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14 Multidimensional Crop Improvement by ILRI and Partners: Drivers, Approaches, Achievements and Impact

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Executive Summary

The problem

Livestock provides food and income for almost 1.3 billion people across the world. Grazing has long been a principal source of feed in much of South Asia and in sub-Saharan Africa. Due to population pressure, land degradation and conversion from grazing to arable land, grazing areas have contracted, resulting in feed shortages. The conversion of grazing land is likely to be aggravated by climate change (Blümmel *et al*., 2015b). The increasing demand for animal-sourced food is another factor in putting pressure on feed from all sources (Blümmel *et al*., 2017).

Feed supply and demand scenarios for South Asia and sub-Saharan Africa have shown that crop residues (CRs) such as straws, stover and haulms commonly provide 50–70% of the feed resources in smallholder systems (Blümmel *et al*., 2014b; Duncan *et al*., 2016). In the highlands of Ethiopia, cereal CRs have emerged as the main components of the livestock diet but are generally poor in their nutritive value with a low crude protein content (4%) and digestible organic matter (less than 50%).

Lignocellulosic biomass from forest, agricultural waste and CRs is the most abundant renewable biomass on earth with a total production estimated to range from about 10 billion to 50 billion t (Sanchez and Cardena, 2008). About 3.8 billion t are contributed by CRs, with cereals contributing 74%, sugar crops 10%, legumes 8%, tubers 5% and oil crops 3% (Lal, 2005). Considering the quantities of CRs available and the high nutritive quality of its basic constituents – hexose and pentose sugars – attempts to improve CR biomass for fodder began a century ago (Fingerling and Schmidt, 1919; Beckmann, 1921).

These and later attempts to improve CR biomass included chemical, physical and biological treatments. Chemical treatments, particularly the use of hydrolytic agents such as sodium hydroxide and ammonia (Jackson, 1977; Owen and Jayasuriya, 1989), received significant research attention. However, little uptake of chemical treatments was observed, despite efforts by the international research and development communities, and investments into chemical straw treatments have declined since (Owen and Jayasuriya, 1989).

The lack of adoption of postharvest treatments of CRs gave way to a new model of improving the fodder value of CRs by selection and plant breeding (Reed *et al*., 1988a) and by identifying anti-nutritive factors in crop biomass (Reed *et al*., 1988b, 1990). In the mid-1990s, the International Livestock Research Institute (ILRI) and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) began a joint programme on improvement of grain and CR traits, focusing on sorghum (*Sorghum bicolor*) and pearl millet (*Pennisetum glaucum* (L.) R. Br.) in the semi-arid tropics of India. *Ex ante* estimates of potential productivity gains from genetic improvement of the digestibility of multidimensional food and fodder crops would produce high rates of economic return in the form of incremental meat, milk and draught power (e.g. Kristjanson and Zerbini, 1999, for pearl millet and sorghum in semi-arid India). Similar work started in West Africa in the 1990s among the International Institute of Tropical Agriculture (IITA), ICRISAT and ILRI, targeting cowpea.

This chapter therefore addresses the following questions. What is the extent of cultivar-dependent variation in CR fodder quality? Can these variations be exploited without detriment to grain yield? Have quality improvements in CRs from plant selection and breeding been achieved? Have such improvements made a field impact on crop and animal productivity?

Scientific impacts

The principal scientific achievement was to force a reconsideration of the single-trait (i.e. grain) model in favour of the multi-trait and whole-plant (i.e. food and fodder) model. While there are as yet few public-sector decisions to include stover traits as cultivar release criteria – sorghum and pearl millet are recent examples – public and private crop-improvement programmes have reoriented their efforts towards whole-plant improvement. Crop-improvement paradigms are changing to whole-plant optimization, as, for example, reflected in the new CGIAR Research Program (CRP) on Grain Legumes and Dryland Cereals.

Under this principal achievement, scientific impacts are the findings that: (i) there is significant variation in CR quality; (ii) such variation does not compromise grain yield; (iii) near-infrared spectroscopy (NIRS) methods are accurate for rapid screening of quality traits; and (iv) recent molecular analyses can detect variations in fodder quality early in breeding material.

NIRS equations were also developed for grains of key crops, including routine quality traits such as protein, starch and fat but also amino and fatty acids.

The fodder quality of CRs can be increased by targeted genetic enhancement using conventional or molecular crop-improvement approaches such as marker-assisted breeding, use of quantitative trait loci (QTLs) or genome-wide association studies (GWAS). Nepolean *et al.* (2009) used QTL to map the genomic regions controlling stover quality and yield traits in pearl millet, while Blümmel *et al.* (2015a), used stay-green QTLs in sorghum. GWAS was used to unravel favourable native genetic variations for traits of agronomic and economic importance across many cereal crops (Vinayan *et al.*, 2013).

Genomic selection (GS) or marker-enabled predictions can predict untested phenotypes from whole-genome information. Blümmel *et al.* (2014b) developed a GS model of fodder quality traits to predict superior lines from a collection of doubled-haploid lines from the maize work of the International Maize and Wheat Improvement Centre (CIMMYT) in Asia.

Apparently, small differences in CR fodder quality result in substantial differences in livestock productivity because of the additive effects of higher diet quality and higher feed intake.

Mapping recommendation domains has allowed spatial stratification of farming systems to better assess the potential of multidimensional cereals (Kristjanson and Zerbini, 1999).

Development impacts

Market studies in India and West Africa have identified significant differences in CR prices attributable to CR quality in India and West Africa. This information is valuable to crop extension programmes.

Adoption studies have shown that materials with higher straw digestibility improve livestock productivity, which is again valuable to extension work.

Plant breeding and selection have led to the availability of crop cultivars with higher-quality CRs in sorghum, pearl millet, groundnut, rice and maize in India, and in cowpea in West Africa.

Higher productivity and income come from sales of CRs and from livestock production. Salient examples are as follows:

- An ILRI-CIMMYT collaboration identified a multidimensional maize hybrid (NK 6240), which is now a very popular hybrid in India (Anandan *et al.*, 2013). ILRI, CIMMYT and Syngenta are now exploring branding for CR fodder quality traits.
- Adoption of improved multidimensional cultivars based on seed production has been difficult and at times contradictory to estimate. Randomized adoption studies by household surveys show generally less adoption than estimates based on seed production.
- Adoption of hybrids is much faster because seed availability is less of a problem than with open-pollinated varieties. Thus, a new dual-purpose maize hybrid (MHM4070 or Lall-454) specifically bred by CIMMYT and ILRI for high temperatures in India reached more than 23,000 ha within 3 years.
- Concomitant increases of about 10% each of pod yield, haulm yield and haulm fodder quality in some new cultivars has provided sufficient incentives for their fast and large-scale adoption.

Policy impacts through the provision of information

Fodder market studies in South Asia and West Africa have shown that: (i) market prices reflect fodder quality differences within and between crops; (ii) customers are willing to pay price premiums for apparently small differences in fodder quality traits; (iii) the price of CRs relative to grain has increased during recent decades (Kelley *et al.*, 1993; Sharma *et al.*, 2010); and (iv) in some Indian markets, income from CR sales exceeded that from grain sales (Samireddypalle *et al.*, 2017).

Capacity building and partnerships on multidimensional crop improvement as outcomes

ILRI has established scientific partnerships in the CGIAR system with ICRISAT, CIMMYT, IITA, national agricultural research and extension systems (NARES) in Ethiopia (Ethiopian Institute of Agricultural Research, EIAR) and India (National Research Centre for Sorghum, now the Indian Institute for Millet Research, IIMR), and the private sector (SeedCo, Syngenta and Advanta).

Affordable and comprehensive phenotyping for food–feed and fodder traits in all key cereal and legume crops is feasible. The ILRI-crop-centre collaboration developed and validated NIRS equations for nitrogen (N), neutral detergent fibre (NDF), acid detergent fibre (ADF), acid detergent lignin (ADL), *in vitro* organic matter digestibility (IVOMD) and metabolizable energy (ME) of CRs of sorghum, pearl millet, groundnut, pigeon pea, chickpea, cowpea, rice, wheat and maize. ILRI NIRS specialists have trained hundreds of laboratory technicians from public and private sectors in South Asia and East and West Africa on NIRS operations. NIRS hubs exist in India and Ethiopia, and NIRS hubs in Nigeria, Mali and Burkina Faso are being established. These hubs are based on NIRS equations developed by ILRI and partners and on extensive training given by ILRI NIRS specialists.

Introduction

The growth in demand for animal-source food in low- and middle-income countries provides challenges and opportunities. A principal challenge is to raise fodder and animal yields per unit of land in a situation where the shrinking natural resource base in terms of land and water makes feed production harder.

In addition, feed resourcing and feeding are at the very interface where positive and negative effects from livestock occur (Blümmel *et al.*, 2013b). Feeds are the single most important input cost into livestock production and largely determine its profitability (Swanepoel *et al.*, 2010). Feed production accounts for the bulk of water required in livestock production (Singh *et al.*, 2004), as well as direct (enteric methane production) and indirect (land use and conversion) greenhouse gas emissions (Steinfeld *et al.*, 2006).

Previous work by the ILRI and partners has identified feed shortage as a major constraint to higher livestock yields; this feed constraint will worsen with the increasing demand for animal-sourced food (Blümmel *et al.*, 2017). Opportunities for improving feed resources are constrained by shortages of arable land and, increasingly, water, and these constraints are likely to become aggravated by climate change (Blümmel *et al.*, 2015b). Feed supply–demand scenarios for South Asia and East and West Africa have shown that CRs such as straws, stover and haulms are already the most important feed resources, commonly providing 50–70% of the feed resources in smallholder mixed crop–livestock systems (Blümmel *et al.*, 2014b; Duncan *et al.*, 2016).

Generally, lignocellulosic biomass from forest, agricultural waste and CRs is the most abundant renewable biomass on earth, with a total production estimated ranging from about 10 billion to 50 billion t (Sanchez and Cardena, 2008). About 3.8 billion t are contributed by CRs, with cereals contributing 74%, sugar crops 10%, legumes 8%, tubers 5% and oil crops 3% (Lal, 2005). Considering the huge quantities of CRs available from agricultural production and the high nutritive quality of their basic constituents – hexose and pentose sugars – it comes as no surprise that attempts to upgrade CR biomass for livestock fodder reach back to the beginning of the 20th century (Fingerling and Schmidt, 1919; Beckmann, 1921). These and later attempts included chemical, physical and biological treatments, but chemical treatments received the maximum attention of researchers, particularly the use of hydrolytic agents such as sodium hydroxide and ammonia (reviewed by Jackson, 1977; Owen and Jayasuriya, 1989). However, comparatively little uptake of these technologies was observed, even though considerable effort was made by the international research and development community (Owen and Jayasuriya, 1989). For example, Owen and Jayasuriya (1989) listed and reviewed 12 major international conferences addressing the improved use of CR biomass for livestock feed from 1981 to 1988 and concluded that large-scale adoption of treatment interventions was very rare and did not continue once project activities ceased, despite efforts to simplify treatment technologies and to use local inputs.

The lack of adoption of postharvest approaches to improving CRs gave way to a new research paradigm of targeted improvement of CR fodder value by plant breeding and selection. This was discussed at an international conference by the International Livestock Centre for Africa (ILCA) in 1987 (Reed *et al*., 1988a). At that time, research on improving CR fodder value at source was largely restricted to barley because of the importance of green barley in the mixed systems of the eastern Mediterranean (Capper *et al*., 1988). The ILCA proceedings (Reed *et al*., 1988a) contained 12 papers: three addressed the use of CRs as livestock feed in smallholder crop–livestock farming systems (globally: McDowell, 1988, and Kossila, 1988; West Asia and North Africa: Nordblom, 1988) and three focused on the limited nutritive quality and characteristics of CRs but exclusively on cereal CRs (Mueller-Harvey *et al*., 1988; Owen and Aboud, 1988; van Soest, 1988). The excellent fodder quality of many of the legume residues was not addressed. Crop and cultivar variations in CR fodder traits were explored by Ørskov (1988) and Capper *et al*. (1988) in some depth with regard to the number of cultivars investigated, while the remaining papers focused more on types of cultivars, such as bird-resistant versus non-bird-resistant cultivars (McIntire *et al*., 1988; Reed *et al*., 1988b), or on very few cultivars (Khush *et al*., 1988; Pearce *et al*., 1988). Both Ørskov (1988) and Capper *et al*. (1988) reported highly significant cultivar-dependent variations in CR fodder quality traits with limited trade-offs with grain yields.

Kelley *et al*. (1993) at ICRISAT surveyed fodder trading of cereal straws and farmer perceptions of grain and straw value in India from a more demand-side perspective. These authors found that farmers paid attention to stover quantity and fodder quality in new sorghum cultivars and that new cultivars could be rejected if found lacking in these traits. The authors furthermore reported that the monetary value of sorghum grain relative to stover decreased from about 6:1 to 3:1 within two decades (1970–1990) and concluded and recommended that crop improvement consider CR fodder traits in future crop improvement work. It was in the mid-1990s that ILRI, a successor of ILCA, and ICRISAT concluded a memorandum of understanding to jointly attempt concomitant improvement of grain and CR traits.

The present chapter reviews the findings, outputs and outcomes of research on multidimensional crops in the tropics, focusing mainly on cereals and grain legumes. Specifically, the chapter addresses the following:

- Establishment of CRs as traded commodities and their changing valuation as the impetus for multidimensional crop improvement.
- Trait identification and development of infrastructure for quick and affordable phenotyping for CR fodder quality.
- Exploitation of existing cultivar-dependent variations in CR fodder quality.
- Targeted genetic enhancement for multi-trait food–feed–fodder cultivars.
- Trade-offs between CR fodder traits and primary traits, notably grain and pod or straw yields.
- Outcomes of multidimensional crop improvement and future work.

Future work on multi-trait crop improvement.

Fodder markets

Increasing the feeding value of CRs by multidimensional crop improvement depends on the inherent variation among cultivars of the same crop in the nutritive value of their residues fed to livestock. Practical evidence of such variation has been observed in fodder markets in India for many years, as reviewed by Kelley *et al*. (1993, 1996).

While the fodder quality of CRs was largely ignored in historical crop-improvement programmes, farmers and fodder traders long recognized differences in the fodder quality of CRs, even within the same species. At the farm level, new pearl millet cultivars that had been improved only for grain yields had sometimes been rejected by farmers because of low CR quantity and quality (Kelley *et al*., 1996), and similar findings were reported by Traxler and Byerlee (1993) for wheat. Kelley *et al*. (1993) reported from surveys of sorghum stover trading from 1985 to 1989 in four districts of Maharashtra, India, that stover from landraces realized on average 41% (range 24–61%) higher prices than modern cultivars. These surveys provided early evidence that CR fodder quality differences are reflected in livestock production responses of some magnitude. In addition, the collaboration between ILRI and ICRISAT starting in the mid-1990s was preceded by an *ex ante* assessment of the impact of improving the quality of sorghum and pearl millet stover on livestock performance (Kristjanson and Zerbini, 1999). These authors calculated that a 1% increase in digestibility in sorghum and pearl millet stover would increase milk, meat and draught power outputs by 6–8%. These estimates appeared very high and were questioned by Thornton *et al.* (2003), who argued that a mere increase in only digestible energy, for example, without regard for protein would not result in a significant improvement in livestock productivity.

One support for a higher productivity impact is market prices of sorghum stover where a difference in digestibility of 5% was associated with price premiums of 25% and higher. Blümmel and Rao (2006) surveyed six major sorghum stover traders in Hyderabad, India, monthly from 2004 to 2005 and observed that six different stover types were usually traded. Customers usually had the choice of two or three sorghum stover types offered by the same trader. The poorest and best-quality stover (perceived in terms of colour, softness, sweetness, etc.) were sold on average for INR3 and INR4 per kg of dry matter, respectively. Blümmel and Rao (2006) investigated these traded stovers for laboratory fodder quality traits, such as crude protein and IVOMD, and related these laboratory traits to stover prices. While stover crude protein content was not related to stover prices, IVOMD accounted for 75% of the price variation. In rice straw, trading differences in IVOMD as low as 2–3 percentage points were associated with similar price premiums (Teufel *et al.*, 2010). Incidentally, these findings were in accord with the above-reported observations of Kelley *et al.* (1993) that stover from sorghum landraces achieved on average mean prices 41% higher than modern cultivars. Customers would not pay such price premiums if feeding of stover from landraces would not result in significantly higher livestock productivity. Findings from the surveys of sorghum stover (Blümmel and Rao, 2006) and rice straw (Teufel *et al.*, 2010) trading are combined in Fig. 14.1.

ILRI-ICRISAT work on fodder trading in India was followed by research in Mali, Niger and Nigeria by ILRI, ICRISAT and IITA. Price premiums related to fodder quality differences were also observed in West African markets (Jarial *et al.*, 2016a,b). Livestock producer preferences for haulms from groundnut or cowpea varied with haulm quality between groundnut and cowpea. Thus, cowpea haulms were costlier than groundnut haulms in fodder markets in Mali and Niger, but they also had superior N content and IVOMD than groundnut haulms, while the reverse was true in Nigeria (Table 14.1).

Price differences between cowpea haulm and groundnut haulm reflected quality differences. There was also consistency in pricing of cowpea haulm, groundnut haulm, sorghum stover and pearl millet stover over 2 years at four fodder markets in Niger (Table 14.2). The average price per kg of legume haulms was about five times that of the cereal stover; the average price per unit of N was about 2.7 times as high. Sorghum stover received about 30% higher prices than pearl millet stover, probably because of a 5% unit difference in IVOMD. Across the four CRs, N accounted for 98% (p = 0.008) of the variation in price and IVOMD for 91% (p = 0.04), respectively. While Jarial *et al.* (2016b) did not report price differences for CRs within crops related to cultivar differences, observations at a fodder market in Kano in September 2016 found cultivar differences in price in sorghum stover and in groundnut haulms (M. Blümmel, personal observation, September 2016).

A further point is the relative monetary value of grains and CRs. In legume haulms, the monetary value of grain and CRs can reach parity (Samireddypalle *et al.*, 2017), and grains can occasionally (e.g. when there is high demand for mutton during Muslim festivals) even be cheaper than haulms (Ayantunde *et al.*, 2014). In sorghum stover trading in India during the past decade, stover prices were about 50–60% that of sorghum grain value (Sharma *et al.*, 2010).

In summary, CR fodder market studies in South Asia and West Africa showed that: (i) traders and customers are aware of CR fodder quality differences within and across crops; (ii) customers are willing to pay considerable price premiums for apparently small differences in fodder quality traits; and (iii) the monetary value of CRs relative

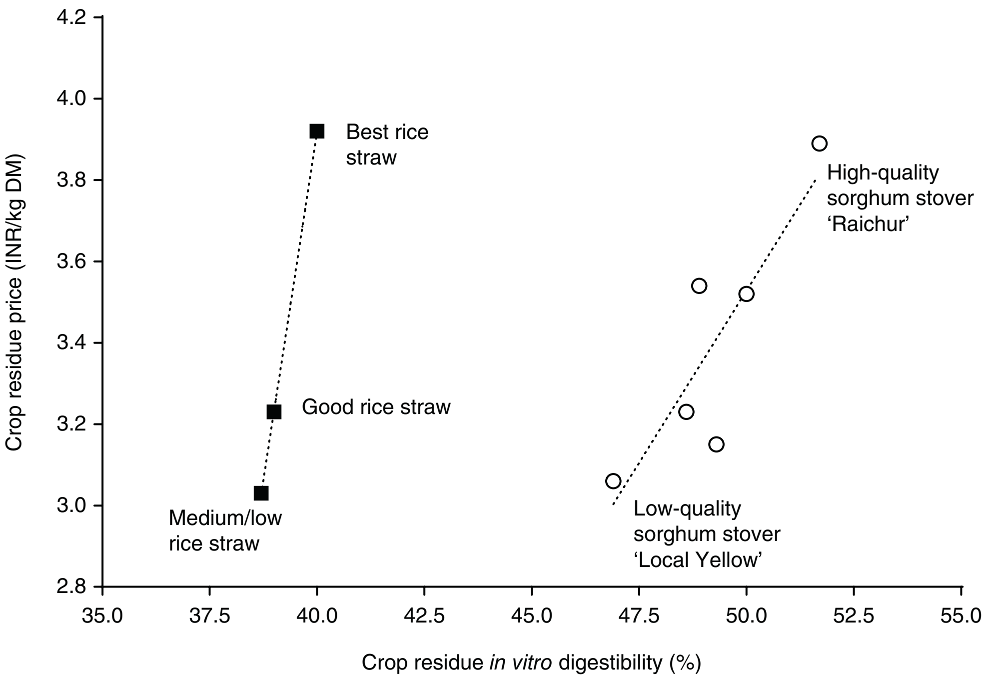

Fig. 14.1. Relationship between cost of sorghum stover and cost of rice straw and their *in vivo* digestibility. DM, dry matter. (Data from Blümmel and Rao, 2006, and Teufel *et al.*, 2010.)

Table 14.1. Prices, relative value and fodder quality traits of cowpea haulm (CPH) and groundnut haulm (GNH) traded in Niger, Mali and Nigeria.

	Niger[a]		Mali[b]		Nigeria[c]	
Variable	CPH	GNH	CPH	GNH	CPH	GNH
Price (US cents/kg)	28	20	95	86	19	72
Price grain:haulm	2.4:1	4:1	1:1.7	1:1.5	3.5:1	1.1:1
Haulm nitrogen (%)	2.2	1.7	2.9	2.4	2.0	2.4
Haulm IVOMD (%)	61.3	58.4	65.4	64.2	55.6	57.1

[a]Jarial *et al*. (2016a) for four fodder markets, over 2 years, bimonthly.
[b]Ayantunde *et al*. (2014) for five fodder markets, over 1 year, monthly.
[c]Samireddypalle *et al*. (2017) for five fodder markets, over 2 years, monthly.

Table 14.2. Average N content, IVOMD and prices (CFA franc) of cowpea haulm, groundnut haulm, sorghum stover and pearl millet stover traded over 2 years at four fodder markets in Niger. (Modified from Jarial *et al.*, 2016b.)

Fodder	N (%)	IVOMD	Price (CFA franc/kg)	Price (CFA franc/N)
Cowpea haulm	2.22	61.3	164	73.9
Groundnut haulm	1.60	58.4	119	74.4
Sorghum stover	1.03	52.2	31	30.1
Pearl millet stover	0.98	47.2	24	24.5

to grain values is considerable and has been increasing over recent decades (Kelley *et al.*, 1993; Sharma *et al.*, 2010). In fact, depending on harvest indices and/or CR fodder quality, more money can be earned from CRs than from the primary product (Samireddypalle *et al.*, 2017). The findings from fodder markets as far apart as West Africa and South Asia send strong signals that both fodder quantity and fodder quality of straws, stovers and haulms do matter.

CR fodder quality and livestock productivity

Livestock productivity trials conducted with the private sector confirmed information from fodder market studies. In India, Miracle Fodder and Feeds Pvt Ltd designed so-called densified total mixed ration (DTMR) feed blocks that consist largely of by-products such as sorghum stover (about 50%), bran, oilcakes and husks (about 36%), with the rest contributed by molasses (8%), maize grain, urea, minerals, vitamins, etc. (Shah, 2007). In a series of experiments with Miracle Fodder and Feeds Pvt Ltd, the authors tested these feed blocks with two objectives: (i) to estimate probable maximum productivity levels on cereal CR-based diets; and (ii) to estimate the importance of the quality of the basic CR going into the blocks on overall livestock performance. In an experiment with a large private Indian buffalo dairy (Anandan *et al.*, 2010), two experimental DTMR feed blocks were produced from low-quality (47% IVOMD) and premium-quality (52% IVOMD) sorghum stover traded in the fodder markets (Blümmel and Rao, 2006).

The results from these trials are reported in Table 14.3. Using premium sorghum stover (‘Raichur’ in Fig. 14.1) resulted in more than 5 kg higher daily milk potential than using the lower-quality stover (‘Local Yellow’ in Fig. 14.1). This differential yield potential was due to higher ME content/kg DTMR and also higher feed intake in the ration containing the premium stover. These accumulating effects of higher ME content and higher feed intake are the reason that apparently small difference in feed quality can have considerable effects on animal performance. The increase in milk potential of 5 kg compared with the ration containing the lower-quality stover explains the decisions of customers to invest in higher-quality stover. However, only part of the incremental increase in milk potential was due to the higher-quality stover, as this group also consumed more concentrate (0.85 kg/day), which contributed about half to the DTMR. The increased milk potential attributable to higher stover quality is estimated to be 2.4 kg/day (increase from 4.4 to 6.8 kg/day; Table 14.3). This would be an increase of about 24% relative to the milk potential of the DTMR with the lower-quality stover of 9.9 kg/day. This increase appears to agree with the price premiums paid for the higher-quality sorghum stover at the fodder markets in India. It also seems to align with the price differences observed between sorghum and pearl millet stover traded at fodder markets in Niger (Table 14.2).

The effect of CR quality on livestock productivity is clearer in cases where the residues are fed as sole diets rather than as basal diets, as is generally the case with cereal CRs. Table 14.4 summarizes work where legume haulms were fed as sole diets to small ruminants. Cultivar-dependent variations in haulm fodder quality were considerable. In the case of groundnut haulms harvested from six different cultivars in Nigeria, sheep could lose weight on haulms from one cultivar while gaining 46 g/day on haulms from another cultivar. In India, weight gains in sheep could differ by more than twofold (from 65 to 137 g/day) depending on haulm fodder quality difference among groundnut cultivars. Similar proportional genotypic variations have been reported for faba bean haulms in Ethiopia (Table 14.4). For unsupplemented barley straw from eight different cultivars, Capper *et al.* (1988) reported daily weight changes from 150 g to little above live weight maintenance. Protein supplementation resulted in cultivar-dependent variations in weight gain from 100 to 250 g/day.

These examples show that the effect of cultivar variations on fodder quality of CRs on livestock productivity can be substantial. The high response in livestock performance to apparently small differences in CR fodder quality is the result of two cumulative effects: higher diet quality and higher feed intake. However, this effect can only be effective where feed is offered *ad libitum*, which is not always the case, and often CRs are in short supply and fed in a restricted fashion (Mayberry *et al.*, 2017). It is also worth pointing out that higher productivity can be achieved on mostly, or even completely, by-product-based

Table 14.3. Milk potential in Indian dairy buffalo fed two DTM feed blocks based on premium-quality (52% digestibility, 7.39 MJ ME/kg) and low-quality (47% digestibility, 6.52 MJ ME/kg) sorghum stover with total by-product proportion of feed blocks greater than 90%. (Data from Blümmel *et al*., 2017, based on the actual milk fat contents of buffalo milk.)

	Low-quality stover	Premium-quality stover
Protein (%)	17.1	17.2
ME (MJ/kg)	7.37	8.46
Voluntary intake of feed block (kg/day)	18.0	19.7
Voluntary intake of feed block (% /kg LW[a])	3.6	3.8
ME intake (MJ/day)	132.7	166.7
ME intake stover (MJ/day)	58.7	72.7
Milk fat (%)[b]	7.4	7.6
Milk potential (kg/day)	9.9	15.5
Milk potential from stover[c]	4.4	6.8
Milk potential from cross-bred cattle (kg/day)	14.0	21.0
Milk potential from stover[c]	6.2	9.2

[a]Live weight (LW) of buffalo was calculated by body measurements and estimated to be on average 506 and 525 kg in the low-quality and premium-quality feed block, respectively.
[b]Milk fat in cattle was assumed to be 4% with a cross-energy content of 3.13 MJ/kg.
[c]Estimated based on ME contribution of stover to ME of DTMR as: ME stover/ME DTMR × milk potential.

Table 14.4. Effect of groundnut and faba bean cultivars on live-weight changes in sheep fed exclusively with haulms offered *ad libitum*.

Experiment	Average (g/day)	Lowest (g/day)	Highest (g/day)
Haulms of ten groundnut cultivars fed to Indian Deccan sheep[a]	94.1	65	137
Haulms of six groundnut cultivars fed to West African Dwarf sheep[b]	26.5	–6	46
Haulms of five faba bean cultivars fed to Ethiopian Arsi sheep[c]	49.2	37.5	64.6

[a]Prasad *et al*. (2010).
[b]Etela and Dung (2011).
[c]Wegi (2016).

feeding systems. In the case of DTMR, milk yields in cross-bred cattle of more than 20 kg/day seem achievable (Table 14.3) and these DTMR consist of more than 90% by-products. Feeding legume haulms as the sole feed to sheep can result in daily weight gains of well over 100 g/day (Table 14.4). These are productivity levels more commonly associated with concentrates than with CR diets. Findings from the livestock productivity trials are consistent with price premiums paid for fodder quality differences (Fig. 14.1, Tables 14.1 and 14.2). It is important to point out that the variations seen in the fodder markets and livestock productivity trials came about largely by chance and that those differences in fodder quality were not the intentional results of crop breeding or selection. We will see in a later section that the fodder quality of CRs can be increased further by targeted genetic enhancement using conventional or molecular breeding crop-improvement approaches.

Trait Identification and Tools for Affordable Phenotyping for Crop Residue Fodder Quality

Validation of laboratory fodder quality traits

Fodder quality is ultimately determined only by livestock production and productivity, but livestock performance trials are unsuitable for routine feed and fodder quality analysis. This is particularly valid in crop improvement, where many samples must be analysed and where initially the biomass availability is low. Simple laboratory fodder quality traits are needed, but these traits must be well correlated with actual livestock performance measurements. 'Simple' here refers not only to logistical and economical laboratory demand but also to the need for the traits to be comprehensible to, and usable by, crop scientists, seed producers, fodder traders and development practitioners with no or little training in livestock nutrition. When the ILRI-ICRISAT collaboration on multidimensional crop improvement started, a wide range of potential morphological, chemical and *in vitro* traits were investigated and related to livestock performance measurements usually obtained with sheep (Sharma *et al.*, 2010).

Ravi *et al.* (2010) investigated morphological, chemical and *in vitro* traits in pearl millet stover and related these traits to organic matter digestibility, organic matter intake, digestible organic matter and N balances in sheep. Generally, fibre components and *in vitro* laboratory traits were more closely related to *in vivo* measurements than morphological traits, even though plant height and stem diameter were both consistently and statistically significantly inversely related to the *in vivo* measurements of 40 pearl millet stovers. In contrast, traits such as leafiness, including estimates of residual green leaf area, which are often employed for sensory phenotyping by crop-improvement programmes and farmers, were less well related to *in vivo* measurements. It is important to realize that all stovers were offered chopped (which is increasingly the practice or the trend, at least for stover utilization in India and elsewhere), which might reduce the importance of leafiness and other morphological traits on intake responses.

Bearing in mind the above considerations about the simplicity and meaningfulness of fodder quality traits, NDF (a cell wall estimate), ADF (an estimate of cellulose) and *in vitro* digestibility seem to be good indicators for ranking fodder quality in pearl millet, sorghum (Ramakrishna *et al.*, 2010) and maize (Ravi *et al.*, 2013) stover, while ADL (an estimate of lignin) seems to predict fodder quality in groundnut haulms better than any of the aforementioned traits (Prasad *et al.*, 2010). Combining different laboratory traits using stepwise multiple regressions improved predictions of *in vivo* measurements in most cases in pearl millet, sorghum stover and groundnut haulms. In all three cases, laboratory traits related to available feed energy (*in vitro* digestibility, ME and fibre constituents) were found to exhibit more consistent relationships with *in vivo* measurements than CR N content (Prasad *et al.*, 2010; Ramakrishna *et al.*, 2010).

Calibration and validation of NIRS tools

Conventional laboratory analysis cannot efficiently cope with the large set of sample entries from multidimensional crop-improvement programmes. NIRS is a non-invasive technique routinely used since the 1960s in the food industry, forage breeding and pharmaceutical industry. Most instruments used are manufactured by FOSS (Forage Analyser 500 and 6500), which has the advantage that NIRS equations developed in one laboratory can be transferred to other laboratories using FOSS. The ILRI-crop-centre collaboration developed and validated NIRS equations for N, NDF, ADF, ADL, IVOMD and ME of CRs of sorghum, pearl millet, groundnut, pigeon pea, chickpea, cowpea, rice, wheat and maize. We generally expected an R^2 value of at least 0.90 between conventionally analysed laboratory traits and blind predictions by NIRS (see also Sharma *et al.*, 2010). With new global interest in monogastric and fish feed, NIRS equations were also developed for grains of key crops, including routine quality traits such as protein, starch and fat (Choudhary *et al.*, 2010) but also amino and fatty acids (Prasad *et al.*, 2015), which still mostly rely on costly high-performance liquid chromatography analysis.

NIRS equations can be transferred across FOSS-type instruments with little spectra standardization to account for instrument-to-instrument variation. Over the past one and a half decades, ILRI NIRS specialists have trained hundreds of laboratory technicians from CGIAR and the national public and private sectors in South Asia and East and West Africa on NIRS operations, including NIRS networking and the generation of NIRS equations. Fully functioning NIRS hubs exist now in India and Ethiopia, and NIRS hubs in Nigeria and Mali are being set up.

Thus, quick, affordable and comprehensive phenotyping for food–feed and fodder traits in all key cereal and legume crops is feasible, but sample processing (drying, grinding and shipping) limit experimental efficiency. Mobile NIRS applications can potentially overcome this constraint. Two new mobile hand-held systems manufactured by Phazir and Brimstone have been explored during the past 2 years to remove, or at least mitigate, the sample processing constraint (Prasad *et al*., 2015). Phazir and Brimstone currently cost about US$40,000 each, but recently an extremely cheap (about US$450–500) and small pocket NIRS system called Scio came on the market and is currently being tested at ILRI in India and Ethiopia.

Exploitation of Existing Cultivar-dependent Variation in CR Fodder Quality

Phenotype pipeline and releases for variations in CR fodder quality

A widespread misconception about how superior CRs can be generated is that targeted crop breeding is invariably required. However, phenotyping for fodder quality to detect genetic differences in food–feed–fodder traits in advanced cultivars and exploiting them often suffices. Exploiting existing variations in traits and targeting genetic enhancement towards specific traits are separate approaches, and the first is possible without the second. The first approach does not require much investment besides phenotyping for CR traits and has short delivery pathways. The second approach requires more investment and time but promises greater impact.

This timespan of crop improvement can be shortened by phenotyping CRs of released cultivars for fodder quality and by promoting superior dual-purpose cultivars with farmers, traders and processors. This approach is particularly promising where the private sector is involved, usually in the promotion and marketing of hybrids. A collaboration between ILRI and CIMMYT identified such a superior dual-purpose maize hybrid (Anandan *et al*., 2013), which is now a very popular hybrid in Asia, and its producer, Syngenta, has recently approached ILRI and CIMMYT for ways of advertising the high fodder quality on the seed packets of the hybrid. ILRI, CIMMYT and Syngenta are now exploring processes to bring about such branding and seed bag labelling for CR fodder quality traits. Work is ongoing in the use of check cultivars analogous to current methods of comparing grain yields of yet-to-be-released cultivars with yields of selected check cultivars; in addition to grain yields, CR quality traits could also be compared. Another option is comparing CR quality of yet-to-be-released cultivars with longer-term average qualities of CRs traded at fodder markets or with the average values of CR qualities given in nutritional textbook/feeding tables for a given country. In any event, getting the private sector interested in dual-purpose traits is of great strategic importance for mainstreaming Multi-dimensional crop improvement and for scaling of new cultivars, as public-sector crop improvement groups are watching the private sector closely.

Phenotyping pipeline hybrids that are close to release is also cost-effective and has short delivery pathways. This was implemented with a private-sector maize programme in India; examples of this work from 2014 onwards are presented in Fig. 14.2, where 24 pipeline hybrids were tested at four locations in India. The hybrids with the highest average grain yield also had highest stover N and second highest stover IVOMD (Fig. 14.2a,b). The variation in stover IVOMD among the top grain yielders of 9–10 t/ha was like the variation between the best and poorest sorghum stover in fodder trading in India (Fig. 14.1) or between the average sorghum and pearl millet stover traded in Niger (Table 14.1), which resulted in appreciable price premiums for the better-quality stover in both cases. The implication for promoting the maize hybrid with the highest IVOMD rather than the lowest IVOMD among the top yielders in dairy productivity can be extrapolated from the findings in Table 14.3. However, while combination of highest grain yields and highest stover traits such as N and IVOMD are entirely feasible, these trait combinations seem to be associated only with intermediate stover yields (Fig. 14.2c,d).

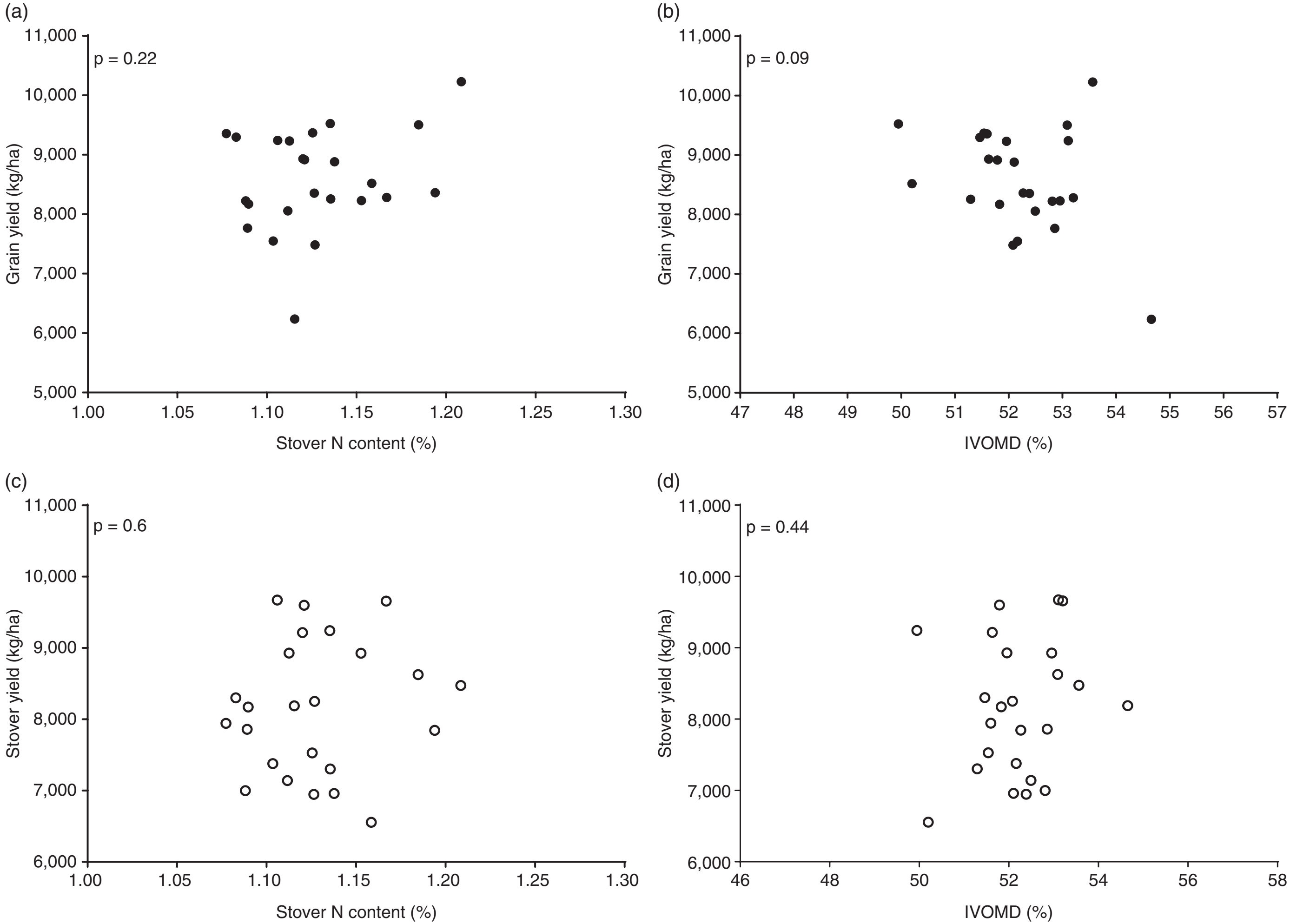

Fig. 14.2. Relationship between stover N and grain yield (a), between stover IVOMD and grain yield (b), between stover N and stover yield (c) and between stover IVOMD and stover yield (d) in 24 pipeline maize hybrids grown at four locations in India.

Institutionalized Multidimensional crop improvement has advanced only slowly. In 2002, the National Research Centre for Sorghum (NRCS) decided to include sorghum stover traits as release criteria for new sorghum cultivars. Interestingly, this was influenced by a visit of the then Director of the NRCS to the sorghum fodder markets in Hyderabad described earlier. This involved seconding NRCS technicians to the ILRI NIRS Hub hosted by ICRISAT to analyse stover of all new sorghum cultivars submitted for release under the All-India Coordinated Research Project (AICRP) on Sorghum (Venkatesh *et al.*, 2006). This work continues and is now being explored for minor millets by IIMR. Stover traits have now also been included as release criteria for pearl millet, although this crop is, paradoxically, currently not under the mandate of IIMR. Less formalized pilot studies have been undertaken with the Indian Directorate for Maize, where the modification of cultivar release criteria to include maize stover traits was discussed during recent annual maize meetings, although without a formal decision yet being taken. The situation is similar in Ethiopia, where the International Centre for Agricultural Research in the Dry Areas (ICARDA) prepared the ground with EIAR by phenotyping lentils, chickpeas and faba beans for haulm fodder quality traits during release processes (Alkhtib *et al.*, 2016, 2017).

Targeted genetic enhancement towards food–feed crop cultivars

The targeted concomitant improvement of grain and CR traits requires more investment and time than the mere detection and exploitation of already existing variations but promises greater impact. In ILRI-ICRISAT-CIMMYT collaborations, both conventional and molecular breeding approaches were applied for targeted genetic enhancement of CR fodder traits within the paradigm of simultaneous improvement of grain and fodder traits.

Recurrent selection

Bidinger *et al.* (2010) showed that within two recurrent selection cycles, digestible organic matter intake of pearl millet stover measured in sheep increased from 12.9 to 15.1 g/kg live weight (LW), an increase of 17%, and the N balance changed from negative (−0.016 g/kg LW/day) to positive (0.05 g/kg LW/day). The improvement in stover quality did not come at any penalty for grain or stover yield. Choudhary *et al.* (2012) investigated the mode of inheritance of stover N and IVOMD. From a full-sibling (FS) base population of pearl millet variety ICMV 221, three high and low N and three high and low IVOMD FSs were selected. Crosses were made for high × high (H × H), low × low (L × L), and high × low (H × L) FS trait contrasts and evaluated at Patancheru, in India, in the rainy seasons of 2007 and 2008. The high- and low-N (HN and LN, respectively) FS parents were 0.85% and 0.72% N, respectively. In the crosses, stover N contents were: HN × HN = 0.85%, LN × LN = 0.73% and HN ×LN = 0.80% ($p < 0.05$). The high- and low-digestibility (HD and LD, respectively) FS parents were 43.3% and 40.3% IVOMD, respectively. In the crosses, stover IVOMD were: HD × HD = 43.7%, LD × LD = 40.3% and HD × LD = 42.2% ($p < 0.05$). The intermediate results of H × L crosses strongly indicated the additive nature of the stover quality traits of N and IVOMD and suggest the application of cyclic breeding methods for increasing stover N content and IVOMD in pearl millet.

A further pilot study was conducted to increase the key fodder quality traits of N content and IVOMD through two cycles of FS recurrent selection of open-pollinated pearl millet cultivar ICMV 221 (base population, C_0). Six experimental varieties were selected from the first cycle (C_1) and second cycle (C_2) of selection for: (i) high grain yield; (ii) high grain and stover yield; (iii) high stover IVOMD, (iv) low stover IVOMD; (v) high stover N content; and (vi) low stover N content. Stover N and IVOMD increased by 9.5% and 2%, respectively, in the C_1 bulk, and by 21% and 5%, respectively, in the C_2 bulk over the base population C_0. The high-N experimental varieties showed the highest N percentage and stover N yield, while the high-digestibility experimental varieties showed the highest ME and IVOMD values from both selection cycles. The findings suggest that stover N and IVOMD can be improved without significant detriment to grain and stover yield.

Hybrid breeding for dual-purpose maize

In South Asia, dual-purpose maize breeding was supported by the CRP on Maize through a competitive grant scheme to ILRI. Zaidi *et al.* (2013) reported substantial variability for stover quality in maize working with germplasm available from CIMMYT-Asia with no negative effect of the stover quality traits (IVOMD and ME) on grain yield, indicating the possibility for simultaneous improvement of both stover quality and grain yield. In addition, substantial progress has been made in identifying trait-specific genomic regions for use in targeted breeding programmes to improve stover quality and grain yield (Vinayan *et al.*, 2013). This breeding initiative for improving stover quality has led to the development of advanced lines with high digestibility (over 50%) and energy (greater than 8.0 MJ/g) for use as parents of new hybrid combinations. Results from evaluation of these experimental hybrids under optimal growing conditions have shown promise in terms of their yield performance (roughly 8.0 t/ha) and *in vitro* digestibility (over 50%). Studies of the performance of commercial hybrids within India also led to identification of promising hybrids such as NK6240 (Syngenta) with high digestibility (over 50%) (Anandan *et al.*, 2013) and high grain yields (over 9.0 t/ha) during the rainy season.

Maize is fast replacing some of the major cereal crops grown widely in these regions and currently ranks first followed by rice and wheat in terms of production and growth. One of the emerging seasons for maize cultivation in India is spring, particularly in South India (usually a rice–fallow system), where adverse weather conditions prevail (high temperature and low rainfall). Several pipeline hybrids and breeding lines have been tested to suit this environment, and preliminary investigations led to identification of potential hybrids that have good grain yield and high stover quality. The progress of this maize hybridization programme to simultaneously improve food and fodder traits is exemplified in Fig. 14.3 using data from sorghum stover trading as reference values; the perceptions of farmers and traders in India are that sorghum stover is nutritionally superior to maize stover (Blümmel *et al.*, 2014b).

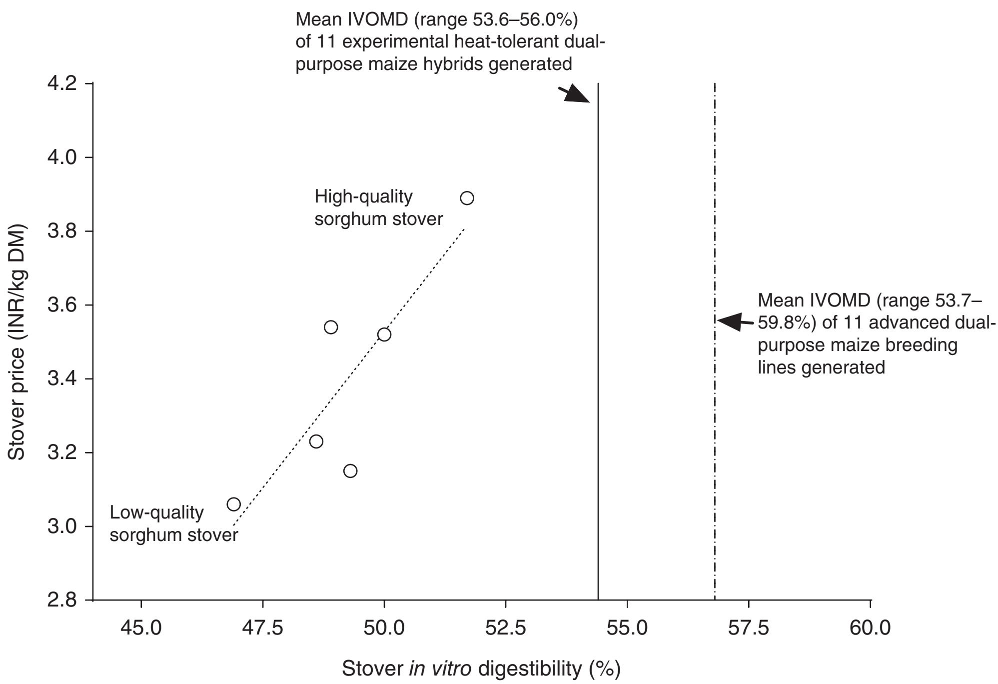

Fig. 14.3. Breeding advances in dual-purpose maize stover quality relative to different sorghum stovers traded in rainfed India in the past decade. (Data from Blummel *et al.*, 2014b).

Fig. 14.3 shows that maize stover is not inferior to sorghum stover, which was also confirmed in trials with dairy animals (Blümmel *et al*., 2014b). Furthermore, the average IVOMD (54.4%) of the new hybrids targeting areas with adverse weather conditions is about 2.5% higher than that of the highest-quality traded sorghum stover (Fig. 14.3). This was one of the sorghum stovers used for the dairy experiments described in Table 14.3. It is very likely that dairy productivity would be substantially further enhanced if the sorghum stover were replaced by a maize stover with 56% IVOMD as available in the new hybrids, and even more so by a maize stover with an IVOMD of close to 60% now available in the new dual-purpose breeding lines (Fig. 14.3).

Similar findings were reported from CIMMYT-ILRI dual-purpose maize breeding research in East Africa (Ethiopia, Tanzania and Kenya). Ertiro *et al*. (2013) produced 60 experimental dual-purpose hybrids from 16 parental lines, yielding 10 t of grain with an IVOMD of up to 62% (range 53.1–62.3%). Mid-parental key stover traits such as IVOMD were well related ($r = 0.78$; $p < 0.0001$) to the IVOMD of the hybrids produced from them, also strongly suggesting the opportunity for dual-purpose hybrid breeding.

QTL identification and backcrossing

Nepolean *et al*. (2009) used QTLs to map the genomic regions controlling stover quality and yield traits in pearl millet. Marker-assisted breeding would be an effective tool to exploit these genomic regions and to choose breeding lines having combinations of better stover quality and high grain yield without linkage drag between these traits. With these objectives in mind, QTLs for stover IVOMD and ME content were identified and introgressed into four parental lines of existing hybrids showing good agronomic performance. Three generations of marker-assisted backcrossing and subsequent selfing of backcrossed progenies having target QTLs was carried out with the help of QTL-flanking microsatellite simple-sequence-repeat markers. Single QTL introgression lines that were homozygous for target regions were identified. Improved hybrids were synthesized from these QTL homozygous lines and were evaluated in multi-location field trials. The results from the laboratory analysis of stover samples showed that one of the improved hybrids was at least 8.5% higher in ME and 6.3% higher in IVOMD than the control hybrid. The new hybrid also produced a 10% increase in grain yield and a 4% increase in stover yield. These results suggest that new hybrids can be developed, concomitantly improving grain and stover traits using QTLs (Nepolean *et al*., 2009).

Blümmel *et al*. (2015a) introgressed stay-green QTLs into the sorghum genetic backgrounds S-35 and R-16, generating 52 and 39 lines, respectively, to investigate the effects of stay-green introgression on stover traits and grain–stover relationships. The stover quality traits analysed were N, IVOMD, ADF, ADL and neutral detergent solubles (= 100 – NDF) using a combination of conventional nutritional laboratory analysis with NIRS. Field trials were conducted under treatments of unlimited (control) and limited water supply. Significant ($p < 0.0001$) differences were found among lines for grain and stover yield and all stover quality traits under both water treatments. Water treatment had greater effects on grain and stover yields, which decreased by between 20% and 32% under water stress, than on stover quality traits, which varied at most by 8% between treatments. Year had the greatest effect among treatments, followed by water treatment and cultivar. Trade-offs between stover quality traits and grain yields were largely absent in both backgrounds. However, the effect of QTLs on selected stover quality traits was background dependent. In S-35, one stay-green QTL (stgB) significantly increased stover IVOMD and grain and stover yield, while no concomitant trait improvement was observed in the background R-16. The QTL in S-35 also increased the water-use efficiency of the whole plant in terms of grain yield, stover yield and stover ME (Blümmel *et al*., 2014a).

GWAS and GS

GWAS have the potential to unravel favourable native genetic variations for traits of agronomic and economic importance across a wide range of cereal crops. Vinayan *et al*. (2013) studied a panel of 276 inbred lines from CIMMYT's

Drought Tolerant Maize for Africa (DTMA) project using their test-cross hybrids with the maize line CML312, and the single crosses were evaluated for grain and stover yields, plant height, days to 50% anthesis and silking, stover N, NDF, ADF, ADL, IVOMD and ME content. GWAS analysis was carried out using genotyping by sequencing, and 55K single-nucleotide polymorphism arrays revealed several regions of significant association for N, ADF and IVOMD, each explaining from 3% to 9% of the phenotypic variance for these fodder quality traits. GWAS was helpful in uncovering genomic regions of interest for target traits.

GS or marker-enabled predictions can predict untested phenotypes from whole-genome information. In one study, GS models were developed for fodder quality traits to predict superior lines from the collection of doubled-haploid lines generated by the Global Maize Program of CIMMYT in Asia. Using high-density genotypic information as well as fodder quality phenotypes of approximately 700 lines from two association panels – DTMA and the CIMMYT-Asia Association Panel (CAAM) – marker effects were obtained for fodder quality traits using GS models. The results indicated significant relationships between genotyping-by-sequencing-derived values and the phenotypes, with r values ranging from $r = 0.44$ to $r = 0.45$ across IVOMD and ME, respectively (Blümmel *et al*., 2014b). These predictions of fodder quality phenotypes in biparental populations indicated that genomic selection can be used to: (i) improve fodder quality in maize breeding populations; and (ii) select parents in breeding for fodder quality from maize repositories without phenotyping the lines.

Trade-offs Among Crop Residue Fodder Traits and Primary Traits

Primary and secondary traits

The increasing importance and demand for CRs as fodder is reflected in four major trends: (i) increasing labour investment in collecting and storing CRs in more extensive systems (Valbuena *et al*., 2015); (ii) farmer preferences for dual-purpose crop varieties; (iii) higher market price for CRs with a higher feed quality; and (iv) higher livestock productivity with CRs with a higher feed quality. Evidence for cultivar preferences based on feed traits comes from farmer rejection of new sorghum and pearl millet cultivars that had been improved only for grain yields and had low stover quantity and quality (Kelley *et al*., 1996). Recently, farmers ranked maize stover traits highly when assessing cultivars in East Africa (de Groote *et al*., 2013). Trading of CRs is expanding in volume and distances, and CR:grain price ratios during the past two decades have decreased (Kelley *et al*., 1993; Blümmel and Rao, 2006; Berhanu *et al*., 2009). Nevertheless, grain yields remain the primary trait that most crop-improvement programmes focus on. When multidimensional crop-improvement programmes target CR traits, they need to address potential trade-offs between grain and CR traits.

It is important to understand what causes trade-offs between grain and CR traits. In its simplest form, a nutrient limited by soil fertility and/or fertilizer application, such as N, is partitioned between grain and the CR. A more complex example is in the partitioning of photosynthetic products (which are not finite quantities such as soil and fertilizer N), notably soluble carbohydrates, which contribute significantly to CR digestibility and therefore to fodder quality. Trade-offs can also arise from more indirect mechanisms of ensuring grain yields and efficient harvest, such as lodging resistance, which can affect fodder quality of CRs through increased stem lignification.

On the most basic level of trade-offs, grain and CR yields were only moderately correlated in sorghum (Blümmel *et al*., 2010), groundnut (Nigam and Blümmel, 2010), pearl millet (Bidinger and Blümmel, 2007), cowpea (Samireddypalle *et al*., 2017), maize (Blümmel *et al*., 2013a) and wheat (Blümmel *et al*., 2012a). Grain yields rarely accounted for more than 50% of the variation in CR yields. In other words, variation in harvest indices were considerable and grain yield is an insufficient predictor of CR yield. Breeding for increases in grain yield was often accompanied by shortening of stems to prevent lodging, resulting in the longer term in increasing harvest indices (Hay, 1995). While this relationship has been shown in temperate cereals, it is less clear in pulses and tropical cereals such as rice and maize (Hay, 1995). In recent years, investments in second-generation biofuel technologies have resulted in renewed interest in variations in harvest indices, as CRs provide valuable feedstock for ethanol production (e.g. Dai *et al.*, 2016). These authors also reported considerable cultivar- and management-dependent variations in harvest indices, suggesting that CR yields cannot be satisfactorily calculated from grain yields. Grain yield and total biomass yield should therefore be recorded in Multidimensional crop-improvement efforts. These considerations are also relevant for conservation agriculture, as higher biomass yield would make the partitioning of CRs between livestock feeding and soil improvement perhaps less contentious (Baudron *et al.*, 2014).

CR N content and grain and CR yield

Relationships between the N content of CRs and grain and CR yields vary. Under balanced crop management, when no restrictions were imposed on fertilizer or water, trade-offs between the N content of CRs and grain and CR yield were largely absent (Fig. 14.4). (The data in Fig. 14.4 were derived from a collaboration between the National Research Center for Sorghum, later renamed the Directorate for Sorghum Research, and Indian Institute for Millet Research). No relationship was observed between the protein content of sorghum stover (which is calculated as stover N × 6.25) and grain yield (Fig. 14.4a). Under high Kharif (sorghum grown in the rainy season in semi-arid India) grain yielders of 5 t/ha, stover protein content could vary from 4% to 7%, the latter being adequate to provide minimum microbial N requirements in the rumen (van Soest, 1994). Sorghum stover protein and stover yield were significantly positively correlated, but the correlation coefficients were low (Fig. 14.4b).

Bidinger and Blümmel (2007) and Blümmel *et al.* (2007a) imposed N restrictions by limiting fertilizer application while increasing pressure on partitioning of N and adjusting planting densities on different cultivars (landraces, open-pollinated varieties (OPVs) and hybrids) of pearl millet. Even under these imposed restrictions, the authors found no inverse relationship between the stover N of pearl millet and grain yields (Fig. 14.5a). However, stover N and straw yield could be significantly inversely associated under low fertility and high population density (Fig. 14.5b).

Water restriction reinforces trade-offs under normal management and growing conditions. For example, in chickpea cultivars, haulm, N and grain yield were inversely correlated (r = −0.41) under normal growing conditions but this association became closer (r = −0.62) under water restriction (Fig. 14.6a). Associations were positive between haulm N and grain yield and again the association was stronger under water restriction (Fig. 14.6b). Similar relationships have been observed for groundnut (Blümmel *et al.*, 2012b).

CR digestibility and grain and CR yield

As with CR N content, relationships between CR digestibility and grain and CR yield are affected by water stress. No relationship was observed

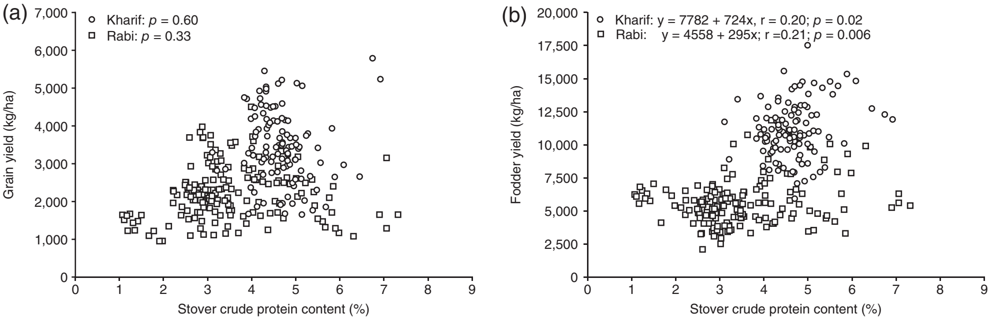

Fig. 14.4. Relationships between mean stover crude protein and grain yield (a) and between mean stover crude protein and stover yield (b) in Kharif and Rabi sorghums submitted for cultivar release from 2002 to 2008. (Unpublished data, Michael Blümmel).

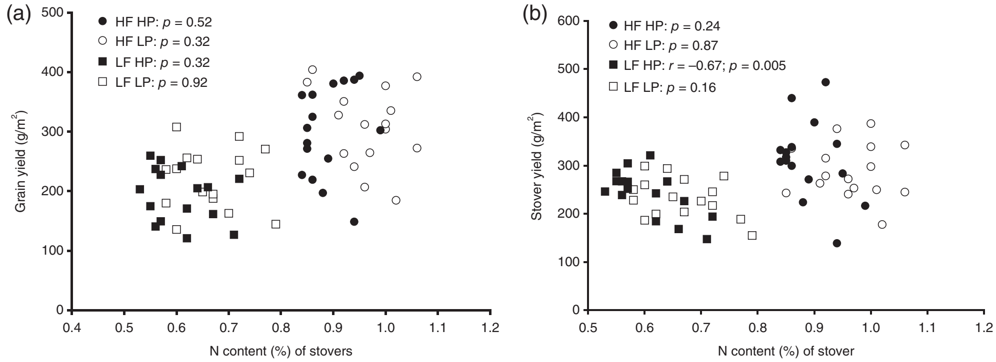

Fig. 14.5. Relationships between N content of pearl millet stover and grain yields (a) and between N content of pearl millet stover and stover yields (b) under high (HF) and low (LF) fertility and high (HP) and low (LP) population density. (Data from Bidinger and Blümmel, 2007).

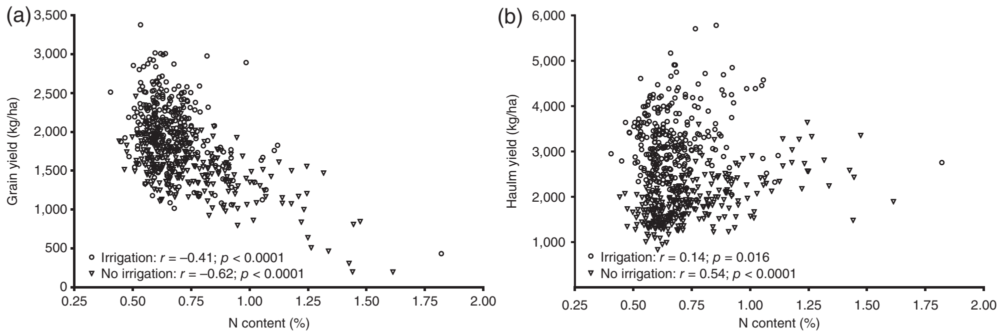

Fig. 14.6. Relationship between haulm N content and grain yield (a) and between haulm N content and haulm yield (b) in 280 chickpea cultivars. (Data from Blümmel *et al.*, 2012b).

between stover digestibility and grain yield in Kharif sorghum, while this relationship was significantly inverse in Rabi sorghum (grown in the dry season) (Fig. 14.7a). The variation in stover digestibility in high Kharif grain yielders of about 5 t/ha was close to 10% (Fig. 14.7a), which is twice the difference observed in sorghum stover trading situations (Fig. 14.1). Even in Rabi sorghum, with the overall negative association between stover digestibility and grain yield, stover digestibility among Rabi high grain yields of about 3.5 t/ha could vary by a similar magnitude.

In pearl millets, stover digestibility and grain yield were unrelated, regardless of N fertilizer level and population density (Fig. 14.8a). In chickpea haulm, digestibility and grain yield were weakly although significantly ($r = -0.13$, $p < 0.03$) associated under irrigation, but the trade-offs became more pronounced ($r = -0.50$, $p < 0.0001$) under water restriction (Fig. 14.9a). In all three crops, stover and haulm digestibility and stover and haulm yields were significantly positively associated (Figs 14.7b and 14.8).

The relationships between stover and haulm digestibility and grain yield would be affected, for example, by arrested translocation of soluble carbohydrate from the stem to the grain or from lignification of stems to prevent or counteract lodging. While these mechanisms might be real, they were expressed only mildly in the relationships of CR digestibility and grain yields in rice (Blümmel *et al.*, 2007b), groundnut (Nigam and Blümmel, 2010), cowpea (Samireddypalle *et al.*, 2017), maize (Blümmel *et al.*, 2013a) and wheat (Blümmel *et al.*, 2012a).

Considerable elasticity exists between biomass yield (grain and CR) and CR fodder quality.

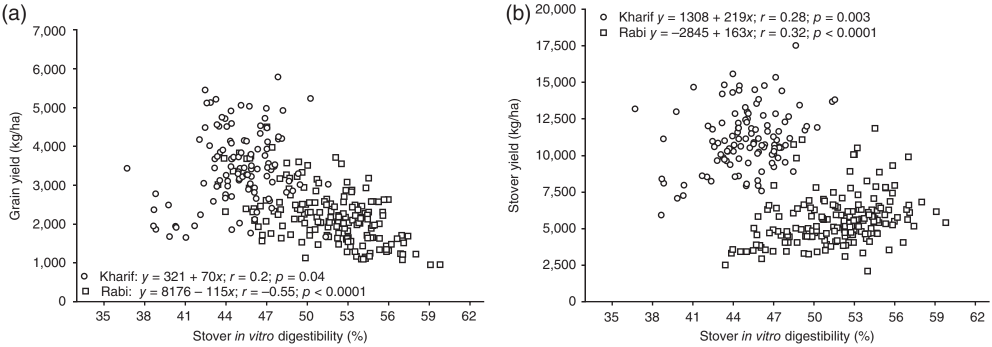

Fig. 14.7. (a) Relationships between mean stover *in vitro* digestibility and grain yield in Kharif and Rabi sorghum cultivars submitted for release from 2002 to 2008. (b) Relationships between mean stover *in vitro* digestibility and stover yield in Kharif and Rabi sorghum cultivars submitted for release from 2002 to 2008. (Data from Blümmel *et al*., 2010).

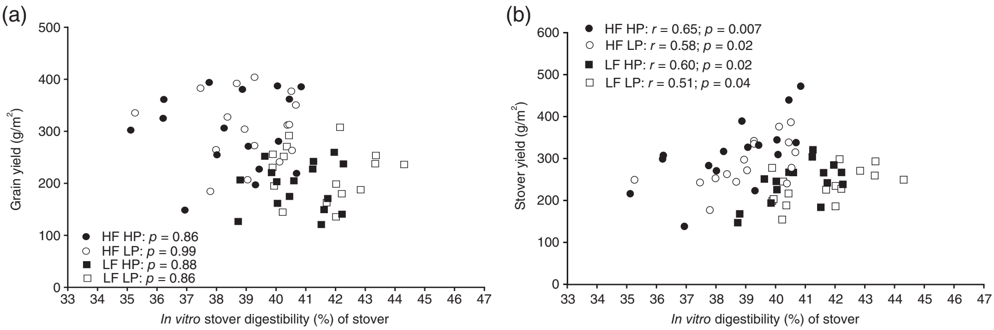

Fig. 14.8. (a) Relationships between *in vitro* digestibility of pearl millet stover and grain yield (a) and between *in vitro* digestibility of pearl millet stover and stover yield under high (HF) and low (LF) fertility and high (HP) and low (LP) population density. (Data from Bidinger and Blümmel, 2007).

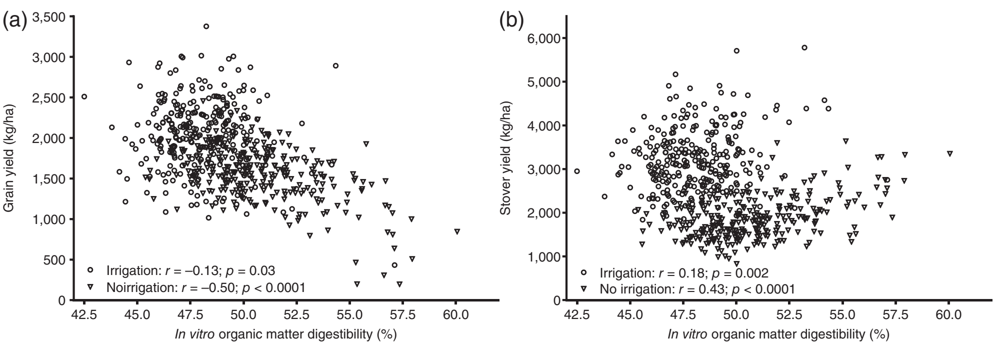

Fig. 14.9. (a) Relationship between haulm digestibility and grain yield in 280 chickpea cultivars and (b) Relationship between haulm digestibility and haulm yield in 280 chickpea cultivars. (Data from Blümmel *et al*., 2012b).

Evidence comes from the water production function for groundnut components. Water stress had a substantial negative effect on biomass yield in groundnut, while fodder quality traits such as N and IVOMD were much less affected (Table 14.5).

Outcomes and Aspects of Impacts of Multidimensional Crop Improvement

Outcomes are commonly defined by behavioural changes and changes in mindsets by secondary beneficiaries. The work presented in this chapter has contributed to such changes in both public and private crop improvement. The principal outcome of research on multi-trait crop improvement was the reconsideration of the single trait (i.e. grain) model in favour of the multi-trait and whole-plant (i.e. food and fodder) model. While there are as yet few formal decisions such as the decision of the NRCS (now IIMR) to include stover traits as new cultivar release criteria in sorghum (and now pearl millet, although under a different mandate), there are strong indications that public and private crop-improvement programmes have reoriented their efforts towards whole-plant improvement. In the design of the second phase of the CRPs, most crop commodity institutes targeted whole-plant improvement for which the expression 'full-purpose crop' established itself. Syngenta was joined by other private breeders such as Seed Co targeting dual-purpose maize in East and southern Africa, exploring branding and seed bag labelling for CR fodder traits in their hybrids.

Much of described work was conducted within the framework of CGIAR and its national partners. While drafting proposals for the second phase of the CRPs (2017–2022), several of the former crop commodity programmes, such as the CRPs on Grain Legumes and Dryland Cereals and on Maize, specifically devoted flagships to work simultaneously for grain and CR improvement, suggesting further mainstreaming of a paradigm shift in crop-improvement efforts. The CGIAR nomenclature chosen for food and fodder improved cultivars was 'full-purpose crops'. These CRPs have considerable reach as they work in global consortia comprising a wide range of national and international public and private research organizations, development practitioners and private-sector companies.

A milestone is reached when cultivar release agencies start to amend release criteria that include CR fodder traits, as has happened with the AICRPs on Sorghum and recently on Pearl Millet. Co-option and buy-in of the private sector will also be crucial. It is encouraging to see the increasing interest of the seed sector in exploring marketing of CR fodder traits. The discovery, proof-of-concept, pilot and, to a lesser degree, scale phases described above have helped to build a community of practice of experts and practitioners from animal nutrition, crop improvement, socio-economics and private-sector seed, feed and dairy companies, and from non-governmental organizations and NARES. This community of practice is the core around which further multi-trait crop-improvement efforts need to take place. CGIAR crop institutes have well-established relationships and collaborations with NARES mandated to work on specific crops.

Table 14.5. Means of grain yields, CR yields, and CR N content and *in vitro* digestibility in groundnut and sorghum cultivars grown under water and control condition at Patancheru, India, in 2009 and 2010. (Data from Blümmel *et al.*, 2012b, 2015a.)

Characteristic	Water management	Groundnut	Sorghum
Grain yield (kg/ha)	Stress	988	2542
	Control	1753	3526
CR yield (kg/ha)	Stress	2916	2970
	Control	3840	3788
CR nitrogen (%)	Stress	2.41	0.71
	Control	2.23	0.72
CR digestibility (%)	Stress	60.9	47.3
	Control	61.6	47.5

Economic impact of multidimensional crop improvement

Describing the adoption of new cultivars is a key variable for estimating the impacts of crop improvement. Assessing levels of adoption of new cultivars is usually done indirectly through the monitoring of seed production and sales and crop-specific seed rates to estimate the areas planted under new cultivars (Teufel *et al*., 2011). An example of the problem of measuring and evaluating adoption is that of an early-maturing, high-yielding and drought-tolerant dual-purpose groundnut variety (ICGV 91114) introduced in the Anantapur district of semi-arid India. ICGV 91114 produced 15% higher pod yields, 17% more haulm and 11% better-quality fodder than the locally grown variety in on-farm trials in three villages in the Anantapur district of India. Farmers who fed their dairy cows and buffaloes the improved fodder saw daily milk production increase by about 10% per animal (Pande *et al*., 2006, p. 23).

An impact study of 376 farmers estimated that adopters of ICGV 91114 earned 34% additional net revenue compared with traditional varieties, including a 29% gain in haulm value, while incurring unit costs that were 6% lower (Birthal *et al*., 2011, p. 22). A non-governmental organization, the Rural Development Trust/Accion Fraterna, promoting the new cultivar estimated, based on seed production and sales, that by 2005 about 10,000–12,000 ha had been planted with ICGV 91114. However, when Teufel *et al*. (2011) tried to trace this adoption using randomly selected villages in the district, they reported only a 'handful' of adopters and concluded that the previous estimates of adoption were dramatic overestimates. ICRISAT staff have since maintained that: (i) ICGV 91114 is the third most popular cultivar in what is called 'Breeder Seed Indented', providing about 13% of all the groundnut seeds produced in this nationwide scheme in India; (ii) groundnut breeders estimated a lower figure of 4% of area coverage; and (iii) 4% of area coverage equals about 185,000 ha under ICGV 91114 (P. Janila, Hyderabad, personal communication, 2016). While the estimates based on seed production and area planted are in considerable disagreement, they are strongly suggestive of more than a 'handful' of adopters. Making direct assessments of areas under new cultivars has obvious logistical challenges; the approaches currently being explored are around genotypic fingerprinting of new cultivars (Kosmowski *et al*., 2016).

The new cultivars benefit farms, fodder markets and livestock production. A general conclusion of our India work on dual-purpose crops is that adoption is faster and broader where the private sector is engaged. This conclusion usually applies to hybrids rather than to OPVs, where seed multiplication is public. Work on multi-trait crop improvement with OPVs identified promising new cultivars to scale (e.g. to more than 100,000 ha) or at least to pilot (more than 1000 ha), but this work was frustrated by a dearth of seed (for one recent trial, just 100 g of seed of a dual-purpose legume was provided). The reason for this lack of seeds in new public-sector OPVs might be related to misplaced incentives in public-sector crop improvement, where the release and registration of new cultivars is recognized rather than their adoption. Often, it would have been necessary, even before piloting, to multiply seed for several years – a challenging proposition. In contrast, where private-sector hybrids are concerned, as they are in maize, seed availability has rarely been a constraint.

The Future

The traditional large-scale seed sector can bring hybrid crop cultivars to scale and collaborate in their 'branding' and seed labelling processes. Small- and medium-sized seed enterprises can move new cultivars from proof-of-concept stage to pilot stage by multiplying basic/foundation seeds of OPVs/niche crops, often obtained from NARES. Once a threshold in supply of OPV seeds is passed, farmer-to-farmer seed exchange becomes significant. Small- and medium-sized feed enterprises can provide decentralized feed processing and value addition to improved CRs, can provide income and employment opportunities to disadvantaged rural people, and can act as a 'pull factor' for the adoption of new cultivars. Large dairy enterprises using smallholder milk suppliers can serve as mediators and conveyors of new cultivars, feed intervention packages and customers for existing small- and medium-sized enterprises, and as stimulators of new ones.

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References

Alkhtib, A.S., Wamatu, J.A., Wegi, T. and Rischkowsky, B.A. (2016) Variation in the straw traits of morphological fractions of faba bean (*Vicia faba* L.) and implications for selecting for food-feed varieties. *Animal Feed Science and Technology* 222, 122–131.

Alkhtib, A.S., Wamatu, J., Ejeta, T.T. and Rischkowsky, B. (2017) Integrating straw yield and quality into multi-dimensional improvement of lentil (*Lens culinaris*). *Journal of the Science of Food and Agriculture* 97, 4135–4141.

Anandan, S., Khan, A.A., Ravi, D., Jeethander, R. and Blümmel, M. (2010) A comparison of sorghum stover based complete feed blocks with a conventional feeding practice in a peri urban dairy. *Animal Nutrition and Feed Technology* 10, 23–28.

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.

Ayantunde, A.A., Blummel, M., Grings, E. and Duncan, A.J. (2014) Price and quality of livestock feeds in suburban markets of West Africa's Sahel: case study from Bamako, Mali. *Revue d'Elévage et de Médecine Vétérinaire des Pays Tropicaux* 67, 13–21.

Baudron, F., Jaleta, M., Okitoi, O. and Tegegne, A. (2014) Conservation agriculture in African mixed crop–livestock systems: expanding the niche. *Agriculture, Ecosystems and Environment* 187, 171–182.

Beckmann, E. (1921) Conversion of grain straw and lupins into feeds of high nutrient value. *Festschrift der Kaiser Wilhelm-Gesellschaft zur Förderung der Wissenschaften* 16, 18–26.

Berhanu, G., Adane, H. and Kahsay, B. (2009) *Feed marketing in Ethiopia: results of a rapid market appraisal. IPMS Working Paper 15*. ILRI, Addis Ababa.

Bidinger, F.R. and Blümmel, M. (2007) Effects of ruminant nutritional quality of pearl millet [*Pennisetum glaucum* (L.) R. Br.] stover: I. Effects of management alternatives on stover quality and productivity. *Fields Crops Research* 103, 129–138.

Bidinger, F.R., Blümmel, M., Hash, C.T. and Choudhary, S. (2010) Genetic enhancement for superior food-feed traits in a pearl millet *(Pennisetum glaucum* (L.) R. Br.) variety by recurrent selection. *Animal Nutrition and Feed Technology* 10, 61–68.

Birthal, P.S., Nigam, S.N., Narayanan, A.V. and Kareem, K. (2011) An economic assessment of the potential benefits of breeding for drought tolerance in crops: a case of groundnut in India. Research Bulletin No. 25. ICRISAT, Andhra Pradesh, India.

Blümmel, M. and Rao, P.P. (2006) Economic value of sorghum stover traded as fodder for urban and peri-urban dairy production in Hyderabad. *India International Sorghum and Millet Newsletter* 47, 97–100.

Blümmel, M., Bidinger, F.R. and Hash, C.T. (2007a) Management and cultivar effect on ruminant nutritional quality of pearl millet [*Pennisetum glaucum* (L.) R. Br.] stover. Effects of cultivar choice on stover quality and productivity. *Fields Crops Research* 103, 119–128.

Blümmel, M., Virk, P. and Xianglin, L. (2007b) Opportunities for improving the fodder value of rice straw by multidimensional crop improvement. In: Wright, I.A (ed.) *Proceedings of the International Symposium on Production and Utilization of Paddy Rice as Feed*, 9–12 October, Japan, China, Korea. pp. 17–21.

Blümmel, M., Vishala, A., Ravi, D., Prasad, K.V.S.V., Ramakrishna Reddy, C. and Seetharama, N. (2010) Multi-environment investigations of food–feed trait relationships in Kharif and Rabi sorghum [*Sorghum bicolor* (L.) Moench] over several years of cultivars testing in India. *Animal Nutrition and Feed Technology* 10, 11–21.

Blümmel, M., Joshi, A.K., Teufel, N. and Wright, I.A. (2012a) Looking beyond grain for overall benefit from wheat in mixed crop livestock systems. Presented at the Wheat for Food Security in Africa Conference, 8–12 October, Addis Ababa. ILRI, Nairobi.

Blümmel, M., Ratnakumar, P. and Vadez, V. (2012b) Opportunities for exploiting variations in haulm fodder traits of intermittent drought tolerant lines in a reference collection of groundnut (*Arachis hypogaea* L.). *Field Crops Research* 126, 200–206.

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., Homann-Kee, T., Valbuana, S., Diego, V., Duncan, A.J. and Herrero, M. (2013b) Biomass in crop–livestock systems in the context of the livestock revolution. *Sécheresse* 24, 330–339.

Blümmel, M., Haileslassie, A., Samireddypalle, A., Vadez, V. and Notenbaert, A. (2014a) Livestock water productivity: feed resourcing, feeding and coupled feed–water resource databases. *Animal Production Science* 54, 1584–1593.

Blümmel, M., Zaidi, P., Vinayan, M., Babu, R. and Yadav, O. (2014b) The fodder value of maize stover vis-à-vis other cereals residues and opportunities for improvement through crop breeding and value addition. In: *12th Asian Maize Conference and Expert Consultation on Maize for Food, Feed, Nutrition and Environmental Security*, 30 October–1 November, Bangkok, Thailand. CIMMYT, Mexico, and APAARI, Bangkok, pp. 82–90.

Blümmel, M., Deshpande, S., Kholova, J. and Vadez, V. (2015a) Introgression of staygreen QTLs for concomitant improvement of food and fodder traits in *Sorghum bicolor*. *Field Crops Research* 180, 228–237.

Blümmel, M., Haileslassie, A., Herrero, M., Beveridge, M., Phillips, M. and Havlik, P. (2015b) Feed resources vis-a-vis livestock and fish productivity in a changing climate. In: Malik, P.K., Bhatta, R. Takahashi, J., Kohn, R. and Prasad, C.S. (eds) *Livestock Production and Climate Change*. CAB International, Wallingford, UK, pp. 8–24.

Blümmel, M., Muller, A., Schader, C., Herrero, M. and Garg, M.R. (2017) The use and abuse of cereals, legumes and crop residues in rations for dairy cattle. In: Webster, J. (ed.) *Achieving Sustainable Production of Milk*, Vol. 3: *Dairy Herd Management and Welfare*. Burleigh Dodds Science Publishing, Cambridge.

Capper, B.S., Thomson, E.F. and Herbert, F. (1988) Genetic variations in the feeding value of barley and wheat straw. In: Reed, J.D., Capper, B.S. and Neate, P.J.H. (eds) *Plant Breeding and the Nutritive Value of Crop Residues. Proceedings of a Workshop, 7–10 December* 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa, pp. 177–193.

Choudhary, S., Hash, C.T., Sagar Prem, Prasad, K.V.S.V. and Blümmel, M. (2010) Near infrared spectroscopy estimation of pearl millet grain composition and feed quality. Proceedings of the 14th International Conference on NIR Spectroscopy. Bangkok, Thailand.

Choudhary, S., Bidinger, F.R., Hash, C.T., Vadez, V. and Blummel, M. (2012) Gene action governing pearl millet stover nitrogen and *in vitro* digestibility and opportunities for improvement. *European Journal of Plant Science and Biotechnology* 6, 129–131.

Dai, J., Bean, B., Brown, B., Bruening, W., Edwards, J., *et al.* (2016) Harvest index and straw yield of five classes of wheat. *Biomass and Bioenergy* 85, 223–227.

de Groote, H., Dema, G., Sonda, G. and Gitonga, Z. (2013) Maize for food and feed in East Africa – the farmer perspective. *Field Crops Research* 153, 22–36.

Duncan, A.J., Bachewe, F., Mekonnen, K., Valbuena, D., Rachier, G., *et al.* (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.

Ertiro, B.T., Zeleke, H., Friesen, D., Blümmel, M. and Twumasi-Afiyie, S. (2013) Relationships 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.

Etela, I. and Dung, D.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.

Fingerling, G. and Schmidt, K. (1919) Die Strohaufschliessung nach dem Beckmannschen Verfahren. 2. Einfluss der Aufschliessungszeit auf den Umfang der Nährwerterschliessung. *Landw. Versuchsst. Sonderdruck*, 115–152.

Hay, R.K.M. (1995) Harvest index: a review of its use in plant breeding and crop physiology. *Annals of Applied Biology* 126, 197–216.

Jackson, M.G. (1977) The alkali treatment of straws. *Animal Feed Science and Technology* 2, 105–130.

Jarial, S., Blümmel, M., Soumana, I., Prasad, K.V.S.V., Issa, S., Ravi, D.K. (2016a) Price-Quality Relationships in Fodder Trading in Niger with Special Regards to Comparisons of Cowpea and Groundnut Haulms with Concentrates and Collected Shrubs and Grasses. In: *Pan-African Grain and World Cowpea Conference*, 28 February–4 March, Livingstone, Zambia. ICRISAT, Niamey.

Jarial, S., Blümmel, M., Soumana, I., Ravi, D.K., Issa, S., Whitbread, A. and Tabo, R. (2016b) Comparison of Cowpea and Groundnut Haulm Trading in Urban and Rural Fodder Markets in Niger. In: *Pan-African Grain and World Cowpea Conference*, 28 February–4 March, Livingstone, Zambia. ICRISAT, Niamey.

Kelley, T.G., Rao, P.P. and Walker, T.S. (1993) The relative value of cereal straw fodder in India: implications for cereal breeding programs at ICRISAT. In: Dvorak, K.A. (ed.) *Social Science Research for Agricultural Technology Development.* CAB International, Wallingford, UK.

Kelley, T.G., Rao, R.P., Weltzien, R.E. and Purohit, M.L. (1996) Adoption of improved cultivars of pearl millet in arid environment: straw yield and quality considerations in western Rajasthan. *Experimental Agriculture* 32, 161–172.

Khush, G.S., Bienvenido, B.O. and Roxas, D.B. (1988) Genetic selection for improved nutritional quality of rice straw – a plant breeder's viewpoint. In: Reed, J.D., Capper, B.S. and Neate, P.J.H. (eds) *Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa, pp. 261–282.

Kosmowski, F., Aragaw, A., Kilian, A., Ambel, A., Ilukor, J., *et al.* (2016) Varietal identification in household surveys: results from an experiment using DNA fingerprinting of sweet potato leaves in Southern Ethiopia. Policy Research Working Paper No. WPS 7812. World Bank Group, Washington, DC.

Kossila, V. (1988) The availability of crop residues in developing countries in relation to livestock populations. ILCA, Addis Ababa.

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. No. 3. ILRI, Nairobi.

Lal, R. (2005) World crop residues production and implications of its use as a biofuel. *Environment International* 31, 575–584.

Mayberry, D., Ash, A., Prestwidge, D., Godde, C.M., Henderson, B., *et al.* (2017) Yield gap analyses to estimate attainable bovine milk yields and evaluate options to increase production in Ethiopia and India. *Agricultural Systems* 155, 43–51.

McDowell, R. (1988) Truth conditions, bivalence, and vericationism. In: *Meaning, Knowledge, and Reality*. Harvard University Press, Cambridge, Massachusetts, pp. 3–28.

McIntire, J., Reed, J.D., Jutzi, S.C., Tedla, A. and Kebede, Y. (1988) Evaluating sorghum cultivars for grain and straw yield. In: Reed, J.D., Capper, B.S. and Neate, P.J.H. (eds) *Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa, pp. 283–300.

Mueller-Harvey, I., McAllan, A.B., Theodorou, M.K. and Beever, D.E. (1988) Phenolics in fibrous crop residues and plants and their effect on the digestion and utilisation of carbohydrates and proteins in ruminants. In: Reed, J.D., Capper, B.S. and Neate, P.J.H. (eds) *Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa, pp. 97–132.

Nepolean, T., Blümmel, M. and Hash, C.T. (2009) Improving straw quality traits through QTL mapping and marker-assisted selection in pearl millet. In: *Forage Symposium 2009: Imaging Trends in Forage Research and Livestock Production*, 16–17 February, CAZRI RRS, Jaisalmer, Rajasthan, India, p. 12.

Nigam, S.N. and Blümmel, M. (2010) Cultivar-dependent variation in food-feed-traits in groundnut (*Arachis hypogaea* L.) (2010) *Animal Nutrition and Feed Technology* 10, 39–48.

Nordblom, T.L. (1988) The importance of crop residues as feed resources in West Asia and North Africa. In: Reed, J.D., Capper, B.S. and Neate, P.J.H. (eds) *Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa, pp. 41–64.

Ørskov, E.R. (1988) Consistency of differences in nutritive value of straw from different varieties in different seasons. In: Reed, J.D., Capper, B.S. and Neate, P.J.H. (eds) *Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa, pp. 163–176.

Owen, E. and Aboud, A.A.O. (1988) Practical problems of feeding crop residues. In: Reed, J.D., Capper, B.S. and Neate, P.J.H. (eds*) Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa, pp. 133–156.

Owen, E. and Jayasuriya, M.C.N. (1989) Use of crop residues as animal feeds in developing countries. *Research and Development in Agriculture* 6, 129–138.

Pande, S., Sreenivas, B., Rao, P., Rao, J. and Reddy, P. (2006) *Farmers' Participatory Management of Diseases for Higher Yield and Nutritive Value of Crop Residues of Groundnut, Deccan Plateau, India.*

Proceedings of a Workshop, 3–4 January 2005, ARS, ANGRAU, Rekulakunta, Anantapur, Andhra Pradesh. ICRISAT, Andhra Pradesh, India.

Pearce, G., Lee, J., Simpson, R. and Doyle, P. (1988) Sources of variation in the nutritive value of wheat and rice straws. In: Reed, J.D., Capper, B.S. and Neate, P.J.H. (eds) *Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa, pp.195–231.

Prasad, K.V.S.V., Khan, A.A., Vellaikumar, S., Devulapalli, R., Ramakrishna, R.C., *et al.* (2010) Observations on livestock productivity in sheep fed exclusively on haulms from ten different genotypes of groundnut. *Animal Nutrition and Feed Technology* 10, 121–126.

Prasad, K.V.S.V., Rashid, M.M., Sharda, P., Ravi, D., Ramana Reddy, Y., *et al.* (2015) Handheld mobile near infrared spectroscopy – a rapid tool for quality evaluation of feeds. Abstract of a presentation at the 9th Biennial Conference of the Animal Nutrition Association, 22–24 January, Guwahati, India.

Ramakrishna, R.C., Khan, A.A., Prasad, K.S.V.S., Ravi, D., Reddy, B.S.V., *et al.* (2010) Stover quality traits for improvement of dual-purpose sorghum. *Animal Nutrition and Feed Technology* 10, 113–119.

Ravi, D., Anandan, S., Khan, A.A., Bidinger, F.R., Nepolean, T., *et al.* (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* 10, 49–59.

Ravi, D., Khan, A.A., Rao, M.S. and Blümmel, M. (2013) A note on suitable laboratory stover quality traits for multidimensional maize improvement. *Fields Crops Research* 153, 58–62.

Reed, J.D., Capper, B. and Neate, P.J.H. (eds) (1988a) *Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa.

Reed, J.D., Kebede, Y. and Fussell, L.K. (1988b) Factors affecting the nutritive value of sorghum and millet crop residues. In: Reed, J.D., Capper, B.S. and Neate, P.J.H. (eds) *Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa, pp. 233–251.

Reed, J.D., Soller, H. and Woodward, A. (1990) Fodder tree and straw diets for sheep: intake, growth, digestibility and the effects of phenolics on nitrogen utilisation. *Animal Feed Science and Technology* 30, 42371–42371.

Samireddypalle, A., Boukar, O., Grings, E., Fatokun, C., Prasad, K.V.S.V., *et al.* (2017) Cowpea and groundnut haulms fodder trading and its lessons for multi-trait cowpea improvement for mixed crop livestock systems in West Africa. *Frontiers of Plant Science* 8, 30.

Sanchez, O.J. and Cardona, C.A. (2008) Trends in biotechnological production of fuel ethanol from different feedstocks. *Bioresource Technology* 99, 5270–5295.

Shah, L. (2007) Delivering nutrition. Power Point Presentation delivered at the CIGAR System Wide Livestock Program Meeting, 17 September, ICRISAT, Patancheru.

Sharma, K., Pattanaik, A.K., Anadan, S. and Blümmel, M. (2010) Food–feed crop research: a synthesis. *Animal Nutrition and Feed Technology* 10, 1–10.

Singh, O.P., Sharma, A., Singh, R. and Shah, T. (2004) Virtual water trade in dairy economy. *Economic and Political Weekly* 39, 3492–3497.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. and de Haan, C. (2006) *Livestock's Long Shadow: Environmental Issues and Options*. FAO, Rome.

Swanepoel, F., Stroebel, A. and Moyo, S. (2010) *The Role of Livestock in Developing Communities: Enhancing Multifunctionality*. University of the Free State and CTA, Cape Town.

Teufel, N., Samaddar, A., Blümmel, M. and Erenstein, O. (2010) Quality characteristics of wheat and rice straw traded in Indian urban centres. Presentation at Tropentag 2010, World Food System – A Contribution from Europe, 14–16 September, Zurich.

Teufel, N., Johnson, N. and Singh, D.K. (2011) The adoption and impact of an improved drought-tolerant, dual-purpose groundnut variety in Southern India. Paper presented at the 7th ASAE International Conference 'Meeting the Challenges Facing Asian Agriculture and Agricultural Economics Toward a Sustainable Future', 13–15 October, Hanoi, Vietnam. ILRI, Nairobi.

Thornton, P.K., Kristjanson, P.M. and Thorne, P.J. (2003) Measuring the potential impacts of improved food–feed crops: methods for *ex ante* assessment. *Field Crops Research* 84, 199–212.

Traxler, G. and Byerlee, D. (1993) A joint-product analysis of the adoption of modern cereal varieties in developing countries. *American Journal of Agricultural Economics* 75, 981–989.

Valbuena, D., Tui, S.H.-K., Erenstein, O., Teufel, N., Duncan, A., *et al.* (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.

van Soest, P.J. (1988) Effect of environment and quality of fibre on the nutritive value of crop residues. In: Reed, J.D., Capper, B.S. and Neate, P.J.H. (eds) *Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, ILCA, Addis Ababa, Ethiopia. ILCA, Addis Ababa, pp. 71–96.
van Soest, P.J. (1994) *The Nutritional Ecology of the Ruminant*, 2nd edn. Cornell University Press, New York.
Venkatesh, B.B., Umkanth, A.V., Madhusudhana, R., Vishala, A.D., Ravi, D., et al. (2006) Genetic enhancement of sorghum stover quality: collaborative research between NRCS and ILRI. *Jowar Samacha* 2, 6–8.
Vinayan, M.T., Raman, B., Jyothsna, T., Zaidi, P.H. and Blümmel, M. (2013) A note on potential candidate genomic regions with implications for maize stover fodder quality. *Fields Crops Research*, 153, 102–106.
Wegi, T. (2016) Effects of feeding different varieties of faba bean (Vicia faba L.) straws with concentrate on feed intake, digestibility, body weight gain and carcass characteristics of Arsi-Bale sheep. MSc thesis, Haramaya University, Dire Dawa, Ethiopia.
Zaidi, P.H., Vinayan, M.T. 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, 79–85.