **40**, 45-52.

Aserse, A. A., Räsänen, L. A., Assefa, F., Hailemariam, A., and Lindström, K. (2012). Phylogeny and genetic diversity of native rhizobia nodulating common bean (Phaseolus vulgaris L.) in Ethiopia. *Systematic and applied microbiology* **35**, 120-131.

Asfaw, A., Almekinders, C. J., Struik, P. C., and Blair, M. W. (2013). Farmers common bean variety and seed management in the face of drought and climate instability in southern Ethiopia. *Scientific Research and Essays* **8**, 1022-1037.

Asfaw, A., and Blair, M. W. (2014). Quantification of drought tolerance in Ethiopian common bean varieties. *Agricultural Sciences* **5**, 124-139.

Assefa, G., and Ledin, I. (2000). Available feed resources and the role of cultivated forage crops in the smallholder farming systems in the central highlands of Ethiopia. *In* "Conference of Ethiopian Society of Animal Production, 8th, Addis Ababa, Ethiopia, 24-26 Aug 2000", pp. 265-278. Ethiopian Society of Animal Production.

Ayele, S., and Bosire, C. (2011). "Farmers' use of improved agricultural inputs and practices: review and synthesis of research in Ethiopia." Ministry of Agriculture and Rural Development and ILRI, Addis Ababa, Ethiopia.

Ayenew, Y. A., Wurzinger, M., Tegegne, A., and Zollitsch, W. (2009). Performance and limitation of two dairy production systems in the North western Ethiopian highlands. *Tropical Animal Health and Production* **41**, 1143–1150.

Ayoade, J., Makhambera, P., and Bodzalekani, M. (1983). Evaluation of crop residues as feeds for goats. 1. Voluntary intakes, digestibility and nitrogen utilization of groundnut and bean haulms. *South African Journal of Animal Science* **13**, 12-13.

Aziz, A., Rehman, H. u., and Khan, N. (2007). Maize cultivar response to population density and planting date for grain and biomass yield. *Sarhad Journal of Agriculture* **23**, 25-30.

Badu-Apraku, B., Oyekunle, M., Obeng-Antwi, K., Osuman, A., Ado, S., Coulibay, N., Yallou, C., Abdulai, M., Boakyewaa, G., and Didjeira, A. (2012). Performance of extra-early maize cultivars based on GGE biplot and AMMI analysis. *The Journal of Agricultural Science* **150**, 473-483.

Banerjee, H., Goswami, R., Chakraborty, S., Dutta, S., Majumdar, K., Satyanarayana, T., Jat, M., and Zingore, S. (2014). Understanding biophysical and socio-economic determinants of maize (Zea mays L.) yield variability in eastern India. *NJAS-Wageningen Journal of Life Sciences* **70**, 79-93.

Barber, G., Offer, N., and Givens, D. (1989). Predicting the nutritive value of silage. *In* "Recent Advances in Animal Nutrition" (W. Haresign and D. J. A. Cole, eds.), pp. 141-158, Butterworths, London.

Baron, V., Najda, H., and Stevenson, F. (2006). Influence of population density, row spacing and hybrid on forage corn yield and nutritive value in a cool-season environment. *Canadian Journal of Plant Science* **86**, 1131-1138.

Barrière, Y., Guillet, C., Goffner, D., and Pichon, M. (2003). Genetic variation and breeding strategies for improved cell wall digestibility in annual forage crops. A review. *Animal Research* **52**, 193-228.

Batterham, E., and Egan, A. (1987). Utilisation of food legumes as feed. *In* "Food legume improvement for Asian farming systems" (E. S. WalEs, Byth, D.E., ed.), pp. 193-200, 1-5 September 1986, Khon Kaen, Thailand.

Baudron, F., Jaleta, M., Okitoi, O., and Tegegn, A. (2014). Conservation agriculture in African mixed crop-livestock systems: Expanding the niche. *Agriculture, Ecosystems and Environment* **187**, 171-182.

Bediye, S., and Sileshi, Z. (1989). "The composition of Ethiopian feedstuffs." Institute of agricultural research (IAR) report no.6. IAR, Addis Ababa, Ethiopia. 34pp.

Bediye, S., Sileshi, Z., Asefa, G., and Gebre, H. (1998). Effect of cultivar and fertilizer application on yield and quality of barley straw. *In* "Proceedings of the 6th annual conference of the Ethiopian society of animal production (ESAP) ", pp. 279-285, 14-15 May, 1998. ESAP, Addis Ababa, Ethiopia.

Bediye, S., Sileshi, Z., and Mengiste, T. (1996). Tef (Eragrostis tef) straw quality as influenced by variety differences and locations. *In* "4th National Conference of the Ethiopian Society of Animal Production". ESAP, 18-19 April 1996, Addis Ababa, Ethiopia.

Beebe, S. E., Rao, I. M., Blair, M. W., and Acosta-Gallegos, J. A. (2010). Phenotyping common beans for adaptation to drought. *Drought Phenotyping in Crops: From Theory to Practice*, 311-334.

Beech, D., and Basinski, J. (1975). Effect of plant populations and row spacings on early and late maize hybrids in the Ord Valley. *Australian Journal of Experimental Agriculture and Animal Husbandry* **15**, 406-413.

Beever, D. E., and Mould, F. (2000). Forage Evaluation for Efficient Ruminant Livestock Production. *In* "Forage evaluation in ruminant nutrition" (D. I. Givens, E. Owen, R. F. E. Axford and H. M. Omed, eds.), pp. 15-42. CABI, Wallingford, UK

Bekele, T., and Yilma, Z. (2004). Feeding Noug (*Guizotia abyssinca*) Cake as Protein Source to Lactating Boran x Jersey Crossbred Cows: Performances in Milk Yield, Reproduction, and Feed Efficiency. *In* "Farm animal biodiversity in Ethiopia: Status and prospects. " (A. Yimegnuhal, Degefa, T ed.), pp. 375-385., Proceedings of the 11th annual conference of the Ethiopian society of animal production (ESAP), August 28-30, 2003, Addis Ababa.

Bernard, J., West, J., Trammell, D., and Cross, G. (2004). Influence of corn variety and cutting height on nutritive value of silage fed to lactating dairy cows. *Journal of Dairy Science* **87**, 2172-2176.

Beyene, Y., Mugo, S., Mutinda, C., Tefera, T., Karaya, H., Ajanda, S., Shuma, J., Tende, R., and Kega, V. (2011a). Genotype by environment interactions and yield stability of stem borer resistant maize hybrids in Kenya. *African Journal of Biotechnology* **30**, 4752-4758.

Beyene, Y., Mugo, S., Pillay, K., Tefera, T., Njoka, S., Karaya, H., and Gakunga, J. (2011b). Testcross performance of doubled haploid maize lines derived from tropical adapted backcross populations. *Maydica* **56**, 351–358.

Beyene, Y., Mugo, S., Semagn, K., Asea, G., Trevisan, W., Tarekegne, A., Tefera, T., Gethi, J., Kiula, B., and Gakunga, J. (2013). Genetic distance among doubled haploid maize lines and their testcross performance under drought stress and non-stress conditions. *Euphytica* **192**, 379-392.

Bhaid, M., and Talapatra, S. (1965). Cowpea as a dual purpose crop. *Indian Journal of Dairy Science* **18**, 153-155.

Bhaid, M., and Talaptra, S. (1965). Cowpea as a dual purpose crop. *Indian Journal of Dairy Science* **18**, 153.

Bidinger, F., and Blümmel, M. (2007). Determinants of ruminant nutritional quality of pearl millet [Pennisetum glaucum (L.) R. Br.] stover: I. Effects of management alternatives on stover quality and productivity. *Field crops research* **103**, 119-128.

Blümmel, M., Bidinger, F., and Hash, C. (2007). Management and cultivar effects on ruminant nutritional quality of pearl millet (Pennisetum glaucum (L.) R. Br.) stover: II. Effects of cultivar choice on stover quality and productivity. *Field crops research* **103**, 129-138.

Blümmel, M., Grings, E. E., and Erenstein, O. (2013a). Potential for dual-purpose maize varieties to meet changing maize demands: synthesis. *Field Crops Research* **153**, 107-112.

Blümmel, M., Tui, S. H.-K., Valbuena, D., Duncan, A. J., and Herrero, M. (2013b). Biomass in crop-livestock systems in the context of the livestock revolution. *Science et changements planétaires/Sécheresse* **24**, 330-339.

Blümmel, M., Zerbini, E., Reddy, B., Hash, C., Bidinger, F., and Khan, A. (2003). Improving the production and utilization of sorghum and pearl millet as livestock feed: progress towards dual-purpose genotypes. *Field Crops Research* **84**, 143-158.

Bogale, G., Wegary, D., Tilahun, L., and Gebre, D. (2012a). Maize Improvement for Low-Moisture Stress Areas of Ethiopia: Achievements and Progress in the Last Decade *In* "Meeting the Challenges of Global Climate Change and Food Security through Innovative Maize Research. Proceedings of the Third National Maize Workshop of Ethiopia. " (M. Worku, Twumasi-Afriyie, S., Wolde, L., Tadesse, B., Demisie G., Bogale, G., Wegary, D. and Prasanna, B.M., ed.), pp. 35-42, Mexico, DF: CIMMYT.

Bogale, S., Melaku, S., and Yami, A. (2008). Potential use of crop residues as livestock feed resources under smallholder farmers conditions in Bale highlands of Ethiopia. *Tropical and Subtropical Agroecosystems* **8**, 107-114.

Bogale, T., Tolera, A., Tewodros, M., Hailu, G., Desalegn, T., Workayew, T., Mazengia, W., and Harun, H. (2012b). Review on Crop Management Research for Improved Maize Productivity in Ethiopia. *In* "Meeting the Challenges of Global Climate Change and Food Security through Innovative Maize Research" (M. Worku, Twumasi-Afriyie, S., Wolde, L., Tadesse, B., Demisie G., Bogale, G., Wegary, and B. M. D. and Prasanna, eds.), pp. 105-114. Mexico, DF: CIMMYT, Proceedings of the Third National Maize Workshop April 18–20, 2011, Addis Ababa, Ethiopia.

Bonsi, M., and Osuji, P. (1997). The effect of feeding cottonseed cake, sesbania or leucaena with crushed maize as supplement to teff straw. *Livestock Production Science* **51**, 173-181.

Bonsi, M., Osuji, P., Tuah, A., and Umunna, N. (1995). Intake, digestibility, nitrogen balance and certain rumen characteristics of Ethiopian Menz sheep fed teff straw supplemented with cotton seed cake, dry sesbania, dry leucaena or fresh leucaena. *Agroforestry Systems* **31**, 243-256.

Boon, E., Engels, F., Struik, P., and Cone, J. (2005). Stem characteristics of two forage maize (Zea mays L.) cultivars varying in whole plant digestibility. II. Relation between in vitro rumen fermentation characteristics and anatomical and chemical features within a single internode. *NJAS-Wageningen Journal of Life Sciences* **53**, 87-109.

Boon, E., Struik, P., Engels, F., and Cone, J. (2012). Stem characteristics of two forage maize (Zea mays L.) cultivars varying in whole plant digestibility. IV. Changes during the growing season in anatomy and chemical composition in relation to fermentation characteristics of a lower internode. *NJAS-Wageningen Journal of Life Sciences* **59**, 13-23.

Boon, E., Struik, P., Tamminga, S., Engels, F., and Cone, J. (2008). Stem characteristics of two forage maize (Zea mays L.) cultivars varying in whole plant digestibility. III. Intra-stem variability in anatomy, chemical composition and in vitro rumen fermentation. *NJAS-Wageningen Journal of Life Sciences* **56**, 101-122.

Borreani, G., Cavallarin, L., Antoniazzi, S., and Tabacco, E. (2006). Effect of the stage of growth, wilting and inoculation in field pea (Pisum sativum L.) silages. I. Herbage composition and silage fermentation. *Journal of the Science of Food and Agriculture* **86**, 1377-1382.

Bouveresse, E., Casolino, C., and De la Pezuela, C. (1998). Application of standardisation methods to correct the spectral differences induced by a fibre optic probe used for

the near-infrared analysis of pharmaceutical tablets. *Journal of Pharmaceutical and Biomedical Analysis* **18**, 35-42.

Bouveresse, E., and Massart, D. (1996a). Standardisation of near-infrared spectrometric instruments: a review. *Vibrational Spectroscopy* **11**, 3-15.

Bouveresse, E., and Massart, D. (1996b). Improvement of the piecewise direct standardisation procedure for the transfer of NIR spectra for multivariate calibration. *Chemometrics and Intelligent Laboratory Systems* **32**, 201-213.

Broughton, W. J., Hernandez, G., Blair, M., Beebe, S., Gepts, P., and Vanderleyden, J. (2003). Beans (Phaseolus spp.)–model food legumes. *Plant and Soil* **252**, 55-128.

Brown, R., Beaty, E., Ethredge, W., and Hayes, D. (1970). Influence of row width and plant population on yield of two varieties of corn (Zea mays L.). *Agronomy Journal* **62**, 767-770.

Brown, W., Moore, J., Kunkle, W., Chambliss, C., and Portier, K. (1990). Forage testing using near infrared reflectance spectoscopy. *Journal of Animal Science* **68**, 1416-1427.

Burken, D. B., Harding, J. L., McGee, A. L., Hoegemeyer, T. C., Klopfenstein, T., and Erickson, G. E. (2013). "Effects of corn hybrid, plant density, and harvest time on yield and quality of corn plants." Nebraska Beef Cattle Reports. Paper 719

Butterworth, M., and Mosi, A. (1986). The intake and digestibility by sheep of oat straw and maize stover offered with different levels of noug (Guizotia abyssinica) meal. *Animal Feed Science and Technology* **16**, 99-107.

Buxton, D. (2004). "Growing quality forages under variable environmental conditions," USDA, Iowa State University, USA.

Buxton, D. R. (1996). Quality-related characteristics of forages as influenced by plant environment and agronomic factors. *Animal Feed Science and Technology* **59**, 37-49.

Campo, L., Monteagudo, A., Salleres, B., Castro, P., and Moreno-Gonzalez, J. (2013). NIRS determination of non-structural carbohydrates, water soluble carbohydrates and other nutritive quality traits in whole plant maize with wide range variability. *Spanish Journal of Agricultural Research* **11**, 463-471.

Capper, B. (1988). Genetic variation in the feeding value of cereal straw. *Animal Feed Science and Technology* **21**, 127-140.

Capper, B. (1990). The role of food legume straw and stubble in feeding livestock. *In* "The Role of Legumes in the Farming Systems of the Mediterranean Areas", pp. 151-162. Springer.

Capper, B., Thomson, E., and Rihawi, S. (1989). Voluntary intake and digestibility of barley straw as influenced by variety and supplementation with either barley grain or cottonseed cake. *Animal Feed Science and Technology* **26**, 105-118.

Carter, M. R. (1984). Identification of the inverse relationship between farm size and productivity: an empirical analysis of peasant agricultural production. *Oxford Economic Papers* **36**, 131-145.

Casler, M. D. (2001). Breeding forage crops for increased nutritional value. *Advan. Agron.* **71**, 51-107.

Casler, M. D., and Van Santen, E. (2010). Breeding objectives in forages. *In* "Fodder Crops and Amenity Grasses", pp. 115-136. Springer.

Casler, M. D., and Vogel, K. P. (1999). Accomplishments and impact from breeding for increased forage nutritional value. *Crop Science* **39**, 12-20.

Cecchi, G., Wint, W., Shaw, A., Marletta, A., Mattioli, R., and Robinson, T. (2010). Geographic distribution and environmental characterization of livestock production systems in Eastern Africa. *Agriculture, Ecosystems and environment* **135**, 98-110.

Chand, R., Prasanna, P. L., and Singh, A. (2011). Farm size and productivity: Understanding the strengths of smallholders and improving their livelihoods. *Economic and Political Weekly* **46**, 5-11.

Cheva-Isarakul, B., and Saengdee, C. (1987). Voluntary intake, nutrient digestibility and nitrogen balance in sheep fed sorghum. Ruminant feeding systems utilizing fibrous agricultural residues-1986. *In* "Proceedings of the 6th Annual Workshop of the Australian-Asian Fibrous Agricultural Residues Research Network" (R. M. Dixon, ed.), pp. 133-138, 1-3 April 1986, Los Baños, International Development Program of Australian Universities and Colleges Ltd., Canberra, Australia.

Coates, D., and Dixon, R. (2011). Developing robust faecal near infrared spectroscopy calibrations to predict diet dry matter digestibility in cattle consuming tropical forages. *Journal of Near Infrared Spectroscopy* **19**, 507-519.

Coleman, S. W., and Moore, J. E. (2003). Feed quality and animal performance. *Field Crops Research* **84**, 17-29.

Cone, J., and Engels, F. (1990). Influence of growth temperature on anatomy and in vitro digestibility of maize tissues. *The Journal of Agricultural Science* **114**, 207-212.

Conrad, H. R., Pratt, A. D., and Hibbs, J. W. (1964). Regulation of feed intake in dairy cows. 1. Change in importance of physical and physiological factors with increasing digestibility. *Journal of Dairy Science* **47**, 54–62.

Cox, J. W., Cherney, D. R., and Hanchar, J. J. (1998). Row spacing, hybrid, and plant density effects on corn silage yield and quality. *Journal of Production Agriculture* **11**, 128-134.

Cox, W. J. (1996). Whole-plant physiological and yield responses of maize to plant density. *Agronomy Journal* **88**, 489-496.

Cox, W. J. (1997). Corn silage and grain yield responses to plant densities. *Journal of Production Agriculture* **10**, 405-410.

Cox, W. J., and Cherney, D. J. (2001). Influence of brown midrib, leafy, and transgenic hybrids on corn forage production. *Agronomy Journal* **93**, 790-796.

Cox, W. J., and Cherney, J. H. (2011). Lack of hybrid by seeding rate interactions for corn growth, silage yield, and quality. *Agronomy Journal* **103**, 1051-1057.

Cozzolino, D., Fassio, A., Fernández, E., Restaino, E., and La Manna, A. (2006). Measurement of chemical composition in wet whole maize silage by visible and near infrared reflectance spectroscopy. *Animal Feed Science and Technology* **129**, 329-336.

Cozzolino, D., Fassio, A., and Gimenez, A. (2001). The use of near-infrared reflectance spectroscopy (NIRS) to predict the composition of whole maize plants. *Journal of the Science of Food and Agriculture* **81**, 142-146.

Crosse, S., Umunna, N., Osuji, P., Tegegne, A., Khalili, H., and Tedla, A. (1998). Comparative yield and nutritive value of forages from two cereal-legume based cropping systems. 2. Milk production and reproductive performance of crossbred dairy cows. *Tropical Agriculture* **75**, 415-421.

CSA (2004). "Agricultural Sample Survey, Report on area and production of major crops of private peasant holdings for the year 2003/4, Meher season, Volume I," Rep. No. 302. Central Statistical Authority, Addis Ababa, Ethiopia.

CSA (2012a). "Agricultural Sample Survey, Report on livestock and livestock characteristics of private peasant holdings for the year 2011/12, Volume II " Rep. No. 532. Central Statistical Agency, Addis Ababa, Ethiopia.

CSA (2012b). "Agricultural Sample Survey Report on area and production of major crops of private peasant holdings for the year 2011/12, Meher season, Volume I." Central Statistical Agency, Addis Ababa, Ethiopia.

CSA (2017). "Agricultural Sample Survey, Report on livestock and livestock characteristics of private peasant holdings for the year 2016/17, Volume II ". Federal democratic republic of Athiopia, Central Statistical Agency (CSA), Addis Ababa, Ethiopia.

CSIRO (2007). "Nutrient requirements of domesticated ruminants," CSIRO publishing.

Cuomo, G. J., Redfearn, D. D., and Blouin, D. C. (1998). Plant density effects on tropical corn forage mass, morphology, and nutritive value. *Agronomy Journal* **90**, 93-96.

Cusicanqui, J. A., and Lauer, J. G. (1999). Plant density and hybrid influence on corn forage yield and quality. *Agronomy Journal* **91**, 911-915.

Dada, S., Adeneye, J., Akinsoyinu, A., Smith, J., and Dashiell, K. (1999). Performance of sheep fed soybean stover and cassava crumb based diets. *Small Ruminant Research* **31**, 229-238.

Dadi, L., Regassa, S., Fikre, A., Mitiku, D., Gaur, P., Gowda, C., and Bantilan, M. (2005). "Adoption studies on improved chickpea varieties in Ethiopia." EIAR AND ICRISAT, Addsi Ababa, Ethiopia. 40pp.

Dakora, F., and Keya, S. (1997). Contribution of legume nitrogen fixation to sustainable agriculture in Sub-Saharan Africa. *Soil Biology and Biochemistry* **29**, 809-817.

De Boever, J., Cottyn, B., Vanacker, J., and Boucqué, C. V. (1995). The use of NIRS to predict the chemical composition and the energy value of compound feeds for cattle. *Animal Feed Science and Technology* **51**, 243-253.

De Groote, H., Dema, G., Sonda, G. B., and Gitonga, Z. M. (2013). Maize for food and feed in East Africa—The farmers' perspective. *Field Crops Research* **153**, 22-36.

Deaville, E., and Flinn, P. (2000). Near-infrared (NIR) spectroscopy: an Alternative Approach for the Estimation of Forage Quality and Voluntary Intake. *In* "Forage evaluation in ruminant nutrition" (D. I. Givens, Owen, E., Axford, R.F.E., Omed, H.M ed.), pp. 301-320. CABI Publishing, Wallingford, UK.

Deinum, B., and Struik, P. (1989). Genetic variation in digestibility of forage maize (Zea mays L.) and its estimation by near infrared reflectance spectroscopy (NIRS). An analysis. *Euphytica* **42**, 89-98.

DeLacy, I., Basford, K., Cooper, M., Bull, J., and McLaren, C. (1996). Analysis of multi-environment trials–an historical perspective. *In* "Plant adaptation and crop improvement" (M. Cooper and G. L. Hammer, eds.), pp. 39-124. CAB International, Wallingford, UK.

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., and Courbois, C. (1999). "Livestock to 2020: the next food revolution.." Food, Agriculture, and the Environment Discussion Paper No. 28, International Food Policy Research Institute, Washington, DC:.

DeLougherty, R. L., and Crookston, R. K. (1979). Harvest index of corn affected by population density, maturity rating, and environment. *Agronomy Journal* **71**, 577-580.

Desalegn, K. (2015). Review on Reproductive and Productive Performance of Fogera Cattle. *European Journal of Applied Sciences* **7**, 235-240.

Devendra, C., and Sevilla, C. (2002). Availability and use of feed resources in crop–animal systems in Asia. *Agricultural Systems* **71**, 59-73.

Dewhurst, R. J., Evans, R., Scollan, N., Moorby, J., Merry, R., and Wilkins, R. (2003). Comparison of grass and legume silages for milk production. 2. In vivo and in sacco evaluations of rumen function. *Journal of Dairy Science* **86**, 2612-2621.

Diao, X., Fekadu, B., Haggblade, S., Taffesse, A. S., Wamisho, K., and Yu, B. (2007). "Agricultural growth linkages in Ethiopia: Estimates using fixed and flexible price models," International Food Policy Research Institute Washington, DC.

Dias-da-Silva, A., and Guedes, C. V. (1990). Variability in the nutritive value of straw cultivars of wheat, rye and triticale and response to urea treatment. *Animal Feed Science and Technology* **28**, 79-89.

Dinka, H., Chala, R., Dawo, F., Bekana, E., and Leta, S. (2010). Major constraints and health management of village poultry production in rift valley of Oromia, Ethiopia. *Am-Eurasian Journal of Agricalture and Enviromental Science* **9**, 529-533.

Dione, M., Pezo, D., Kyalo, G., Mayega, L., Nadiope, G., and Lukuyu, B. (2015). Perception and practices of farmers on the utilization of sweetpotato, and other root tubers, and banana for pig feeding in smallholder crop-livestock systems in Uganda. *Livestock Research for Rural Development* **27**, Article #226.

Dixon, J. A., Li, X., Msangi, S., Amede, T., Bossio, D. A., Ceballos, H., Ospina, B., Howeler, R. H., Reddy, B., and Abaidoo, R. (2010). "Feed, food and fuel: Competition and potential impacts on small-scale crop-livestock-energy farming systems." ILRI, Nairobi: ILRI (International Livestock Research Institute). 114pp.

Dixon, R., and Coates, D. (2010). Application of near infrared spectroscopy to improve animal production in developing countries. *In* "Sustainable Improvement of Animal Production and Health. FAO/IAEA International Symposium on Sustainable Improvement of Animal Production and Health" (N. E. Odongo, Garcia, M., Viljoen, G.J., ed.), pp. 167-174, 2-11 June 2009, Vienna, Austria.

Dolstra, O., Medema, J., and Jong, A. (1992). Genetic improvement of cell-wall digestibility in forage maize (Zea mays L.). I. Performance of inbred lines and related hybrids. *Euphytica* **65**, 187-194.

Dong, C. F., Shen, Y. X., Ding, C. L., Xu, N. X., Cheng, Y. H., and Gu, H. R. (2013). The feeding quality of rice (Oryza sativa L.) straw at different cutting heights and the related stem morphological traits. *Field Crops Research* **141**, 1-8.

Doyle, P. T., Devendra, C., and Pearce, G. R. (1986). "Rice straw as a feed for ruminants," IDP, Canberra. 117pp.

Duncan, A., Gerard, B. G., Valbuena, D., Blummel, M., and Tarawali, S. (2011). Crop residues in smallholder systems: Pressures and trade-offs. Nairobi, Kenya: ILRI (International Livestock Research Institute). 4pp.

Duncan, A. J., Bachewe, F., Mekonnen, K., Valbuena, D., Rachier, G., Lule, D., Bahta, M., and Erenstein, O. (2016). Crop residue allocation to livestock feed, soil improvement and other uses along a productivity gradient in Eastern Africa. *Agriculture, Ecosystems and Environment* **228**, 101-110.

Duncan, A. J., Teufel, N., Mekonnen, K., Singh, V. K., Bitew, A., and Gebremedhin, B. (2013). Dairy intensification in developing countries: effects of market quality on farm-level feeding and breeding practices. *Animal* **7**, 2054–2062.

Dwyer, L., Stewart, D., and Tollenaar, M. (1991). Changes in plant density dependence of leaf photosynthesis of maize (Zea mays L.) hybrids, 1959 to 1988. *Canadian Journal of Plant Science* **71**, 1-11.

Dwyer, L., Stewart, D., and Tollenaar, M. (1992). Analysis of maize leaf photosynthesis under drought stress. *Canadian Journal of Plant Science* **72**, 477-481.

Ebro, A., Nsahlai, I., Yami, A., and Umunna, N. (2004). Effect of supplementing graded levels of forage legumes on performance of crossbred calves fed tef (Eragrostis tef) straw. *Journal of Applied Animal Research* **26**, 107-112.

Ebro, A., Tadesse, T., and Abebe, T. (2005). The supplementation of haricot bean residue with lablab (Lablab purpureus) hay in the diet of Arsi bulls and heifers (Bos indicus). *Tropical Science* **45**, 114-117.

Ebro, A., Umunna, N., Yami, A., and Nsahlai, I. (1995). Effect of cowpea (Vigna unguiculata) and Lablab (Lablab purpureus) hay supplementation on nitrogen and energy utilization in calves fed tef (Eragrostis tef) straw. *In* "Proceedings of the 3rd annual conference of the Ethiopian Society of Animal Production ". ESAP, 27-29 Apr 1995, Addis Ababa, Ethiopia.

Eckman, D., Shenk, J., Wangsness, P., and Westerhaus, M. (1983). Prediction of Sheep Responses by near Infrared Reflectance Spectroscopy. *Journal of Dairy Science* **66**, 1983-1987.

Edney, M., Morgan, J., Williams, P., and Campbell, L. (1994). Analysis of feed barley by near infrared reflectance technology. *Journal of Near Infrared Spectroscopy* **2**, 33-41.

Edwards, J., Purcell, L., and Vories, E. (2005). Light interception and yield of short-season maize (Zea mays L.) hybrids in the mid-south. *Agronomy Journal* **97**, 225-234.

Ellis, F., and Freeman, H. A. (2004). Rural livelihoods and poverty reduction strategies in four African countries. *Journal of Development Studies* **40**, 1-30.

Emiru, T. S. (2014). Population dynamics and its impact on land use/cover in Ethiopia: the case of Manduara Disctrict of Metekel Zone, Benshangul-Gumuz Regional State. Geography, University of South Africa.

Engels, F. M., and Schuurmans, J. L. (1992). Relationship between structural development of cell walls and degradation of tissues in maize stems. *Journal of the Science of Food and Agriculture* **59**, 45-51.

Erenstein, O. (2002). Crop residue mulching in tropical and semi-tropical countries: An evaluation of residue availability and other technological implications. *Soil and Tillage Research* **67**, 115-133.

Erenstein, O. (2003). Smallholder conservation farming in the tropics and sub-tropics: a guide to the development and dissemination of mulching with crop residues and cover crops. *Agriculture, Ecosystems and Environment* **100**, 17-37.

Erenstein, O., Blummel, M., and Grings, E. (2013). Potential for dual-purpose maize varieties to meet changing maize demands: Overview. *Field Crops Research* **153**, 1-4.

Erenstein, O., and Thorpe, W. (2010). Crop–livestock interactions along agro-ecological gradients: a meso-level analysis in the Indo-Gangetic Plains, India. *Environment, Development and Sustainability* **12**, 669-689.

Erickson, D., Meyer, D., and Foster, A. (1982). The effect of genotypes on the feed value of barley straws. *Journal of Animal Science* **55**, 1015-1026.

Erskine, W. (1983). Relationship between the yield of seed and straw in lentil. *Field Crops Research* **7**, 115-121.

Erskine, W., Kusmenoglu, I., Muehlbauer, F., and Summerfield, R. (2000). Breeding for increased biomass and persistent crop residues in cool-season food legumes. *In* "Linking Research and Marketing Opportunities for Pulses in the 21st Century" (R. Knight, ed.), pp. 191-197. Springer.

Erskine, W., Rihawi, S., and Capper, B. (1990). Variation in lentil straw quality. *Animal Feed Science and Technology* **28**, 61-69.

Ertiro, B. T., Twumasi-Afriyie, S., Blümmel, M., Friesen, D., Negera, D., Worku, M., Abakemal, D., and Kitenge, K. (2013a). Genetic variability of maize stover quality

and the potential for genetic improvement of fodder value. *Field Crops Research* **153**, 79-85.

Ertiro, B. T., Zeleke, H., Friesen, D., Blummel, M., and Twumasi-Afriyie, S. (2013b). Relationship between the performance of parental inbred lines and hybrids for food-feed traits in maize (Zea mays L.) in Ethiopia. *Field Crops Research* **153**, 86-93.

Esbensen, K. H., Geladi, P., and Larsen, A. (2014). The RPD myth... *In* "mythbusters in chemometrics", Vol. 25, pp. 24-28. NIR news.

Eshete, G. (2002). An assessment of feed resources, their management and impact on livestock productivity in the Ginchi watershed area, MSc. Thesis. Alemaya University, Alemaya, Ethiopia.

Etela, I., and Dung, D. (2011). Utilization of stover from six improved dual-purpose groundnut (Arachis hypogaea L.) cultivars by West African dwarf sheep. *African Journal of Food, Agriculture, Nutrition and Development* **11**, 4538-4545.

FAO (2009). "The state of food and agriculture : Livestock in the balance. ," Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (2012). "Crop residue based densified total mixed ration– A user-friendly approach to utilise food crop by-products for ruminant production," by T.K. Walli, M.R. Garg and Harinder P.S. Makkar. FAO Animal Production and Health Paper No. 172. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAOSTAT (2012). Agricultural Production Statistics 2011. FAO Statistics Division. Rome.

Farm-Africa (2017). *In* "https://www.farmafrica.org/ethiopia/ethiopia". Farm Africa. Accessed on 19 September 2017.

Farrow, A. (2014). "Managing factors that affect the adoption of grain legumes in Ethiopia in the N2Africa project."

Feder, G., Just, R. E., and Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. *Economic Development and Cultural Change* **33**, 255-298.

Fekadu, D., Bediye, S., Kehaliw, A., Daba, T., Kitaw, G., and Assefa, G. (2010a). Near Infrared Reflectance Spectroscopy (NIRS) for determination of chemical entities of natural pasture from Ethiopia. *Agriculture and Biology Journal of North America* **1**, 919-922.

Fekadu, D., Bediye, S., and Sileshi, Z. (2010b). Characterizing and predicting chemical composition and in vitro digestibility of crop residue using near infrared reflectance spectroscopy (NIRS). *Livestock Research for Rural Development, 22, Article #29*.

Fernandez-Rivera, S., and Klopfenstein, T. (1989). Yield and quality components of corn crop residues and utilization of these residues by grazing cattle. *Journal of Animal Science* **67**, 597-605.

Fernandez-Rivera, S., Midou, A., and Marichatou, H. (1994). Effect of food allowance on diet selectivity and intake of pearl millet (*Pennisetum glaucum*) stover leaves by sheep. *Animal Production* **58**, 249–256.

Ferris, S., and Kaganzi, E. (2008). "Evaluating marketing opportunities for haricot beans in Ethiopia," Rep. No. 7, ILRI (International Livestock Research Institute), Nairobi, Kenya.

Feyissa, F., Tolera, A., and Melaku, S. (2007). Nutritive value of different varieties and morphological fractions of oats harvested at the soft dough stage. *Tropical Science* **47**, 188-196.

Fivawo, N., and Msolla, S. (2012). The diversity of common bean landraces in Tanzania. *TaJONAS: Tanzania Journal of Natural and Applied Sciences* **2**, 337-351.

Flachowsky, G., Tiroke, K., and Schein, G. (1991). Botanical fractions of straw of 51 cereal varieties and in sacco degradability of various fractions. *Animal Feed Science and Technology* **34**, 279-289.

Fleischer, J., Barnes, A., Awumbila, B., Amaning-Kwarteng, K., and Tieku, C. (1989). Grain Yield and nutritive value of crop residues from three varieties of maize (Zea Mays L) crop. *In* "Overcoming Constraints to the Efficient Utilization of Agricultural By-Products as Animal Feed" (A. N. Said, Dzowela, B.H., ed.), pp. 239-255. ILCA, Addis Ababa, Ethiopia, Proceedings of the African Research Network for Agricultural By-products (ARNAB), Bamenda, Cameroun

Forbes, J. M. (2007). "Voluntary Food Intake and Diet Selection in Farm Animals," 2nd/Ed. CAB International, Wallingford, UK.

Foster, J., Lamb, G., Tillman, B., Marois, J., Wright, D., and Maddox, M. (2012). In sacco degradation kinetics of fresh and field-cured peanut (Arachis hypogaea L.) forage harvested at different maturities. *Animal Feed Science and Technology* **171**, 52-59.

Franke, A., Van Den Brand, G., and Giller, K. (2014). Which farmers benefit most from grain legumes in Malawi? An ex-ante impact assessment based on farm characteristions and model explorations. *European Journal of Agronomy* **58**, 28-38.

Fujita, K., Ofosu-Budu, K., and Ogata, S. (1992). Biological nitrogen fixation in mixed legume-cereal cropping systems. *Plant and Soil* **141**, 155-175.

Gambin, B. L., Coyos, T., Di Mauro, G., Borrás, L., and Garibaldi, L. A. (2016). Exploring genotype, management, and environmental variables influencing grain yield of late-sown maize in central Argentina. *Agricultural Systems* **146**, 11-19.

Gebeyehu, S., and Assefa, H. (2003). Genotype x environment interaction and stability analysis of seed yield in navy bean genotypes. *African Crop Science Journal* **11**, 1-7.

Gebrehiwot, L., and Mohammed, J. (1989). The potential of crop residues, particularly wheat straw, as livestock feed in Ethiopia. *In* "Overcoming Constraints to the Efficient Utilization of Agricultural By-products as Animal Feed. African Research Network for Agricultural By-products (ARNAB), ILCA, Addis Ababa, Ethiopia", pp. 142-154.

Gebremedhin, B., Fernandez-Rivera, S., Hassena, M., Mwangi, W., and Ahmed, S. (2007). "Maize and livestock: Their inter-linked roles in meeting human needs in Ethiopia." ILRI Research Report 6. ILRI (International Livestock Research Institute), Nairobi, Kenya. 103 pp.

Gebremedhin, B., Hirpa, A., and Berhe, K. (2009). " Feed marketing in Ethiopia: Results of rapid market appraisal." Improving Productivity and Market Success (IPMS) of Ethiopian farmers project Working Paper 15. ILRI (International Livestock Research Institute), Nairobi, Kenya.

Gebremeskel, Y., Estifano, A., and Melau, S. (2011). Effect of selected faba bean (Vicia faba L.) varietal difference on straw DM yield, chemical composition and nutritional quality. *Journal of the Dry Lands* **4**, 333-340.

Gebretsadik, R., Shimelis, H., Laing, M., Tongoona, P., and Mandefro, N. (2014). A diagnostic appraisal of the sorghum farming system and breeding priorities in Striga infested agro-ecologies of Ethiopia. *Agricultural Systems* **123**, 54-61.

Gebreyohannes, G., and Hailemariam, G. (2011). "Challenges, opportunities and available good practices related to zero grazing in Tigray and Hararghe, Ethiopia," Drylands Coordination Group Report No. 66, 10, 2011.

Geleti, D. (2005a). Maize Grain Yield, Yield Components and Laboratory Evaluation of the Nutritional Value of Maize Residue Succeeding a Fallow of Panicum and Stylosanthes Binary Mixture. *In* "Participatory innovation and research: lessons for livestock development. Proceedings of the 12th annual conference of the Ethiopian society of animal production (ESAP) " (A. Yimegnuhal, Degefa, T, ed.), pp. 165-172, August 12-14, 2004, ESAP, Addis Ababa, Ethiopia.

Geleti, D. (2005b). Effect of Variety on Maize Grain Yield, Plant Fractions and Nutritional Value of the Stover. *In* "Participatory innovation and research: lessons for livestock development. Proceedings of the 12th annual conference of the Ethiopian society of animal production (ESAP) " (A. Yimegnuhal, Degefa, T ed.), pp. 181-185, August 12-14, 2004, ESAP, Addis Ababa, Ethiopia.

Geleti, D. (2005c). Effect of degree and time of defoliation of leaves on maize grain and residue yields, and nutritional value of the stover. *In* "Participatory innovation and research: lessons for livestock development. Proceedings of the 12th annual conference of the Ethiopian society of animal production (ESAP) " (A. Yimegnuhal, Degefa, T, ed.), pp. 217-223, August 12-14, 2004, ESAP, Addis Ababa, Ethiopia.

Geleti, D., Tolera, A., Mengistu, A., and Hailemariam, M. (2011). Effect of variety of maize on yield of grain, residue fractions and the nutritive value of the whole stover. *Ethiopian Journal of Applied Science and Technology* **2**, 91-96.

Genter, C., and Camper, H. (1973). Component plant part development in maize as affected by hybrids and population density. *Agronomy Journal* **65**, 669-671.

German, L. (2010). Local knowledge and scientific perceptions: questions of validity in environmental knowledge. *In* "Beyond the Biophysical: Knowledge, Culture,and Power in Agriculture and Natural Resource Management" (L. German, Ramisch, J.J., Verma, R. , ed.), pp. 99-125. Springer.

Givens, D., and Deaville, E. (1999). The current and future role of near infrared reflectance spectroscopy in animal nutrition: a review. *Australian Journal of Agricultural Research* **50**, 1131-1145.

Givens, D., Everington, J. M., and Adamson, A. (1989). The digestibility and metabolisable energy content of grass silage and their prediction from laboratory measurements. *Animal Feed Science and Technology* **24**, 27-43.

Givens, D., Everington, J. M., and Adamson, A. (1990). The nutritive value of spring-grown herbage produced on farms throughout England and Wales over 4 years. III. The prediction of energy values from various laboratory measurements. *Animal Feed Science and Technology* **27**, 185-196.

Givens, D., Moss, A. R., and Adamson, A. (1992). The chemical composition and energy value of high temperature dried grass produced in England. *Animal feed science and technology* **36**, 215-228.

Graham, P. H., and Vance, C. P. (2003). Legumes: importance and constraints to greater use. *Plant physiology* **131**, 872-877.

Graybill, J., Cox, W., and Otis, D. (1991). Yield and quality of forage maize as influenced by hybrid, planting date, and plant density. *Agronomy Journal* **83**, 559-564.

Grings, E. E., Tarawali, S., Blummel, M., Musa, A., Fatokun, C., Hearne, S., and Boukar, O. (2012). Cowpea in evolving livestock systems. *In* "Innovative research along the cowpea value chain", pp. 322-333. IITA, Proceedings of the Fifth World Cowpea Conference on improving livelihoods in the cowpea value chain through advancement in science, 27 September-1 October 2010, Saly, Senegal.

Gryseels, G. (1988). Role of livestock on mixed smallholder farms in the Ethiopian highlands. A case study from the Baso and Worena Wereda near Debre Berhan, Ph.D. Thesis, Wageningen Agricultural University, Wageningen.

Gupta, B., Johnson, D., and Hinds, F. (1978). Soybean straw intake and nutrient digestibility by sheep. *Journal of Animal Science* **46**, 1086-1090.

Gurmu, F. (2013). Assessment of Farmers' Criteria for Common Bean Variety Selection: The case of Umbullo Watershed in Sidama Zone of the Southern Region of Ethiopia. *Ethiopian e Journal for Research and Innovation Foresight* **5**, 4-13.

Guthrie, J., Reid, D., and Walsh, K. B. (2005). Assessment of internal quality attributes of mandarin fruit. 2. NIR calibration model robustness. *Australian Journal of Agricultural Research* **56**, 417-426.

Gutierrez-Ornelas, E., and Klopfenstein, T. (1991). Changes in availability and nutritive value of different corn residue parts as affected by early and late grazing seasons. *Journal of Animal Science* **69**, 1741-1750.

Habib, G., Shah, S., and Inayat, K. (1995). Genetic variation in morphological characteristics, chemical composition and in vitro digestibility of straw from different wheat cultivars. *Animal Feed Science and Technology* **55**, 263-274.

Haile, M., Mekbib, F., and Zelleke, H. (2012). Performance and Farmers' Evaluation of Released Common Bean Varieties in Dawro Zone, Southwestern Ethiopia. *Journal of Crop Improvement* **26**, 197-210.

Halderman, M. (2004). "The political economy of poor-poor livestock policy-making in Ethiopia," Rep. No. 19. Poor-Poor Livestock Policy Initiatives, FAO, Rome, Italy.

Halim, R., Buxton, D., Hattendorf, M., and Carlson, R. (1989). Water-stress effects on alfalfa forage quality after adjustment for maturity differences. *Agronomy Journal* **81**, 189-194.

Hansey, C. N., Lorenz, A. J., and de Leon, N. (2010). Erratum to: Cell Wall Composition and Ruminant Digestibility of Various Maize Tissues Across Development. *BioEnergy Research* **3**, 295-304.

Harika, A. S., Tripathi, H. P., and Saxena, V. K. (1995). Maize stover. *In* "Handbook for straw feeding systems" (K. Singh, Schiere, J.B., ed.), pp. 379-381. Indian Council of Agricultural Research, Krishi Bhavan, New Delhi, India

Hart, S. (1990). Effects of altering the grain content of sorghum silage on its nutritive value. *Journal of Animal Science* **68**, 3832-3842.

Hashemi, A. M., Herbert, S. J., and Putnam, D. H. (2005). Yield response of corn to crowding stress. *Agronomy Journal* **97**, 839-846.

Hassen, A., Gizachew, L., and Rethman, N. (2006). Effect of Lablab purpureus and Vicia atropurpuria as an intercrop, or in a crop rotation, on grain and forage yields of maize in Ethiopia. *Tropical Grasslands* **40**, 111-118.

Heaney, D. (1973). Effects of the degree of selective feeding allowed on forage voluntary intake and digestibility assay results using sheep. *Canadian Journal of Animal Science* **53**, 431-438.

Herbert, F., Thomson, E., and Capper, B. (1994). Effect of genotype on the morphological characteristics, chemical composition and feeding value of nine barley straws, and responses to soya-bean meal supplementation. *Animal Science* **58**, 117-126.

Herrero, M., Grace, D., Njuki, J., Johnson, N., Enahoro, D., Silvestri, S., and Rufino, M. C. (2013). The roles of livestock in developing countries. *Animal* **7**, 3-18.

Herrero, M., Thornton, P., Gerber, P., Van der Zijpp, A., Van de Steeg, J., Notenbaert, A., Lecomte, P., Tarawali, S., and Grace, D. (2010). The way forward for livestock and the environment. *In* "The Role of Livestock in Developing Communities: Enhancing Multifunctionality" (F. Swanepoel, Stroebel, A., Moyo, S., ed.), pp. 51-76. SUN MeDIA Bloemfontein South Africa.

Heuzé, V., Tran, G., Lebas, F., and Nozière, P. (2013). Common bean (Phaseolus vulgaris). *In* "Feedipedia.org. A programme by INRA, CIRAD, AFZ and FAO".

Heuzé, V., Tran, G., Nozière, P., and Lebas, F. (2015). Common bean (Phaseolus vulgaris). *In* "Feedipedia, a programme by INRA, CIRAD, AFZ and FAO".

Hindrichsen, I., Osuji, P., Odenyo, A., Madsen, J., and Hvelplund, T. (2002). Effects of supplementation of a basal diet of maize stover with different amounts of Leucaena diversifolia on intake, digestibility, nitrogen metabolism and rumen parameters in sheep. *Animal Feed Science and Technology* **98**, 131-142.

Holden, L. (1999). Comparison of methods of in vitro dry matter digestibility for ten feeds. *Journal of Dairy Science* **82**, 1791-1794.

Hoskinson, R. L., Karlen, D. L., Birrell, S. J., Radtke, C. W., and Wilhelm, W. (2007). Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. *Biomass and Bioenergy* **31**, 126-136.

Hundie, D., Beyene, F., and Duguma, G. (2013). Early Growth and Reproductive Performances of Horro Cattle and their F1 Jersey Crosses in and around Horro-Guduru Livestock Production and Research Center, Ethiopia. *Science, Technology and Arts Research Journal* **2**, 134-141.

Ibbotson, C., Phillips, M., Turner, P., and Delaney, M. (1982). alkali treatment of whole crop cereals. II. Farm-scale feasibility trial with barley. *Experimental husbandry* **38** 154–162.

IBM (2011). "IBM SPSS Statistics for Windows, Version 20.0," IBM Corp, Armonk, NY IBM Corp.

ILCA (1987). "ILCA Annual Report 1986/87." ILCA, Addis Ababa, Ethiopia.

Jackson, M. (1978). "Treating straw for animal feeding. An assessment of its technical and economic feasibility," FAO Animal production and health paper 10, FAO, Rome, Italy.

Jahnke, H. E. (1982). "Livestock production systems and livestock development in tropical Africa," Kieler Wissenschaftsverlag Vauk Kiel.

Jaleta, M., Kassie, M., and Erenstein, O. (2015). Determinants of maize stover utilization as feed, fuel and soil amendment in mixed crop-livestock systems, Ethiopia. *Agricultural Systems* **134**, 17-23.

Jaleta, M., Kassie, M., and Shiferaw, B. (2013). Tradeoffs in crop residue utilization in mixed crop–livestock systems and implications for conservation agriculture. *Agricultural Systems* **121**, 96-105.

Jewell, S., and Campling, R. (1986). Aqueous ammonia treatment of wheat straw: voluntary intake and digestibility in cattle. *Animal Feed Science and Technology* **14**, 81-93.

Johnson, J. M., Wilhelm, W. W., Karlen, D. L., Archer, D. W., Wienhold, B., Lightle, D. T., Laird, D., Baker, J., Ochsner, T. E., and Novak, J. M. (2010). Nutrient removal as a function of corn stover cutting height and cob harvest. *BioEnergy Research* **3**, 342-352.

Joshi, A., Rao, A. S., Doyle, P., Oosting, S., Singh, M., Harika, A., Deinum, B., and Ibrahim, M. (1995). Variation in the quantity and quality of crop residues. *In* "Handbook for Straw Feeding Systems" (K. Singh, Schiere, J.B. , ed.), pp. 245-261, ICAR, New Delhi, India.

Julier, B., Guines, F., Ecalle, C., and Huyghe, C. (2001). From description to explanation of variations in alfalfa digestibility. *In* "Proceedings of the XIV Eucarpia Medicago sp. Group Meeting. Zaragoza", Vol. 45, pp. 19-23.

Jung, H., and Allen, M. (1995). Characteristics of plant cell walls affecting intake and digestibility of forages by ruminants. *Journal of Animal Science* **73**, 2774-2790.

Kabaija, E., and Little, D. (1988). Nutrient quality of forages in Ethiopia with particular reference to mineral elements. *In* "Pasture Network for Eastern and Southern Africa.(Panesa). Proc. of 3rd Workshop", pp. 440-448. ILCA, Addis Ababa.

Kafilzadeh, F., and Maleki, E. (2012). Chemical composition, in vitro digestibility and gas production of straws from different varieties and accessions of chickpea. *Journal of Animal Physiology and Animal Nutrition* **96**, 111-118.

Kaitho, R., Umunna, N., Nsahlai, I., Tamminga, S., and Van Bruchem, J. (1998a). Utilization of browse supplements with varying tannin levels by Ethiopian Menz sheep: 1. Intake, digestibility and live weight changes. *Agroforestry Systems* **39**, 145-159.

Kaitho, R., Umunna, N., Nsahlai, I., Tamminga, S., and Van Bruchem, J. (1998b). Effect of feeding graded levels of Leucaena leucocephala, Leucaena pallida, Sesbania sesban and Chamaecytisus palmensis supplements to teff straw given to Ethiopian highland sheep. *Animal Feed Science and Technology* **72**, 355-366.

Kalmbacher, R. (1983). Distribution of dry matter and chemical constituents in plant parts of four Florida native grasses. *Journal of Range Management*, 298-301.

Karlen, D., and Camp, C. (1985). Row spacing, plant population, and water management effects on corn in the Atlantic Coastal Plain. *Agronomy Journal* **77**, 393-398.

Kassa, M., Yebo, B., and Habte, A. (2014). The response of haricot bean (Phaseolus vulgaris L.) varieties to phosphorus levels on nitosols at Wolaita Zone, Ethiopia. *Greener Journal of Plant Breeding and Crop Science* **2**, 82-87.

Kebede, B. (2006). Methane production and energy partitioning in Bos indicus cattle (Borana breed) fed on selected tropical feeds in Ethiopia, MSc thesis, Haramaya University, Haramaya, Ethiopia.

Kebede, B. (2016). Impact of Climate Variability on Food Security at Rural Household Level: The Case of Misrak Badawacho Woreda, SNNPR, Ethiopia. MSc thesis, AAU, Addis Ababa, Ethiopia.

Kennington, L., Hunt, C., Szasz, J., Grove, A., and Kezar, W. (2005). Effect of cutting height and genetics on composition, intake, and digestibility of corn silage by beef heifers. *Journal of Animal Science* **83**, 1445-1454.

Khan, M., Muhammad, A., Ahamad, N., Khan, K., Khan, S. U., and Chaudhry, Z. (2015). Variability of Vigour and Viability of Various Varieties of Common Bean (Phaesolus vulgaris L.) Land Races. *American-Eurasian Journal of Agriculture and Enviromental Science* **15**, 957-961.

Kimhi, A. (2006). Plot size and maize productivity in Zambia: is there an inverse relationship? *Agricultural Economics* **35**, 1-9.

Kiniry, J., and Echarte, L. (2005). Comments on “Yield response of corn in crowding stress” by Hashemi et al. *Agronomy Journal* **97**, 1472.

Klopfenstein, T., Erickson, G., and Berger, L. (2013). Maize is a critically important source of food, feed, energy and forage in the USA. *Field Crops Research* **153**, 5-11.

Koralagama, D. (2004). Characterization and evaluation of cowpea (Vigna unguiculata) genotypes under Ethiopia conditions and their potential as forage protein supplements for ruminants, University of Reading, PhD thesis, University of Reading, United Kingdom.

Koralagama, K., Mould, F., Fernandez-Rivera, S., and Hanson, J. (2008). The effect of supplementing maize stover with cowpea (Vigna unguiculata) haulms on the intake and growth performance of Ethiopian sheep. *Animal* **2**, 954-691.

Kossila, V. (1988). The availability of crop residues in developing countries in relation to livestock populations. *In* "Plant breeding and the nutritive value of crop residues: Proceedings of the Workshop held at ILCA, Addis Ababa, Ethiopia (ed. JD Reed, BS Capper and PJH Neate)", pp. 29-39.

Kristjanson, P. M., and Zerbini, E. (1999). "Genetic enhancement of sorghum and millet residues fed to ruminants: an ex ante assessment of returns to research," ILRI Impact Assessment Series 3. ILRI (International Livestock Research Institute), Nairobi, Kenya. 52 pp.

Kumar, N., and Tkui, K. (2014). Reproductive performance of crossbred dairy cows in Mekelle, Ethiopia. *Scientific Journal of Animal Science* **3**, 35-40.

Kusmenoglu, I., and Muehlbauer, F. J. (1998). Genetic variation for biomass and residue production in lentil: I. Relation to agronomic traits. *Crop science* **38**, 907-910.

Lal, R. (2005). World crop residues production and implications of its use as a biofuel. *Environment International* **31**, 575-584.

Lam, M. S. W. Q., Martinez, Y., Barbier, O., Jauneau, A., and Pichon, M. (2013). Maize cell wall degradability, from whole plant to tissue level: different scales of complexity. *Maydica* **58**, 103-110.

Larbi, A., Dung, D., Olorunju, P., Smith, J., Tanko, R., Muhammad, I., and Adekunle, I. (1999). Groundnut (Arachis hypogaea) for food and fodder in crop-livestock systems: forage and seed yields, chemical composition and rumen degradation of leaf and stem fractions of 38 cultivars. *Animal Feed Science and Technology* **77**, 33-47.

Larbi, A., Hassan, S., Kattash, G., El-Moneim, A. A., Jammal, B., Nabil, H., and Nakkul, H. (2010). Annual feed legume yield and quality in dryland environments in north-west Syria: 1. Herbage yield and quality. *Animal Feed Science and Technology* **160**, 81-89.

Lardy, G., Anderson, V., and Dahlen, C. (2015). "Alternative feeds for ruminants." AS1182 Revised, NDSU Extension service, North Dakota State University.

Larson, E., and Clegg, M. (1999). Using corn maturity to maintain grain yield in the presence of late-season drought. *Journal of Production Agriculture* **12**, 400-405.

Lawal, J., and Oluyole, K. (2008). Factors influencing adoption of research results and agricultural technologies among cocoa farming households in Oyo State, Nigeria. *International Journal of Sustainable Crop Production* **3**, 10-12.

Lazier, J. (1981). Effect of cutting height and frequency on dry matter production of Codariocalyx gyroides (syn. Desmodium gyroides) in Belize, Central America. *Tropical Grasslands* **15**, 10-16.

Leng, R. A. (1990). Factors affecting the utilisation of 'poor-quality' forages by ruminants particularly under tropical conditions. *Nutrition Research Reviews* **3**, 277–303.

Lenné, J., Fernandez-Rivera, S., and Blümmel, M. (2003). Approaches to improve the utilization of food–feed crops—synthesis. *Field Crops Research* **84**, 213-222.

Lenné, J., and Thomas, D. (2006). Integrating Crop—Livestock Research and Development in Sub-Saharan Africa: Option, Imperative or Impossible? *Outlook on Agricultutre* **35**, 167-175.

Lewis, A. L., Cox, W. J., and Cherney, J. H. (2004). Hybrid, maturity, and cutting height interactions on corn forage yield and quality. *Agronomy Journal* **96**, 267-274.

Li, H., Xu, L., Liu, W., Fang, M., and Wang, N. (2014). Assessment of the nutritive value of whole corn stover and its morphological fractions. *Asian-Australasian Journal of Animal Sciences* **27**, 194-200.

Li, X., Ison, R., Kellaway, R., Stimson, C., Annison, G., and Joyce, D. (2011). Agronomic characteristics of annual Trifolium legumes and nutritive values as predicted by near-infrared reflectance (NIR) spectroscopy. *Crop and Pasture Science* **62**, 1078-1087.

Liang, M.-y., Wang, G.-y., Liang, W.-l., Shi, P.-f., Jing, D., Peng, S., and HU, C.-s. (2015). Yield and quality of maize stover: Variation among cultivars and effects of N fertilization. *Journal of Integrative Agriculture* **14**, 1581-1587.

Lijalem, T., Daniel, A., and Ermias, T. (2016). Assessment of Beef Cattle Fattening in Selected Districts of Hadya Zone, Southern Ethiopia. *Journal of Biology, Agriculture and Healthcare* **6**, 167-172.

Lin, L.-Z., Harnly, J. M., Pastor-Corrales, M. S., and Luthria, D. L. (2008). The polyphenolic profiles of common bean (Phaseolus vulgaris L.). *Food chemistry* **107**, 399-410.

Lippke, H. (1980). Forage characteristics related to intake, digestibility and gain by ruminants. *Journal of Animal Science* **50**, 952-961.

Lobago, F., Bekana, M., Gustafsson, H., and Kindahl, H. (2007). Longitudinal observation on reproductive and lactation performances of smallholder crossbred dairy cattle in Fitche, Oromia region, central Ethiopia. *Tropical Animal Health and Production* **39**, 395–403.

Long, N. (1990). From paradigm lost to paradigm regained? The case for an actor-oriented sociology of development. *European Review of Latin American and Caribbean Studies* **49**, 3-24.

López, S., Davies, D. R., Giraldez, F. J., Dhanoa, M., Dijkstra, J., and France, J. (2005). Assessment of nutritive value of cereal and legume straws based on chemical composition and in vitro digestibility. *Journal of the Science of Food and Agriculture* **85**, 1550-1557.

López, S., Dijkstra, J., and France, J. (2000). Prediction of Energy Supply in Ruminants, with Emphasis on Forages. *In* "Forage evaluation in ruminant nutrition" (D. I. Givens, E. Owen, R. F. E. Axford and H. M. Omed, eds.), pp. 63-94. CABI, Wallingford, UK.

Lukuyu, B. A., Murdoch, A., Romney, D., Mwangi, D., Njuguna, J., McLeod, A., and Jama, A. (2013). Integrated maize management options to improve forage yield and quality on smallholder farms in Kenya. *Field Crops Research* **153**, 70-78.

Lundvall, J., Buxton, D., Hallauer, A., and George, J. (1994). Forage quality variation among maize inbreds: in vitro digestibility and cell-wall components. *Crop Science* **34**, 1672-1678.

Lutz, J., Camper, H., and Jones, G. (1971). Row spacing and population effects on corn yields. *Agronomy Journal* **63**, 12-14.

Lynch, J., O'Kiely, P., and Doyle, E. (2014). A note on the chemical composition and in vitro digestibility of contrasting stover components of maize grown in climatically

marginal conditions and harvested at differing maturities. *Irish Journal of Agricultural and Food Research*, 205-211.

Makkar, H. P., Goodchild, A. V., El-Moneim, A. A., and Becker, K. (1996). Cell-constituents, tannin levels by chemical and biological assays and nutritional value of some legume foliage and straws. *Journal of the Science of Food and Agriculture* **71**, 129-136.

Makumbi, D., Kanampiu, F., Mugo, S., and Karaya, H. (2015). Agronomic Performance and Genotype× Environment Interaction of Herbicide-Resistant Maize Varieties in Eastern Africa. *Crop Science* **55**, 540-555.

Manyuchi, B., Hovell, F. D., Ndlovu, L., Topps, J., and Tigere, A. (1997). The use of groundnut hay as a supplement for sheep consuming poor quality natural pasture hay. *Animal Feed Science and Technology* **69**, 17-26.

MARC (2014). Melkassa Agricultural Research Centre http://www.eiar.gov.et/index.php/melkassa-agricultural-research-center.

Marten, G. (1989). Current applications of NIRS technology in forage research. *In* "Near Infrared Reflectance Spectroscopy (NIRS): Analysis of Forage Quality. " (G. C. Marten, Shenk, J. S., Barton, F. E. , ed.), pp. 45-48. USDA, ARS, Agricultural Handbook No 643, Springfield, VA, USA.

Marten, G., Brink, G., Buxton, D., Halgerson, J., and Hornstein, J. (1984). Near infrared reflectance spectroscopy analysis of forage quality in four legume species. *Crop Science* **24**, 1179-1182.

Masterson, T. (2007). "Productivity, technical efficiency, and farm size in Paraguayan agriculture. ," Working Paper No . 490. 37pp.

Mathison, G., Hsu, H., Soofi-Siawash, R., Recinos-Diaz, G., Okine, E., Helm, J., and Juskiw, P. (1999). Prediction of composition and ruminal degradability characteristics of barley straw by near infrared reflectance spectroscopy. *Canadian Journal of Animal Science* **79**, 519-523.

McCullough, D., Aguilera, A., and Tollenaar, M. (1994). N uptake, N partitioning, and photosynthetic N-use efficiency of an old and a new maize hybrid. *Canadian Journal of Plant Science* **74**, 479-484.

McDermott, J., Staal, S., Freeman, H., Herrero, M., and Van de Steeg, J. (2010). Sustaining intensification of smallholder livestock systems in the tropics. *Livestock science* **130**, 95-109.

McDonald, P., Edwards, R., and Greenhalgh, J. (1988). "Animal nutrition, 4th ed," Longman Scientific and Technical, Harlow, Essex, UK.

McDonald, P., Edwards, R. A., Greenhalgh, J. F. D., Morgan, C. A., Sinclair, L. A., and Wilkinson, R. G. (2002). "Animal nutrition," 7th /Ed. Pearson education.

McDowell, R. E. (1972). "Improvement of livestock production in warm climates," W.H.Freeman & Co Ltd, Francisco, Calif.

McGee, A. L., Johnson, M., Rolfe, K. M., Harding, J. L., and Klopfenstein, T. J. (2012). "Nutritive Value and Amount of Corn Plant Parts," Nebraska Beef Cattle Reports. Paper 648.

McMeniman, N., Elliott, R., and Ash, A. (1988). Supplementation of rice straw with crop by-products. I. Legume straw supplementation. *Animal Feed Science and Technology* **19**, 43-53.

Méchin, V., Argillier, O., Rocher, F., Hébert, Y., Mila, I., Pollet, B., Barriére, Y., and Lapierre, C. (2005). In search of a maize ideotype for cell wall enzymatic degradability using histological and biochemical lignin characterization. *Journal of Agricultural and Food Chemistry* **53**, 5872-5881.

Mekasha, A., Gerard, B., Tesfaye, K., Nigatu, L., and Duncan, A. J. (2014). Inter-connection between land use/land cover change and herders'/farmers' livestock feed resource management strategies: a case study from three Ethiopian eco-environments. *Agriculture, Ecosystems & Environment* **188**, 150-162.

Mekbib, F. (1997). Farmer participation in common bean genotype evaluation: the case of eastern Ethiopia. *Experimental Agriculture* **33**, 399-408.

Mekbib, F. (2002). Simultaneous selection for high yield and stability in common bean (Phaseolus vulgaris) genotypes. *The Journal of Agricultural Science* **138**, 249-253.

Mekbib, F. (2003). Yield stability in common bean (Phaseolus vulgaris L.) genotypes. *Euphytica* **130**, 147-153.

Mekoya, A., Oosting, S. J., Fernandez-Rivera, S., and Van der Zijpp, A. J. (2008). Farmers' perceptions about exotic multipurpose fodder trees and constraints to their adoption. *Agroforestry Systems* **73**, 141-153.

Melaku, S., Peters, K. J., and Tegegne, A. (2003). In vitro and in situ evaluation of selected multipurpose trees, wheat bran and Lablab purpureus as potential feed supplements to tef (Eragrostis tef) straw. *Animal Feed Science and Technology* **108**, 159-179.

Melchinger, A., Schmidt, G., and Geiger, H. (1986). Evaluation of Near Infra-red Reflectance Spectroscopy for Predicting Grain and Stover Quality Traits in Maize. *Plant Breeding* **97**, 20-29.

Menbere, S. (2005). Characterization of livestock production system; A case study of Yerer water shed, Adaa Liben district of east Showa, Ethiopia, M. Sc Thesis, Alemaya University, Ethiopia. 184p.

Mengistu, A. (1985). Feed resources in Ethiopia. *In* "Animal Feed Resources for Small-scale Livestock Producers. Proceedings of the 2nd PANESA Workshop Held in Nairobi, Kenya, 11-15 November 1985" (J. A. Kategile, Said, A.N., Dzowela, B.H., ed.), pp. 143-162.

Mengistu, A. (2010). Comparative analysis of maize-livestock innovation systems in Awassa, Bako and Ambo areas of Ethiopia, PhD thesis. Haramaya University, Haramaya, Ethiopia. 123pp.

Mengistu, W. (2001). Prickly pear cactus (Opuntia ficus-indica) as feed to ruminants, MSc Thesis presented to Swedish University of Agricultural Sciences, Uppsala, Sweden, 88p.

Milford, R., and Minson, D. (1965). The relation between the crude protein content and the digestible crude protein content of tropical pasture plants. *Journal of the British Grassland Society* **20**, 177-179.

Minson, D. (1990). "Forage in ruminant nutrition," Academic Press. Inc.

Mohamed-Saleem, M. (1995). Fragile East African highlands: a development vision for smallholder farmers in the Ethiopian highlands. *Outlook on agriculture* **24**, 111-116.

Mohamed-Saleem, M., and Tedla, A. (1995). Feed improvement to support intensification of ruminant production systems in the Ethiopian highlands. *In* "Proceedings of the 3rd National Conference of the Ethiopian Society of Animal Production". Ethiopian Society of Animal Production Addis Ababa, Ethiopia.

Mohammed, I. (2005). Effect of feeding different levels of khat (Chata edulis) leftover on feed intake and growth performance of goats fed on sorghum stover, MSc. Thesis. Haramaya University, Haramaya, Ethiopia.

Mokhtarpour, H., Teh, C., Saleh, G., Selamat, A., Asadi, M. E., and Kamkar, B. (2011). Corn yield response to crowding stress and cropping season. *Archives of Agronomy and Soil Science* **57**, 853-871.

Morales-Ruiz, A., Loeza-Corte, J., Díaz-López, E., Morales-Rosales, E., Franco-Mora, O., Mariezcurrena-Berasaín, M., and Estrada-Campuzano, G. (2016). Efficiency on the Use of Radiation and Corn Yield under Three Densities of Sowing. *International Journal of Agronomy* **2016**, 1-5.

Moritz, M. (2010). Crop–livestock interactions in agricultural and pastoral systems in West Africa. *Agriculture and Human Values* **27**, 119-128.

Morrison, T., Kessler, J., and Buxton, D. (1994). Maize internode elongation patterns. *Crop Science* **34**, 1055-1060.

Mosi, A., and Butterworth, M. (1985). The voluntary intake and digestibility of combinations of cereal crop residues and legume hay for sheep. *Animal Feed Science and Technology* **12**, 241-251.

Moss, A. R., and Givens, D. (1990). Chemical composition and in vitro digestion to predict digestibility of field-cured and barn-cured grass hays. *Animal feed science and technology* **31**, 125-138.

Murphy, A. M., and Colucci, P. E. (1999). A tropical forage solution to poor quality ruminant diets: A review of Lablab purpureus. *Livestock Research for Rural Development* **11**.

N2Africa (2014). Better beans through better agricultural practices for farmers in Ethiopia.

Nafziger, E. D. (1994). Corn planting date and plant population. *Journal of Production Agriculture* **7**, 59-62.

Negasa, A., Chiche, Y., Seyoum, K., and Kefyalew, A. (1993). Importance, Production Practices, Constraints and Research Needs of Maize Production Under Small Holder Farmers in Ethiopia: Review of Farming System Research. *In* "First National Maize Workshop of Ethiopia, 5-7 May 1992 ". IAR, Addis Ababa, Ethiopia.

Negash, D., Animut, G., Urgie, M., and Mengistu, S. (2017). Chemical Composition and Nutritive Value of Oats (*Avena sativa*) Grown in Mixture with Vetch (*Vicia villosa*) with or Without Phosphorus Fertilization in East shoa Zone, Ethiopia. *Journal of Nutrition and Food Sciences* **7**, 1-6.

Negassa, A., Rashid, S., and Gebremedhin, B. (2011). "Livestock production and marketing." International Food Policy Research Institute (IFPRI) – Ethiopia Strategy Support Program II (ESSP II), Working Paper 26. IFPRI, Addis Ababa, Ethiopia.

Negassa, W., Gebrekidan, H., and Friesen, D. (2005). Integrated use of farmyard manure and NP fertilizers for maize on farmers' fields. *Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS)* **106**, 131-141.

Neylon, J., and Kung, L. (2003). Effects of cutting height and maturity on the nutritive value of corn silage for lactating cows. *Journal of Dairy Science* **86**, 2163-2169.

Nielsen, R. (2016). Grain fill stages in corn. *In* "Corny News Network ". Purdue University.

Nigam, S., and Blummel, M. (2010). Cultivar-dependent variation in food-feed-traits in groundnut (Arachis hypogaea L.). *Animal Nutrition and Feed Technology* **10S**, 39-48.

Njie, M., and Reed, J. D. (1995). Potential of crop residues and agricultural by-products for feeding sheep in a Gambian village. *Animal Feed Science and Technology* **52**, 313-323.

Norman, H. C., Hulm, E., Humphries, A. W., Hughes, S. J., Law, R., Rowe, T., and Vercoe, P. E. (2015). Broad NIRS calibrations to predict nutritional value of the southern feed base. *In* "Building Productive, Diverse and Sustainable Landscapes", Proceedings of the 17th ASA Conference, 20-24 September, 2015, Hobart, Australia. Web site www.agronomy2015.com.au.

Norris, K., Barnes, R., Moore, J., and Shenk, J. (1976). Predicting forage quality by infrared replectance spectroscopy. *Journal of Animal Science* **43**, 889-897.

Norton, B. (1982). Differences between species in forage quality. *In* "Nutritional Limits to Animal Production from Pastures: proceedings of an international symposium held at St. Lucia, Queensland, Australia, August 24-28, 1981/edited by JB Hacker", pp. 89-100. Farnham Royal, UK: Commonwealth Agricultural Bureaux, 1982.

Norwood, C. A., and Currie, R. S. (1996). Tillage, planting date, and plant population effects on dryland corn. *Journal of Production Agriculture* **9**, 119-122.

Notenbaert, A., Herrero, M., De Groote, H., You, L., Gonzalez-Estrada, E., and Blummel, M. (2013). Identifying recommendation domains for targeting dual-purpose maize-based interventions in crop-livestock systems in East Africa. *Land Use Policy* **30**, 834-846.

Nyambati, E. M., Muyekho, F. N., Onginjo, E., and Lusweti, C. M. (2010). Production, characterization and nutritional quality of napier grass [Pennisetum purpureum (Schum.)] cultivars in Western Kenya. *African Journal of Plant Science* **4**, 496-502.

Oliveira, F. C. L. d., Jobim, C. C., Silva, M. S. d., and Bumbieris Júnior, V. H. (2013). Productive characteristics of maize hybrids at different cutting heights for silage and organic matter and mineral rates in post-harvest residues. *Acta Scientiarum. Animal Sciences* **35**, 133-138.

Omokanye, A., Onifade, O., Olorunju, P., Adamu, A., Tanko, R., and Balogun, R. (2001). The evaluation of dual-purpose groundnut (Arachis hypogaea) varieties for fodder and seed production at Shika, Nigeria. *The Journal of Agricultural Science* **136**, 75-79.

Orodho, A. (2006). The role and importance of Napier grass in the smallholder dairy industry in Kenya. *In* "Food and Agriculture Organization, Rome ", Vol. 24.

Ørskov, E. (1991). Manipulation of fibre digestion in the rumen. *Proceedings of the Nutrition Society* **50**, 187-196.

Ørskov, E., Reid, G., and Kay, M. (1988b). Prediction of intake by cattle from degradation characteristics of roughages. *Animal Production* **46**, 29-34.

Ørskov, E., Shand, W., Tedesco, D., and Morrice, L. (1990). Rumen degradation of straw. 10. Consistency of differences in nutritive value between varieties of cereal straws. *Animal Science* **51**, 155-162.

Ørskov, E., Tait, C., Reid, G., and Flachowski, G. (1988a). Effect of straw quality and ammonia treatment on voluntary intake, milk yield and degradation characteristics of faecal fibre. *Animal Production* **46**, 23-27.

Osafo, E. L. K. (1993). Sorghum stover as a forage: cultivar effects on yield and effect of chopping, amounts offered, supplementation and variety on intake, selection and liveweight gain in Ethiopian sheep and cattle, PhD thesis. University of Reading, Reading, UK.

Osafo, E. L. K., Owen, E., Said, A. N., Gill, M., and Sherington, J. (1997). Effects of amount offered and chopping on intake and selection of sorghum stover by Ethiopian sheep and cattle. *Animal Science* **65**, 55–62.

Osuji, P., Sibanda, S., and Nsahlai, I. (1993). Supplementation of maize stover for Ethiopian Menz sheep: effects of cottonseed, noug (Guizotia abyssinica) or sunflower cake with or without maize on the intake, growth, apparent digestibility, nitrogen balance and excretion of purine derivatives. *Animal Science* **57**, 429-436.

Park, R., Agnew, R., Gordon, F., and Steen, R. (1998). The use of near infrared reflectance spectroscopy (NIRS) on undried samples of grass silage to predict chemical composition and digestibility parameters. *Animal Feed Science and Technology* **72**, 155-167.

Park, R., Gordon, F., Agnew, R., Barnes, R., and Steen, R. (1997). The use of near infrared reflectance spectroscopy on dried samples to predict biological parameters of grass silage. *Animal Feed Science and Technology* **68**, 235-246.

Paterson, J. A., Belyea, R. L., Bowman, J. P., Kerley, M. S., and Williams, J. V. (1994). The Impact of Forage Quality and Supplementation Regimen on Ruminant Animal Intake and Performance. *In* "Forage Quality, Evaluation, and Utilization" (G. C. Fahey-Jr., ed.), pp. 59-114, The National Conference on Forage Quality, Evaluation, and UtilizationUniversity of Nebraska, Lincoln, 13-15 April 1994, Madison, WI, USA.

Patil, A., Oak, M., Taware, S., Tamhankar, S., and Rao, V. (2010). Nondestructive estimation of fatty acid composition in soybean [Glycine max (L.) Merrill] seeds using Near-Infrared Transmittance Spectroscopy. *Food Chemistry* **120**, 1210-1217.

Pearce, G., Lee, J., Simpson, R., and Doyle, P. (1988). Sources of variation in the nutritive value of wheat and rice straws. *In* "Plant Breeding and the Nutritive Value of Crop Residues" (J. D. Reed, Capper, B.S., Neate, P.J.H. , ed.), pp. 195-231, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia.

Pieltain, M., Castañón, A., Flores, M., and Castañón, J. (1996). Nutritive value of postharvest bean by-products (Phaseolus vulgaris L.) for ruminants. *Animal Feed Science and Technology* **62**, 271-275.

Pierna, J. A. F., Sanfeliu, A. B., Slowikowski, B., von Holst, C., Maute, O., Han, L., Amato, G., de la Roza Delgado, B., Marín, D. P., Lilley, G., Dardenne, P., and Baeten, V. (2013). Standardization of NIR microscopy spectra obtained from inter-laboratory studies by using a standardization cell. *Biotechnologie, Agronomie, Société et Environnement* **17**, 547-555.

Pixley, K., and Bjarnason, M. (2002). Stability of grain yield, endosperm modification, and protein quality of hybrid and open-pollinated quality protein maize (QPM) cultivars. *Crop Science* **42**, 1882–1890.

Poppi, D., Minson, D., and Ternouth, J. (1981). Studies of cattle and sheep eating leaf and stem fractions of grasses. 1. The voluntary intake, digestibility and retention time in the reticulo-rumen. *Australian Journal of Agricultural Research* **32**, 99-108.

Powell, J. (1984). Sorghum and millet yields and stover consumption by livestock in the sub-humid zone of Nigeria. *Tropical Agriculture* **62**, 77-81.

Powell, J., Fernandez-Rivera, S., Hiernaux, P., and Turner, M. (1996). Nutrient cycling in integrated rangeland/cropland systems of the Sahel. *Agricultural Systems* **52**, 143-170.

Prasad, K., Khan, A., Vellaikumar, S., Devulapalli, R., Ramakrishna Reddy Ch, N. S., and Blümmel, M. (2010). Observations on livestock productivity in sheep fed exclusively on haulms from ten different genotypes of groundnut. *Animal Nutrition and Feed Technology* **10S**, 121-126.

Preston, T. R., and Leng, R. A. (1987). "Matching ruminant production systems with available resources in the tropics and sub-tropics," Penambul Books, Armidale, Australia. 245pp.

Quinlan, R. J., Quinlan, M. B., Dira, S., Caudell, M., Sooge, A., and Assoma, A. A. (2015). Vulnerability and resilience of Sidama enset and maize farms in southwestern Ethiopia. *Journal of Ethnobiology* **35**, 314-336.

Rafiq, M., Dixon, R., Hosking, B., and Egan, A. (2002). Leaf content of straw diets influences supplementation responses by sheep. *Animal Feed Science and Technology* **100**, 93-106.

Ramana Reddy, Y., Ravi, D., Reddy, C. R., Prasad, K., Zaidi, P., Vinayan, M., and Blümmel, M. (2013). A note on the correlations between maize grain and maize stover quantitative and qualitative traits and the implications for whole maize plant optimization. *Field Crops Research* **153**, 63-69.

Randolph, T., Schelling, E., Grace, D., Nicholson, C. F., Leroy, J., Cole, D., Demment, M., Omore, A., Zinsstag, J., and Ruel, M. (2007). Role of livestock in human nutrition and health for poverty reduction in developing countries. *Journal of Animal Science* **85**, 2788-2800.

Rao, N., Silim, S. N., Simtowe, F., Gaur, P., Gowda, C., and Monyo, E. (2012). "Enhancing Chickpea Productivity and Production in Eastern and Southern Africa. Engaging Smallholder Farmers, Tropical Legumes II Project, Progress of Phase 1."

Rattunde, H., Zerbini, E., Chandra, S., and Flower, D. (2001). Stover quality of dual-purpose sorghums: genetic and environmental sources of variation. *Field Crops Research* **71**, 1-8.

Ravi, D., Anandan, S., Khan, A., Bidinger, F., Nepolean, T., Hash, C., and Blümmel, M. (2010). Morphological, chemical and in vitro traits for prediction of stover quality in pearl millet for use in multidimensional crop improvement. *Animal Nutrition and Feed Technology* **10S**, 49-59.

Ravi, D., Khan, A., Saibutcharao, M., and Blümmel, M. (2013). A note on suitable laboratory stover quality traits for multidimensional maize improvement. *Field Crops Research* **153**, 58-62.

Raymond, F. D., Alley, M. M., Parrish, D. J., and Thomason, W. E. (2009). Plant density and hybrid impacts on corn grain and forage yield and nutrient uptake. *Journal of Plant Nutrition* **32**, 395-409.

Reddy, B., Reddy, P. S., Bidinger, F., and Blümmel, M. (2003). Crop management factors influencing yield and quality of crop residues. *Field Crops Research* **84**, 57-77.

Reed, J. D., Capper, B. S., and Neate, P. J. (1988b). "Plant Breeding and the Nutritive Value of Crop Residues: Proceedings of a Workshop Held at ILCA, Addis Ababa, Ethiopia, 7-10 December 1987," ILRI (aka ILCA and ILRAD).

Reed, J. D., and Goe, M. R. (1989). "Estimating the nutritive value of cereal crop residues: Implications for developing feeding standards for draught animals." ILCA Bulletin 34, July 1989.

Reed, J. D., Kebede, Y., and Fussell, L. K. (1988a). Factors affecting the nutritive value of sorghum and millet crop residues. *In* "Plant breeding and the nutritive value of crop residues" (J. D. Reed, Capper, B.S., Neat, P.J.H. , ed.), pp. 233-258, Proceedings of a workshop held at ILCA, 7-10 December 1987, ILCA, Addis Ababa, Ethiopia.

Renard, C. (1997). "Crop residues in sustainable mixed crop/livestock farming systems," CAB International Wallingford, UK.

Reynolds, C. K. (2000). Forage Evaluation Using Measurements of Energy Metabolism. *In* "Forage evaluation in ruminant nutrition" (D. I. Givens, E. Owen, R. F. E. Axford and H. M. Omed, eds.), pp. 95-111. CABI, Wallingford, UK.

Richards, R. (2000). Selectable traits to increase crop photosynthesis and yield of grain crops. *Journal of Experimental Botany* **51**, 447-458.

Rodriguez, D., de Voil, P., Rufino, M. C., Odendo, M., and van Wijk, M. (2017). To mulch or to munch? Big modelling of big data. *Agricultural Systems* **153**, 32-42.

Romney, D., Thorne, P., Lukuyu, B., and Thornton, P. K. (2003). Maize as food and feed in intensive smallholder systems: management options for improved integration in mixed farming systems of east and southern Africa. *Field Crops Research* **84**, 159-168.

Romney, D. L., and Gill, M. (2000). Intake of Forages. *In* "Forage evaluation in ruminant nutrition" (D. I. Givens, E. Owen, R. F. E. Axford and H. M. Omed, eds.), pp. 43-62. CABI, Wallingford, UK.

Rosales-Serna, R., Kohashi-Shibata, J., Acosta-Gallegos, J. A., Trejo-López, C., Ortiz-Cereceres, J. n., and Kelly, J. D. (2004). Biomass distribution, maturity acceleration and yield in drought-stressed common bean cultivars. *Field Crops Research* **85**, 203-211.

Roth, G. W. (1994). Hybrid quality and yield differences for corn silage in Pennsylvania. *Journal of Production Agriculture* **7**, 50-54.

Rotz, C., and Muck, R. (1994). Changes in forage quality during harvest and storage. . *In* "Forage quality Evaluation, and Utilization " (J. George, Fahey, C, ed.), pp. 828-868. Inc, American Society of Agronomy, Madison, Wisconsin, USA.

Roxas, D., Karim, S., Lapitan, R., Pascual, F., Castillo, L., and Carangal, V. (1985). Composition and in vitro digestibility of residues from selected cowpea (Vigna unguiculata) varieties. *In* "Ruminant feeding systems utilizing fibrous agricultural residues" (R. M. Dixon, ed.). University of Melbourne, Bogor, Indonesia.

Rufino, M. C., Dury, J., Tittonell, P., Van Wijk, M. T., Herrero, M., Zingore, S., Mapfumo, P., and Giller, K. E. (2011). Competing use of organic resources, village-level

interactions between farm types and climate variability in a communal area of NE Zimbabwe. *Agricultural Systems* **104**, 175-190.

Saïdou, A. (2006). Converging strategies by farmers and scientists to improve soil fertility and enhance crop production in Benin, PhD Thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Sampaio, C. B., Detmann, E., Paulino, M. F., Valadares Filho, S. C., de Souza, M. A., Lazzarini, I., Paulino, P. V. R., and de Queiroz, A. C. (2010). Intake and digestibility in cattle fed low-quality tropical forage and supplemented with nitrogenous compounds. *Tropical Animal Health and Production* **42**, 1471-1479.

Sangoi, L. (2001). Understanding plant density effects on maize growth and development: an important issue to maximize grain yield. *Ciência Rural* **31**, 159-168.

Sangoi, L., Gracietti, M., Rampazzo, C., and Bianchetti, P. (2002). Response of Brazilian maize hybrids from different eras to changes in plant density. *Field Crops Research* **79**, 39-51.

Sarlangue, T., Andrade, F. H., Calviño, P. A., and Purcell, L. C. (2007). Why do maize hybrids respond differently to variations in plant density? *Agronomy Journal* **99**, 984-991.

SAS (2009). "SAS/STAT ® 9.2 User's Guide, Second Edition. Cary, NC: SAS Institute Inc."

Saxena, M., Silim, S., and Singh, K. (1990). Effect of supplementary irrigation during reproductive growth on winter and spring chickpea (Cicer arietinum) in a Mediterranean environment. *The Journal of Agricultural Science* **114**, 285-293.

Schiere, J., Joshi, A., Seetharam, A., Oosting, S., Goodchild, A., Deinum, B., and Van Keulen, H. (2004). Grain and straw for whole plant value: implications for crop management and genetic improvement strategies. *Experimental Agriculture* **40**, 277-294.

Schiere, J., and Nell, A. (1993). Feeding of urea treated straw in the tropics. I. A review of its technical principles and economics. *Animal Feed Science and Technology* **43**, 135-147.

Schiere, J. B., and Ibrahim, M. N. M. (1989). "Feeding of Urea-ammonia Treated Rice Straw," Pudoc, Wageningen, the Netherlands, 125pp.

Scholtz, G., Van der Merwe, H., and Tylutki, T. (2009). Prediction of chemical composition of South African Medicago sativa L. hay from a near infrared reflectance spectroscopy spectrally structured sample population. *South African Journal of Animal Science* **39**, 183-187.

Schulthess, U., Tedla, A., Mohamed-Saleem, M., and Said, A. N. (1995). Effects of variety, altitude, and undersowing with legumes on the nutritive value of wheat straw. *Experimental Agriculture* **31**, 169-176.

Schwartz, H. F., and Langham, M. A. C. (2016). Growth stages of bean (Phaseolus vulgaris L.). Legume ipmPIPE Dignostic pocket series. *In* "Colorado State University and South Dakota State University".

Scobbie, L., Russell, W., Provan, G. J., and Chesson, A. (1993). The newly extended maize internode: a model for the study of secondary cell wall formation and consequences for digestibility. *Journal of the Science of Food and Agriculture* **61**, 217-225.

Scully, B., and Wallace, D. (1990). Variation in and relationship of biomass, growth rate, harvest index, and phenology to yield of common bean. *Journal of the American Society for Horticultural Science* **115**, 218-225.

Scully, B., Wallace, D., and Viands, D. (1991). Heritability and correlation of biomass, growth rates, harvest index, and phenology to the yield of common beans. *Journal of the American Society for Horticultural Science* **116**, 127-130.

Shaheb, M. R., Islam, M. N., Nessa, A., Hossain, M. A., and Sarker, A. (2015). Impact of harvest stage on seed yield quality and storability of french bean. *Bangladesh Journal of Agricultural Research* **40**, 641-656.

Sharma, K., Pattanaik, A., Anandan, S., and Blummel, M. (2010). Food-feed crops research: A synthesis. *Animal Nutrition and Feed Technology* **10S**, 1-10.

Shaw, R., and Loomis, W. (1950). Bases for the prediction of corn yields. *Plant Physiology* **25**, 225-244.

Shenk, J. S., Fales, S. L., and Westerhaus, M. O. (1993). Using near infrared reflectance product library files to improve prediction accuracy and reduce calibration costs. *Crop Science* **33**, 578-581.

Shenk, J. S., and Westerhaus, M. O. (1991a). Populations structuring of near infrared spectra and modified partial least squares regression. *Crop Science* **31**, 1548-1555.

Shenk, J. S., and Westerhaus, M. O. (1991b). Population definition, sample selection, and calibration procedures for near infrared reflectance spectroscopy. *Crop science* **31**, 469-474.

Shenk, J. S., and Westerhaus, M. O. (1993). Near infrared reflectance analysis with single and multiproduct calibrations. *Crop Science* **33**, 582-584.

Shenk, J. S., and Westerhaus, M. O. (1994). The application of near infrared reflectance spectroscopy (NIRS) to forage analysis. *In* "Forage quality, evaluation, and

utilization" (J. George, Fahey, C. , ed.), pp. 406-449. American Society of Agronomy, Madison, Wisconsin, USA.

Shenk, J. S., Westerhaus, M. O., and Abrams, S. M. (1989). 2. Protocol for NIR calibrations: Monitoring analysis results and recalibration. *In* "Near Infrared Spectroscopy (NIRS): Analysis of Forage Quality. Agriculture Handbook" (G. C. Marten, Shenk, J. S., Barton, F. E. , ed.), Vol. 643, pp. 104-110. United States Department of Agriculture, Springfield, VA, USA.

Shenk, J. S., Westerhaus, M. O., and Hoover, M. R. (1979). Analysis of Forages by Infrared Reflectance1. *Journal of Dairy Science* **62**, 807-812.

Siddique, K., Loss, S., Regan, K., and Jettner, R. (1999). Adaptation and seed yield of cool season grain legumes in Mediterranean environments of south-western Australia. *Australian Journal of Agricultural Research* **50**, 375-388.

Siddique, K. H., Johansen, C., Turner, N. C., Jeuffroy, M.-H., Hashem, A., Sakar, D., Gan, Y., and Alghamdi, S. S. (2012). Innovations in agronomy for food legumes. A review. *Agronomy for sustainable development* **32**, 45-64.

Sileshi, Z., and Bediye, S. (1989). Utilization of feed resources and feeding systems in the central zone of Ethiopia. *In* "Proceedings of the third national livestock improvement conference. Addis Ababa, Ethiopia", pp. 24-26.

Sileshi, Z., Owen, E., Dhanoa, M. S., and Theodorou, M. K. (1996). Prediction of in situ rumen dry matter disappearance of Ethiopian forages from an in vitro gas production technique using a pressure transducer, chemical analyses or in vitro digestibility. *Animal Feed Science and Technology* **61**, 73-87.

Singh, B., Ajeigbe, H., Tarawali, S. A., Fernandez-Rivera, S., and Abubakar, M. (2003). Improving the production and utilization of cowpea as food and fodder. *Field Crops Research* **84**, 169-177.

Sinnaeve, G., Dardenne, P., Agneessens, R., and Biston, R. (1994). The use of near infrared spectroscopy for the analysis of fresh grass silage. *Journal of Near Infrared Spectroscopy* **2**, 79-84.

Sisay, Z., Shenkoru, T., Tegegne, A., and Amanuel, Y. W. (2006). Feed intake, water balance and water economy in highland sheep fed teff (Eragrostis teff) straw and supplemented with graded levels of Leucaena leucocephala. *Ethiopian Journal of Animal Production*, 67.

Smith, J., Naazie, A., Larbi, A., Agyemang, K., and Tarawali, S. (1997). Integrated crop-livestock systems in sub-Saharan Africa: an option or an imperative? *Outlook on Agriculture* **26**, 237-246.

Smith, K., and Flinn, P. (1991). Monitoring the performance of a broad-based calibration for measuring the nutritive value of two independent populations of pasture using near infrared reflectance (NIR) spectroscopy. *Australian Journal of Experimental Agriculture* **31**, 205-210.

Somda, J., Nianogo, A. J., Nassa, S., and Sanou, S. (2002). Soil fertility management and socio-economic factors in crop-livestock systems in Burkina Faso: a case study of composting technology. *Ecological Economics* **43**, 175-183.

Stanton, D., Grombacher, A., Pinnisch, R., Mason, H., and Spaner, D. (2007). Hybrid and population density affect yield and quality of silage maize in central Alberta. *Canadian Journal of Plant Science* **87**, 867-871.

Stapleton, J. (2016). Unlocking the potential of Ethiopia's livestock sector: growth, jobs and environmental sustainability. *In* "https://news.ilri.org/2016/02/04/unlocking-the-potential-of-the-livestock-sector-ethiopia/".

Steen, R., Gordon, F., Dawson, L., Park, R., Mayne, C., Agnew, R., Kilpatrick, D., and Porter, M. (1998). Factors affecting the intake of grass silage by cattle and prediction of silage intake. *Animal Science* **66**, 115-127.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., and de Haan, C. (2006). "Livestock's long shadow: environmental issues and options," Food and Agriculture Organisation., Nairobi, Kenya.

Stimson, C., Kellaway, R., Tassell, R., and Ison, R. (1991). Prediction of the nutrient content of botanical fractions from annual legumes by near-infrared reflectance spectroscopy. *Grass and Forage Science* **46**, 99-105.

Stuth, J., Jama, A., and Tolleson, D. (2003). Direct and indirect means of predicting forage quality through near infrared reflectance spectroscopy. *Field Crops Research* **84**, 45-56.

Subedi, K., and Ma, B. (2009). Assessment of some major yield-limiting factors on maize production in a humid temperate environment. *Field Crops Research* **110**, 21-26.

Sulo, T., Chumo, K. P., and Chepng'eno, W. (2012). Socioeconomic factors affecting the adoption of improved agricultural technologies among women in Marakwet County Kenya. *Journal of Emerging Trends in Economics and Management Sciences* **3**, 312-317.

Sundstol, F. (1985). Procedures for research into the treatment of crop residues and agro-industrial by-products in developing countries. *In* "Better utilization of crop residues and by-products in animal feeding: research guidelines. 1. State of knowledge. " (T.

R. Preston, Kossila, V.L., Goodwin, J., Reed, S.B., ed.). FAO, ILCA Headquarters, Addis Ababa, Ethiopia.

Suttie, J. M. (2000). "Hay and straw conservation: for small-scale farming and pastoral conditions," FAO Plant Production and Protection Series No. 29, Food and Agriculture Organisation of the United Nations, Rome, Italy.

Tadesse, D., Alem, T., Wossen, T., and Sintayehu, A. (2014). Evaluation of Improved Varieties of Haricot Bean in West Belessa, Northwest Ethiopia. *International Journal of Science and Research (IJSR)* **3**, 2756-2759.

Tang, S., Gan, J., Sheng, L., Tan, Z., Tayo, G., Sun, Z., Wang, M., and Ren, G. (2008). Morphological fractions, chemical composition and in vitro fermentation characteristics of maize stover of five genotypes. *Animal* **2**, 1772-1779.

Tang, S., Tan, Z., Zhou, C., Jiang, H., Jiang, Y., and Sheng, L. (2006). A comparison of in vitro fermentation characteristics of different botanical fractions of mature maize stover. *Journal of Animal and Feed Sciences* **15**, 505-515.

Tar'an, B., Michaels, T. E., and Pauls, K. P. (2002). Genetic mapping of agronomic traits in common bean. *Crop Science* **42**, 544-556.

Tarawali, S., Herrero, M., Descheemaeker, K., Grings, E., and Blümmel, M. (2011). Pathways for sustainable development of mixed crop livestock systems: Taking a livestock and pro-poor approach. *Livestock Science* **139**, 11-21.

Tegegne, A., Gebremedhin, B., and Hoekstra, D. (2010). "Livestock input supply and service provision in Ethiopia: Challenges and opportunities for market-oriented development," Rep. No. 20. ILRI (International Livestock Research Institute), Nairobi, Kenya.

Tekrony, D., and Egli, D. (1997). Accumulation of seed vigour during development and maturation. *In* "Basic and applied aspects of seed biology", pp. 369-384. Springer.

Tetio-Kagho, F., and Gardner, F. (1988a). Responses of maize to plant population density. I. Canopy development, light relationships, and vegetative growth. *Agronomy Journal* **80**, 930-935.

Tetio-Kagho, F., and Gardner, F. (1988b). Responses of maize to plant population density. II. Reproductive development, yield, and yield adjustments. *Agronomy Journal* **80**, 935-940.

Thapa, S. (2007). The relationship between farm size and productivity: empirical evidence from the Nepalese mid-hills. *In* "Paper presented at the 106th seminar of the EAAE, Pro-poor development in low income countries: Food, agriculture, trade, and environment ", pp. 1-16, 25-27 October 2007, Montpellier, France.

Thomison, P., and Jordan, D. (1995). Plant population effects on corn hybrids differing in ear growth habit and prolificacy. *Journal of Production Agriculture* **8**, 394-400.

Thomson, E., Rihawi, S., and Nersoyan, N. (1990). Nutritive value and yields of some forage legumes and barley harvested as immature herbage, hay and straw in North-West Syria. *Experimental Agriculture* **26**, 49-56.

Thorne, P., Thornton, P. K., Kruska, R. L., Reynolds, L., Waddington, S. R., Rutherford, A. S., and Odero, A. N. (2002). "Maize as Food, Feed, and Fertiliser in Intensifying Crop-livestock Systems in East and Southern Africa: An Ex Ante Impact Assessment of Technology Interventions to Improve Smallholder Welfare." ILRI Impact Assessment Series 11. ILRI (International Livestock Research Institute), Nairobi, Kenya, 123pp.

Thornton, P. K., and Herrero, M. (2001). Integrated crop–livestock simulation models for scenario analysis and impact assessment. *Agricultural Systems* **70**, 581-602.

Thornton, P. K., Kruska, R., Henninger, N., Kristjanson, P., Reid, R., and Robinson, T. (2003). Locating poor livestock keepers at the global level for research and development targeting. *Land Use Policy* **20**, 311-322.

Tilley, J. M., and Terry, R. (1963). A two-stage technique for the in vitro digestion of forage crops. *Grass and forage science* **18**, 104-111.

Tittonell, P., Gérard, B., and Erenstein, O. (2015). Tradeoffs around crop residue biomass in smallholder crop-livestock systems–What's next? *Agricultural Systems* **134**, 119-128.

Tokatlidis, I., and Koutroubas, S. (2004). A review of maize hybrids' dependence on high plant populations and its implications for crop yield stability. *Field Crops Research* **88**, 103-114.

Tolera, A. (2007). "Feed resources for producing export quality meat and livestock in Ethiopia: Examples from selected Woredas in Oromia and SNNP regional states." Ethiopia Sanitary and Phytosanitary standards and Livestock and Meat Marekting Program (SPS-LMM), Texas Agricultural Experiment Satiation (TAES)/Texas A&M Univesrity System, Addis Ababa, Ethiopia. 77pp.

Tolera, A., Berg, T., and Sundstøl, F. (1999). The effect of variety on maize grain and crop residue yield and nutritive value of the stover. *Animal Feed Science and Technology* **79**, 165-177.

Tolera, A., and Sundstøl, F. (1999). Morphological fractions of maize stover harvested at different stages of grain maturity and nutritive value of different fractions of the stover. *Animal Feed Science and Technology* **81**, 1-16.

Tolera, A., and Sundstøl, F. (2000). Supplementation of graded levels of Desmodium intortum hay to sheep feeding on maize stover harvested at three stages of maturity: 1. Feed intake, digestibility and body weight change. *Animal Feed Science and Technology* **85**, 239-257.

Tolera, A., Sundstøl, F., and Said, A. N. (1998). The effect of stage of maturity on yield and quality of maize grain and stover. *Animal Feed Science and Technology* **75**, 157-168.

Tolera, A., Tsegaye, B., and Berg, T. (2008). Effects of variety, cropping year, location and fertilizer application on nutritive value of durum wheat straw. *Journal of Animal Physiology and Animal Nutrition* **92**, 121-130.

Tolessa, B., Gobezayehu, T., Worku, M., Desalegne, Y., Mulatu, K., and Gezahgne, B. (1993). Genetic improvement of maize in Ethiopia: a review. *In* "Proceedings of the First National Maize Workshop of Ethiopia" (B. Tolessa, Ransom, J. K, ed.), pp. pp 13-22. IAR/CIMMYT, Addis Ababa., 5-7 May 1992, Addis Ababa, Ethiopia.

Tolla, N., Mirkena, T., and Yimegnuhal, A. (2002). Comparison of the efficiency of compensatory growth of Borana and Arsi cattle in Ethiopia. *Ethiopian Journal of Animal Production* **2**, 11-23.

Tollenaar, M. (1989). Genetic improvement in grain yield of commercial maize hybrids grown in Ontario from 1959 to 1988. *Crop Science* **29**, 1365-1371.

Tollenaar, M., and Bruulsema, T. (1988). Efficiency of maize dry matter production during periods of complete leaf area expansion. *Agronomy Journal* **80**, 580-585.

Tollenaar, M., Deen, W., Echarte, L., and Liu, W. (2006). Effect of crowding stress on dry matter accumulation and harvest index in maize. *Agronomy Journal* **98**, 930-937.

Tollenaar, M., and Wu, J. (1999). Yield improvement in temperate maize is attributable to greater stress tolerance. *Crop Science* **39**, 1597-1604.

Tsegaye, D., Tadesse, W., and Bayable, M. (2012). Genotype X environment interactions and grain yield stability of haricot bean varieties in Northwest Ethiopia. *Scientific Research and Essays* **7**, 3487-3493.

Tullu, A., Kusmenoglu, I., McPhee, K., and Muehlbauer, F. (2001). Characterization of core collection of lentil germplasm for phenology, morphology, seed and straw yields. *Genetic Resources and Crop Evolution* **48**, 143-152.

Umunna, N., Nsahlai, I., and Osuji, P. (1995). Degradability of forage protein supplements and their effects on the kinetics of digestion and passage. *Small Ruminant Research* **17**, 145-152.

Valbuena, D., Erenstein, O., Tui, S. H.-K., Abdoulaye, T., Claessens, L., Duncan, A. J., Gérard, B., Rufino, M. C., Teufel, N., and van Rooyen, A. (2012). Conservation Agriculture in mixed crop–livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Research* **132**, 175-184.

Valbuena, D., Tui, S. H.-K., Erenstein, O., Teufel, N., Duncan, A., Abdoulaye, T., Swain, B., Mekonnen, K., Germaine, I., and Gérard, B. (2015). Identifying determinants, pressures and trade-offs of crop residue use in mixed smallholder farms in Sub-Saharan Africa and South Asia. *Agricultural Systems* **134**, 107-118.

Valdes, E., Hunter, R., and Jones, G. (1987). Comparison of near infrared calibrations for estimating in vitro digestibility in whole-plant corn hybrids. *Canadian Journal of Animal Science* **67**, 557-562.

Valdes, E., Jones, G., and Hoekstra, G. (1990). Effect of growing year and application of a multi-year calibration for predicting quality parameters by near infrared reflectance spectroscopy in whole-plant corn forage. *Canadian Journal of Plant Science* **70**, 747-755.

Van Hiep, N., Wiktorsson, H., and Van Man, N. (2008). The effect of cutting interval on foliage yield and chemical composition of Tropical Kudzu (Pueraria phaseoloides) cultivated as cover-crop in rubber plantation. *Livestock Research for Rural Development.* **20**.

Van Soest, P. (1965). Symposium on factors influencing the voluntary intake of herbage by ruminants: voluntary intake in relation to chemical composition and digestibility. *Journal of Animal Science* **24**, 834-843.

Van Soest, P. (1967). Development of a comprehensive system of feed analyses and its application to forages. *Journal of animal Science* **26**, 119-128.

Van Soest, P. J. (1994). "Nutritional ecology of the ruminant," 2nd /Ed. Cornell University Press, Ithaca, 476pp.

Van Soest, P. v., Robertson, J., and Lewis, B. (1991). Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science* **74**, 3583-3597.

Vogel, K., and Sleper, D. (1994). Alteration of plants via genetics and plant breeding. *In* "Forage quality, evaluation, and utilization" (F. J. George, C. , ed.), pp. 891-921. American Society of Agronomy Madison, Wisconsin, USA.

Vogel, K. P., Pedersen, J. F., Masterson, S. D., and Toy, J. J. (1999). Evaluation of a filter bag system for NDF, ADF, and IVDMD forage analysis. *Crop Science* **39**, 276-279.

Walelign, T. (1995). The effects of stovers of sorghum varieties and protein sources on intake, digestibility and live weight gain in cattle, MSc thesis, Alemaya University, Ethiopia.

Walsh, K., O'kiely, P., Moloney, A., and Boland, T. (2008). Intake, digestibility, rumen fermentation and performance of beef cattle fed diets based on whole-crop wheat or barley harvested at two cutting heights relative to maize silage or ad libitum concentrates. *Animal Feed Science and Technology* **144**, 257-278.

Wang, H., Wu, Y., Liu, J., and Qian, Q. (2006). Morphological fractions, chemical compositions and in vitro gas production of rice straw from wild and brittle culm1 variety harvested at different growth stages. *Animal Feed Science and Technology* **129**, 159-171.

Ward, R., Smith, G., Wallace, J., Urquhart, N., and Shenk, J. (1982). Estimates of intake and quality of grazed range forage by near infrared reflectance spectroscopy. *Journal of Animal Science* **54**, 399-402.

Weiss, W. (1993). Predicting Energy Values of Feeds. *Journal of Dairy Science* **76**, 1802-1811.

Weston, R. (2002). Constraints on feed intake by grazing sheep. *In* "Sheep nutrition " (M. Freer, Dove, H., ed.), pp. 27-50. CABI, Wallingford, UK.

White, L. M., Hartman, G. P., and Bergman, J. W. (1981). In vitro digestibility, crude protein, and phosphorus content of straw of winter wheat, spring wheat, barley, and oat cultivars in eastern Montana. *Agronomy Journal* **73**, 117-121.

Widdicombe, W. D., and Thelen, K. D. (2002a). Row width and plant density effect on corn forage hybrids. *Agronomy Journal* **94**, 326-330.

Widdicombe, W. D., and Thelen, K. D. (2002b). Row width and plant density effects on corn grain production in the northern Corn Belt. *Agronomy Journal* **94**, 1020-1023.

Wilhelm, W. W., Johnson, J. M., Lightle, D. T., Karlen, D. L., Novak, J. M., Barbour, N. W., Laird, D. A., Baker, J., Ochsner, T. E., and Halvorson, A. D. (2011). Vertical distribution of corn stover dry mass grown at several US locations. *BioEnergy Research* **4**, 11-21.

Wilkins, R. J. (2000). Forages and Their Role in Animal Systems. *In* "FORAGE EVALUATION IN RUMINANT NUTRITION" (D. I. Givens, E. Owen, R. F. E. Axford and H. M. Omed, eds.), pp. 1-14. CABI, Wallingford, UK.

Williams, P., and Norris, K. (2001). "Near-Infrared Technology in the Agricultural and Food Industry " Second Edition/Ed. American Association of Cereal Chemists, Inc. , St Paul, Minnesota, USA. 312 pp.

Williams, P. C. (1975). Application of near infrared reflectance spectroscopy to analysis of cereal grains and oilseeds. *Cereal Chemistry* **52**, 561-576.

Williams, P. C. (1987). Variables affecting near infrared spectroscopic analysis. *In* "Near-Infrared Technology in the Agricultural and Food Industries" (P Williams and K. Norris, eds.), pp. 143-167. American Association of Cereal Chemists Inc, St Paul, MN.

Williams, P. C. (2001). Implementation of near-infrared technology. *In* "Near-infrared technology in the agricultural and food industries" (P. C. Williams, Norris, K.H., ed.), Vol. 2, pp. 145–169. American Association of Cereal Chemist St. Paul, Minnesota, USA.

Williams, T. O., Fernández-Rivera, S., and Kelley, T. G. (1997). The influence of socioeconomic factors on the availability and utilization of crop residues as animal feeds. *In* "Crop residues in sustainable mixed crop/livestock farming systems" (C. Renard, ed.), pp. 25-39. CAB International Wallingford, UK.

Williams, T. O., Hiernaux, P., and Fernández-Rivera, S. (2000). Crop-livestock systems in sub-Saharan Africa: Determinants and intensification pathways. *In* "Property rights, risk and livestock development in Africa" (N. Mccarthy, Swallow. B., Kirk, M., Hazell, P., ed.), pp. 132-151, IFPRI. Washington D.C.

Wilson, J. (1993). "Organization of forage plant tissues. In 'Forage cell wall structure and digestibility'.(Eds HG Jung, DR Buxton, RD Hatfield, J Ralph) pp. 1–32." ASA-CSSA-SSSA: Madison, WI.

Wilson, J. (1994). Cell wall characteristics in relation to forage digestion by ruminants. *The Journal of Agricultural Science* **122**, 173-182.

Wilson, J., and Hatfield, R. (1997). Structural and chemical changes of cell wall types during stem development: consequences for fibre degradation by rumen microflora. *Australian Journal of Agricultural Research* **48**, 165-180.

Wilson, J., and Kennedy, P. (1996). Plant and animal constraints to voluntary feed intake associated with fibre characteristics and particle breakdown and passage in ruminants. *Australian Journal of Agricultural Research* **47**, 199-225.

Windham, W., Mertens, D., and Barton, F. (1989). 1. Protocol for NIRS calibration: sample selection and equation development and validation. *In* "Near infrared reflectance spectroscopy (NIRS): Analysis of forage quality" (G. C. Marten, Shenk, J. S., Barton, F. E. , ed.), pp. 96-103. United States Department of Agriculture, Springfield, VA, USA.

Workayehu, T., Habte, T., Bogale, T., and Woldetsadik, G. (1993). Effect of Cultural Practice on Grain Yield of Maize. *In* "First National Maize Workshop of Ethiopia, Addis Ababa (Ethiopia), 5-7 May 1992", pp. 81-85. IAR.

Workayehu, T., Mazengia, W., Mekonen, B., Debelle, T., Bogale, T., Abate, B., Ali, H. M., and Mesfin, T. (2002). Development of appropriate cultural practices for maize production in Ethiopia. *In* "Enhancing the Contribution of Maize to Food Security in Ethiopia", pp. 56-60. CIMMYT, Proceedings of the Second National Maize Workshop of Ethiopia, 12-16 November 2001, 12-16 November 2001, Addis Ababa, Ethiopia.

Worku, M., and Zelleke, H. (2008). Genotype x Environment interaction and yield stability of maize. *East African Journal of Science* **2**, 7-12.

World-Bank ( 2009). "Minding the stock: bringing public policy to bear on livestock sector development," Rep. No. 44010-GLB.

Wossink, G., De Buck, A., Van Niejenhuis, J., and Haverkamp, H. (1997). Farmer perceptions of weed control techniques in sugarbeet. *Agricultural Systems* **55**, 409-423.

Wu, Z., and Roth, G. (2005). "Considerations in managing cutting height of corn silage." Extension publication DAS 03-72, Pennsylvania State University, College Park.

Yan, W., and Wallace, D. H. (1995). Breeding for negatively associated traits. *Plant Breeding Reviews* **13**, 141-177.

Yeheyis, L., Tsegahun, A., and Bediye, Y. M. a. S. (2005). Growth Performance of Yearling Menz Ram Lambs Fed on Different Pulse Crop Residues. *In* "Participatory Innovation and Research: Lessons for Livestock Development" (A. Yimegnuhal, Degefa, T ed.), pp. 229-232, Proceedings of the 12th Annual conference of the Ethiopian Society of Animal Production (ESAP), August 12-14, 2004, Addis Ababa, Ethiopia.

Yoseph, T., Shiferaw, G. G. W., and Mekonnen, T. S. E. (2014). Evaluation of Common Bean [Phaseolus Vulgaris (L.)] Varieties, for Yield and Yield Components. *Journal of Biology, Agriculture and Healthcare* **4**, 22-25.

Yuste-Lisbona, F. J., González, A. M., Capel, C., García-Alcázar, M., Capel, J., De Ron, A. M., Santalla, M., and Lozano, R. (2014). Genetic variation underlying pod size and color traits of common bean depends on quantitative trait loci with epistatic effects. *Molecular Breeding* **33**, 939-952.

Zaidi, P., Vinayan, M., and Blümmel, M. (2013). Genetic variability of tropical maize stover quality and the potential for genetic improvement of food-feed value in India. *Field Crops Research* **153**, 94-101.

Zelalem, Z. (2014). Evaluation of agronomic traits of different haricot bean (Phaseolus vulgaris L.) lines in Metekel zone, north western part of Ethiopia. *Wudpecker Journals* **3**, 39-43.

Zemmelink, G., and 't Mannetje, L. (2002). Value for animal production (VAP): a new criterion for tropical forage evaluation. *Animal Feed Science and Technology* **96**, 31-42.

Zerbini, E., and Thomas, D. (2003). Opportunities for improvement of nutritive value in sorghum and pearl millet residues in South Asia through genetic enhancement. *Field Crops Research* **84**, 3-15.

Zimmer, E., Gurrath, P., Paul, C., Dhillon, B., Pollmer, W., and Klein, D. (1990). Near infrared reflectance spectroscopy analysis of digestibility traits of maize stover. *Euphytica* **48**, 73-81.

Zingore, S., Tittonell, P., Corbeels, M., Van Wijk, M. T., and Giller, K. E. (2011). Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. *Nutrient Cycling in Agroecosystems* **90**, 87-103.

## Appendix

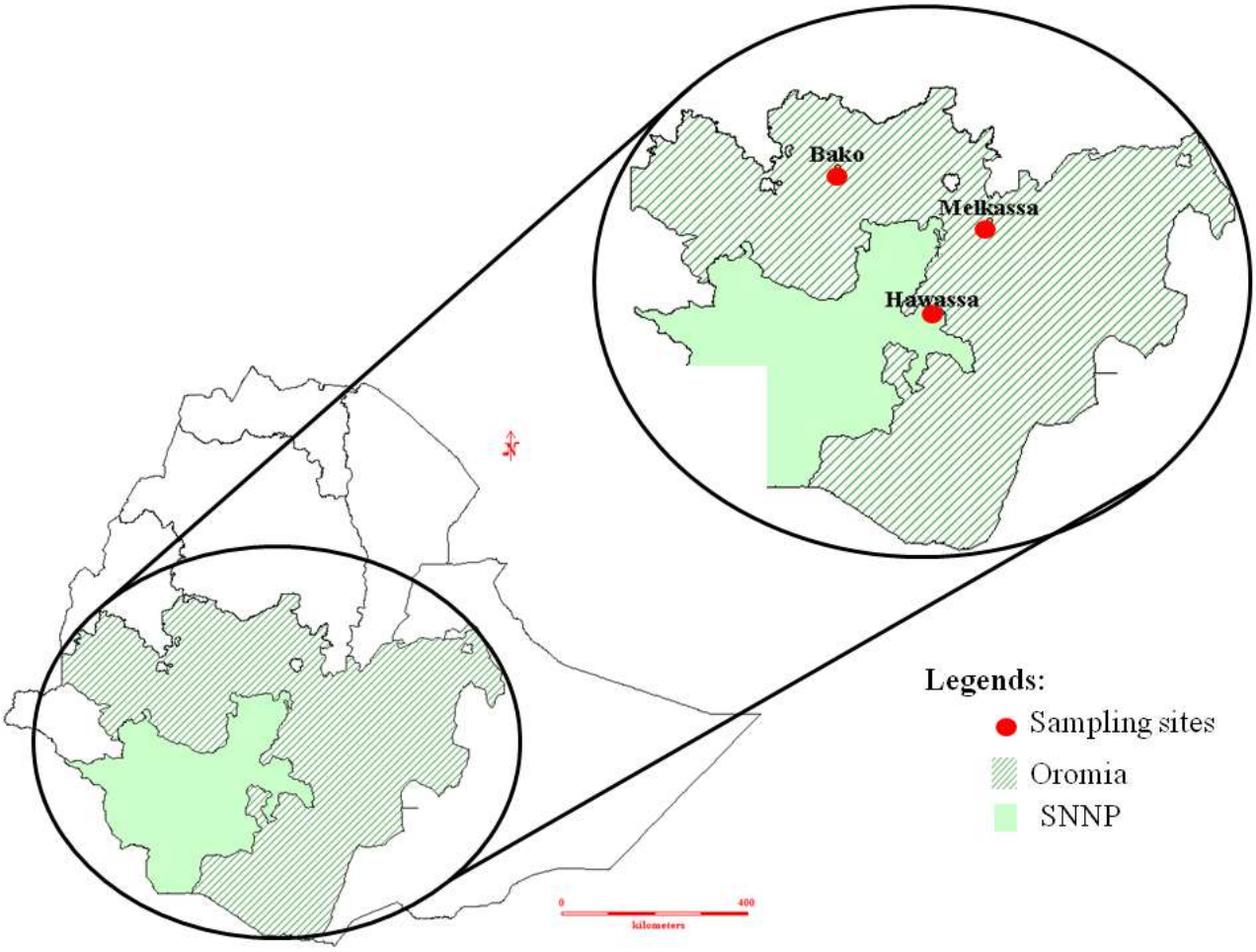


Figure A4.1 Map showing the study sites of Chapter 4 in Oromia and SNNP regional states, Ethiopia.

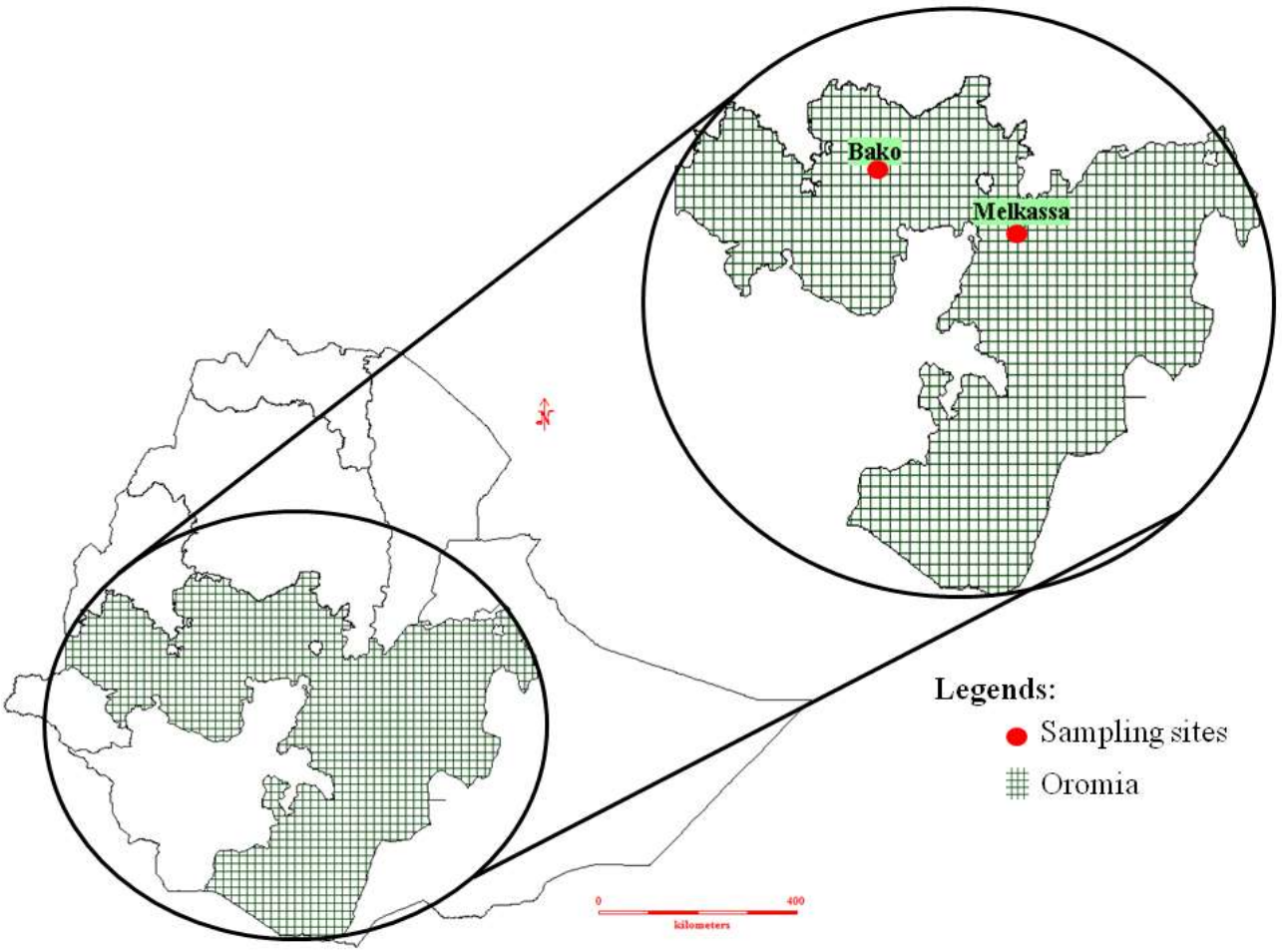


Figure A5.1 Map showing the study sites of Chapter 5 in Oromia regional state, Ethiopia.

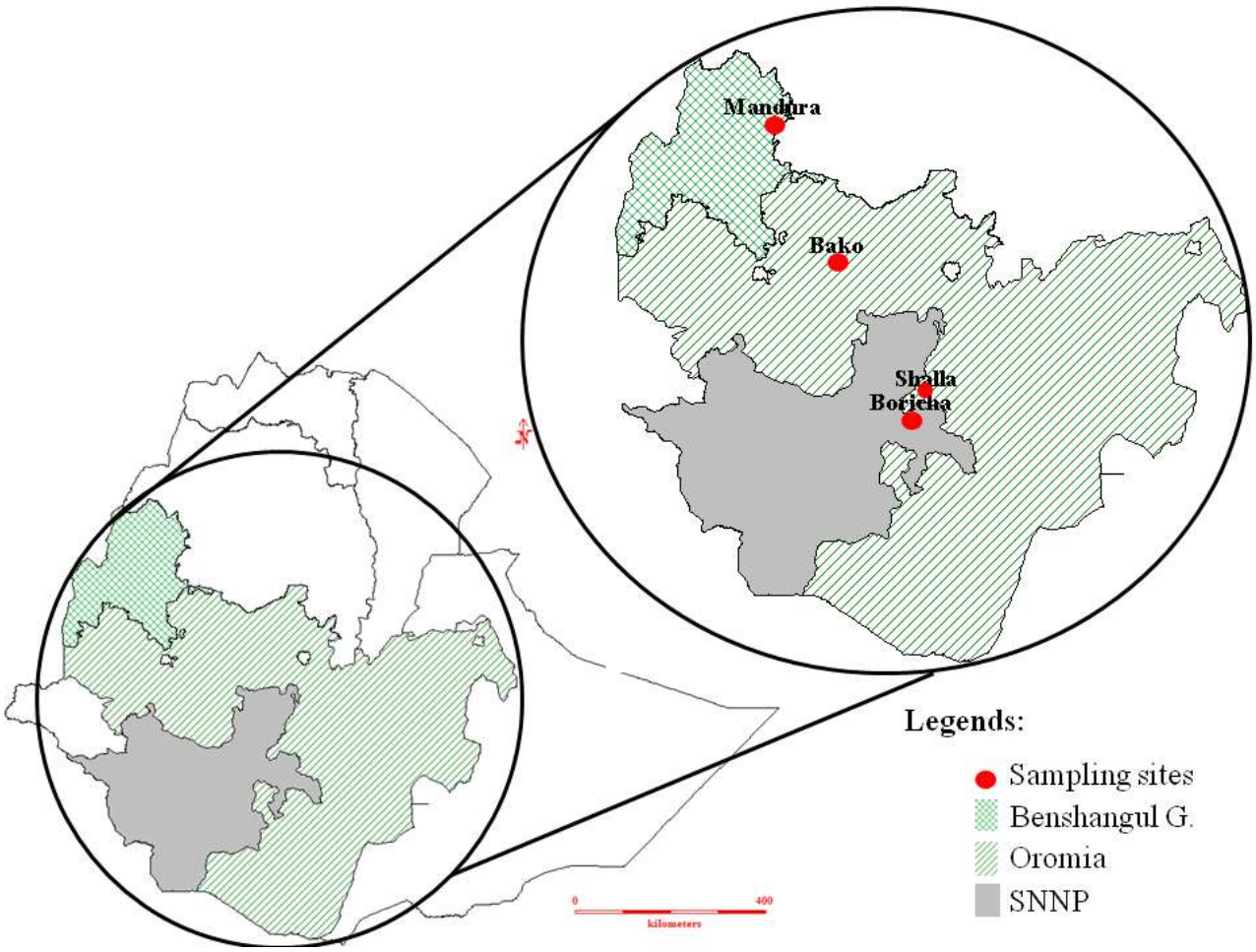


Figure A6.1 Map showing the study sites of Chapter 6 in Benshangul Gumuz, Oromia and SNNP regional states, Ethiopia.

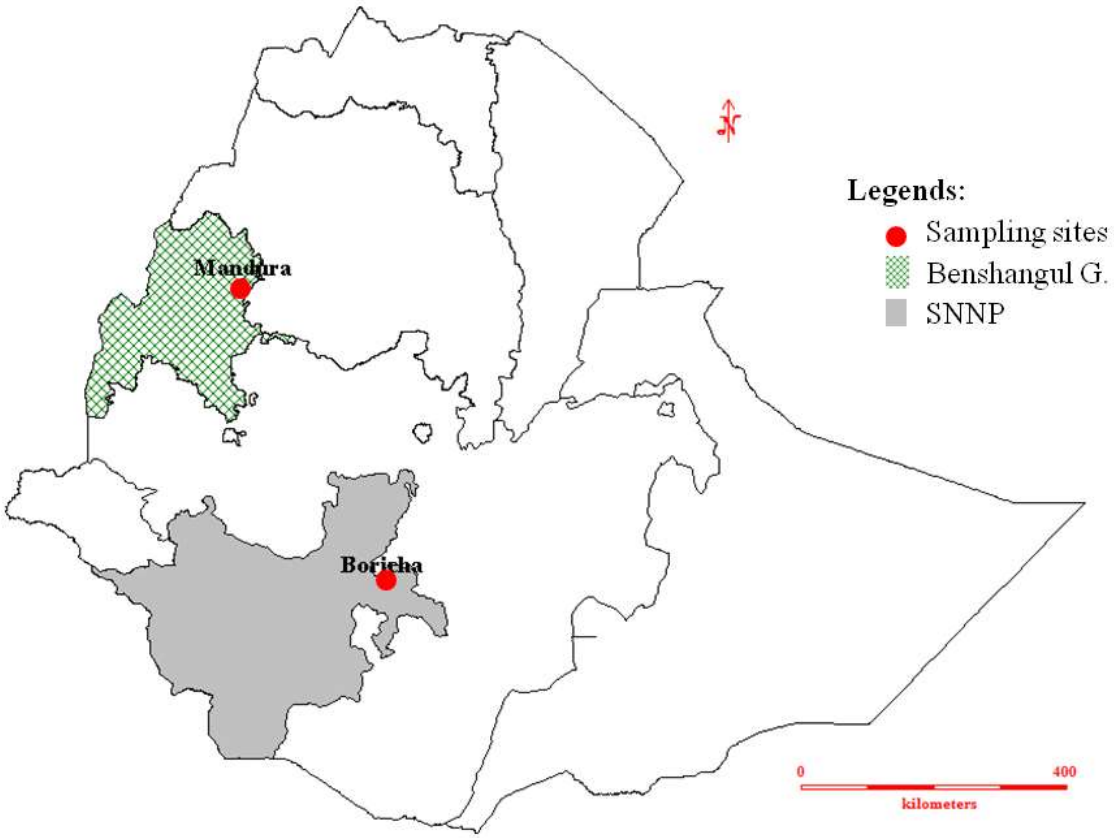


Figure A7.1 showing the study sites of Chapter 7 in Benshangul Gumuz and SNNP regional states, Ethiopia.

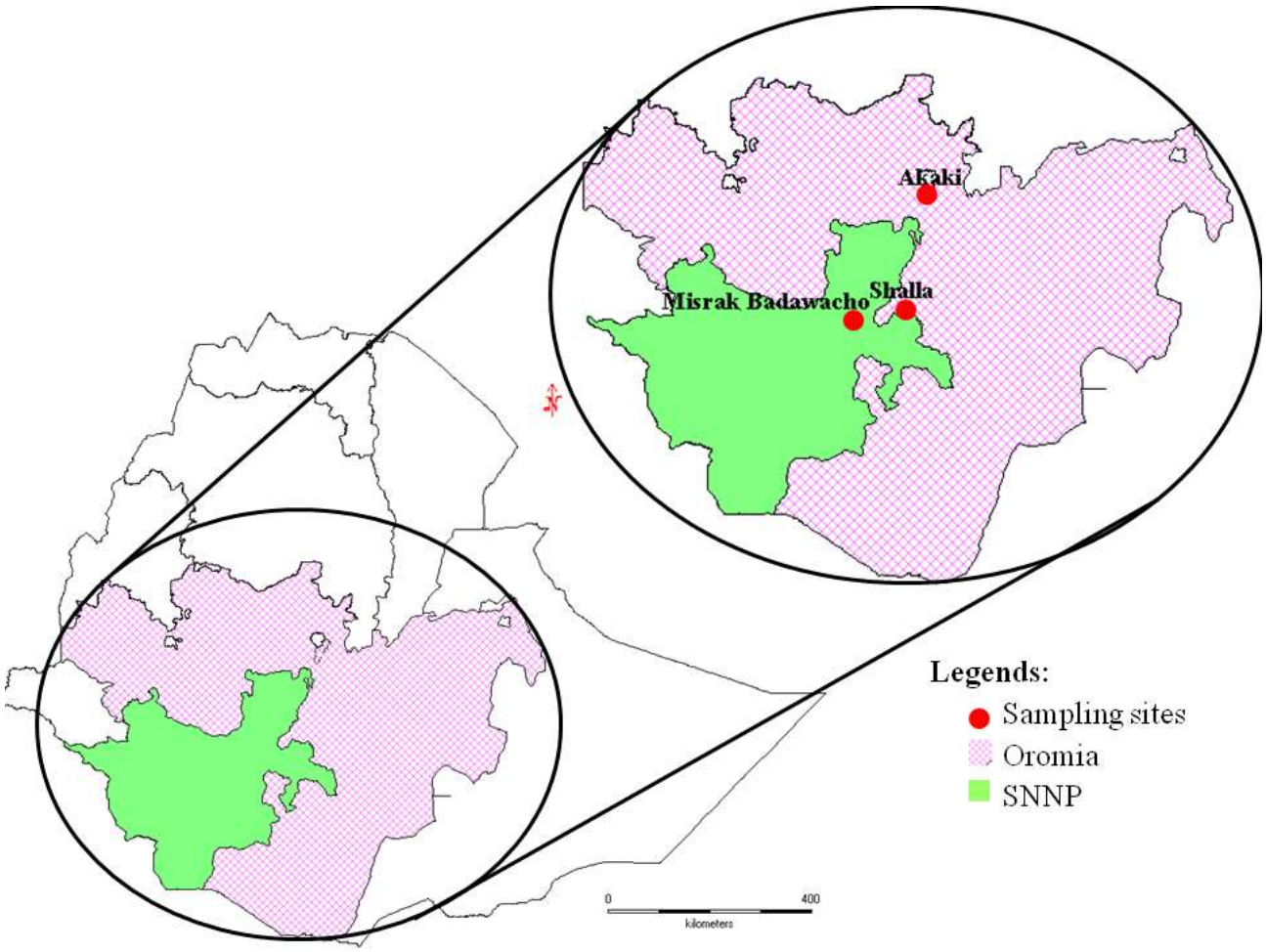


Figure A8.1 Map showing the survey study sites of Chapter 8 in Oromia and SNNP regional states, Ethiopia.