Co-benefits of mitigation options in the CCAFS-Mitigation Options Tool (CCAFS-MOT)

Working Paper No. 229

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

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Abstract

Approximately 30% of total global greenhouse gas (GHG) emissions are from the agriculture, forestry, and other land use (AFOLU) sectors. There is increasing interest in identifying sources and sinks of GHG emissions due to the rising negative impacts of climate change. This has resulted in the creation of GHG accounting tools that allows the quantification and reporting of GHG emissions. One such tool is the CGIAR Research Program for Climate Change, Agriculture and Food Security Mitigation Options Tool (CCAFS-MOT), which calculates emissions from a variety of crops, rice, grassland and livestock. This tool is distinct in that it provides a range of mitigation options that are ranked in order of mitigation potential. This paper investigates benefits associated with the mitigation options presented in the CCAFS-MOT other than emission reduction. Co-benefits include increased yield from crops and livestock, improved soil quality and fertility, and reduced production costs, all of which can help improve food security and alleviate poverty.

Keywords

Climate change mitigation; Agriculture; Greenhouse gases.

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Contents

Acronyms

AMF	Arbuscular mycorrhizal fungi
AWD	Alternate wetting and drying
BMP	Biochemical methane potential
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CP	Crude protein
CR	Controlled release
CROP	Cost Reducing Operating Principles
CT	Condensed tannins
DM	Dry matter
DMI	Dry matter intake
DMPP	3,4-Dimethylpyrazole phosphate
DS	Drum seeder
EONR	Economically optimal nitrogen rates
FP	Farmers practice
GHG	Greenhouse gas
GHGI	Greenhouse gas intensity
$g\ kg^{-1}$	Grams per kilogram
$gTS\ L^{-1}$	Grams of total solids per litre
ha	Hectare
H_2S	Hydrogen sulphide

kg ha^{-1}	Kilograms per hectare
kgN	Kilograms of nitrogen
kgN ha^{-1} yr^{-1}	Kilograms of nitrogen per hectare per year
kgP ha^{-1} yr^{-1}	Kilograms of phosphorous per hectare per year
kWh	Kilowatt hours
kWh tTS^{-1}	Kilowatt hours per tonne of total solids
LEV	Land expectation value
L ha^{-1}	Litres per hectare
Mg ha^{-1}	Megagrams per hectare
Mg ha^{-1} yr^{-1}	Megagrams per hectare per year
Mg kg^{-1}	Milligrams per kilogram
MJ	Megajoule
MUN	Milk urea nitrogen
NaOH	Sodium hydroxide
NCP	North China Plain
NDF	Neutral detergent fibre
NEB	Net economic benefit
NI	Nitrification inhibitors
N ha^{-1}	Nitrogen per hectare
NH_3	Ammonia
NO	Nitric oxide
N_2O	Nitrous oxide
NUE	Nitrogen use efficiency

PBC	Plant bioactive compounds
PPC	Purple prairie clover
RB	Rice-fava bean
RF	Rice-fallow
RSN	Residual soil nitrate
RT	Reduced tillage
RW	Rice-wheat
SOC	Soil organic carbon
SOM	Soil organic matter
TC	Tea catechin
TCH	Tonnes of cane per hectare
$t\ ha^{-1}$	Tonnes per hectare
$TgN\ yr^{-1}$	Teragrams of nitrogen per year
$\mu mol\ m^{-2}\ s^{-1}$	Micromoles per metres squared per second
XND	Xiang Nong Da

I. Introduction

The Intergovernmental Panel on Climate Change (IPCC) identified that the agricultural sector as one of the main sources of anthropogenic greenhouse gas (GHG) emissions. The agriculture, forestry, and other land use (AFOLU) sectors are responsible for around 30% of total GHG emissions worldwide (Colomb et al. 2013). Increasing emissions from AFOLU are fuelled by a number of trends, including growing global population, changing dietary habits and preferences, and agricultural production activities. For example, there has been a drastic increase in the global application of N fertiliser over the past few decades; by 2050 application rates are expected to reach approximately 165 TgN yr^{-1} (Galloway et al. 2004). The adverse effects of climate change have resulted in increased awareness of the importance in identifying sources and sinks of GHG emissions and the necessity for accurate GHG reporting (Whittaker et al. 2013). To meet this requirement, a number of GHG accounting tools have been developed that allow users to quantify GHG emissions associated with agricultural production (Peter et al. 2017).

The CGIAR Research Program on Climate Change, Agriculture and Food Security - Mitigation Options Tool (CCAFS-MOT)[1] is a free, excel-based tool that calculates GHG emissions from crops, rice, grassland, and livestock from around the world by combining several empirical models. The CCAFS-MOT requires minimal input data, and results can be obtained within approximately five minutes (Feliciano et al. 2017). The tool provides a variety of mitigation options that are ranked in order of mitigation potential; this allows users to identify agricultural management practices that can reduce emissions while sequestering carbon.

This paper investigates the co-benefits associated with the mitigation options presented in the CCAFS-MOT. Information regarding the co-benefits was obtained by means of a literature search of Science Direct using the title of the mitigation option alongside the key words ‘benefits’, ‘economic analysis’, and ‘cost analysis’.

[1] https://ccafs.cgiar.org/mitigation-option-tool-agriculture#.WiAw7VVl9hE

The objective of this paper is to identify the benefits associated with improved management practices that are a secondary function of emission reduction, such as an increase in yield, improved soil fertility, greater manure quality, improved livestock efficiency, and reduced costs. Awareness of co-benefits may promote the uptake of mitigation measures in agriculture, improve food security, and/or increase the incomes of farmers in developing countries, which in turn would help alleviate poverty.

The first section discusses co-benefits related to mitigation practices for crops, rice, and grassland; the benefits are mainly improved yield, soil security, water security, and economic benefits. The second section discusses co-benefits of three types of livestock mitigation options: manure management, biogas, and diet management. The benefits of manure management and biogas are centred around manure handling, manure quality, and cost reduction; while the benefits of diet management are mostly related to improved diet, improved efficiency, and improved yield.

II. Co-benefits of mitigation options in crops, grassland and rice

2.1 Reduced and zero tillage

Reduced carbon dioxide emissions

In the first hours following tillage, carbon dioxide (CO_2) is released due to increased mineralisation and decomposition of organic matter due to increased microbial activity from increased oxygen availability. However, the mitigation option of reduced/no till increases CO_2 accumulation in the soil (Buragiene et al. 2015). Buragiene et al. (2015) studied the effect of five tillage methods on CO_2 emissions in Lithuania; the results show that over 3 years, with trials in autumn and spring, the average emissions were highest for deep ploughing (2.18 μmol m^{-2} s^{-1}) followed by shallow ploughing (1.95 μmol m^{-2} s^{-1}), deep cultivation (1.96 μmol m^{-2} s^{-1}), shallow cultivation (1.89 μmol m^{-2} s^{-1}) and no till (1.59 μmol m^{-2} s^{-1}). This shows a link between the depth of cultivation and CO_2 emissions. Additionally, deeper cultivations required more energy and diesel fuel, causing more CO_2 emissions. No till emitted 107 kg ha^{-1} CO_2, while other methods emitted 2-2.5 times more (Buragiene et al., 2015). These results are supported by Safa and Tabatabaeefer (2008), who found fuel consumption by machinery planting wheat to be 75-121 L ha^{-1} using conventional tillage but 14.2-20.7 L ha^{-1} for direct drilling. These findings are further supported by Šarauskis et al. (2014), who found deeper cultivations to require more time and fuel and produce more CO_2 emissions from machinery when cultivating maize in Lithuania. Interestingly, the same study found that over three years the highest average dry mass yields were under deep ploughing (15.2 Mg ha^{-1}) and no till (15.4 Mg ha^{-1}) while the lowest were under deep cultivation (14.0 Mg ha^{-1}).

Results described above may change over time, as some studies have shown no till yields to decline over time as soil compaction increases, while other studies have found yields improve as soil fauna, fungi and bacteria populations increase. The soil at the study site was a sandy loam, less prone to compaction and more suited to no till.

When yield is examined against fuel expenditure, no till has the highest efficiency index, while deep cultivation has the lowest.

Improved yield

The results from a 12-year study by Zhang et al. (2015) showed that the average maize yields in northeast China were improved under reduced (10.71 t ha^{-1}) and zero tillage (10.67 t ha^{-1}), as compared to conventional tillage (10.21 t ha^{-1}). These results contradict the findings of other studies in northeast China, such as a 7-year study by Chen et al. (2011a), where maize yields significantly decreased under reduced tillage. The inconsistency in the findings can be attributed to the difference in the study period duration. Periods longer than 10 years allow soil bacteria and fungi populations to recover and earthworms to distribute organic matter in the top soil. Also, yields from conventional tillage were found to be higher in cool-humid climates with poorly drained soil, whereas in well-drained soil in warmer, drier climates yields from conservation tillage were found to be higher. In cool-humid climates, this impedes the adoption of conservation tillage because farmers' main concern tends to be yield (Zhang et al. 2015). Although there was no significant difference in yield stability among the three treatments, it was found that no tillage yielded higher in years of adverse weather where other treatments yielded poorly. Thus, no tillage could be useful in marginal areas to offset the impact of adverse weather conditions (Zhang et al. 2015).

It should be noted that findings regarding yield may change over time. Use of no tillage reduces oxygen content of subsurface soil layers due to smaller pore sizes, compaction from machinery and higher biological activity on the soil surface. Over time it is possible that this can reduce suitability of the soil for plant growth (Buragiene et al., 2015).

Soil security

Soil biodiversity - Agricultural soils have been found to be depleted of mycorrhiza species compared to forest soils, which has been attributed to regular soil disturbance and application of pesticides and fertiliser (Hijri et al., 2006). Reduced tillage minimises soil disturbance and reduces the damage to soil microorganisms. Oehl et al. (2003, 2004) found an inverse relationship between management intensity and populations of arbuscular mycorrhizal fungi (AMF), with the highest populations being in semi natural grassland, followed by organically managed land. Furthermore, Oehl et al. (2003, 2004) found some AMF species below the plough line, suggesting that tillage and application of agrochemicals negatively affects AMF populations. Brito et al. (2012) confirms this result, finding AMF species diversity to be higher under no tillage compared to conventional tillage systems. Additionally, the abundance of certain species changed under different tillage treatments, which shows that some species are more tolerant to soil disturbance than others. Schnoor et al. (2011) showed that species that reproduce using spores and species that proliferate after ploughing, are more resilient to ploughing when compared to species that use mycelia. These authors found *G. mosseae* and *G.caledonium* to be more abundant in agricultural soils that are disturbed regularly, as these species sporulate regularly. Conversely, Schnoor et al. (2011) also found diversity to be greater in semi-natural grassland, where a greater proportion sporulate rarely and grow extensive mycelia. Species diversity improves the resilience of the soil to biotic and abiotic stress and improves plant nutrient uptake, as the hardiest AMF species are not those with the greatest nutrient acquisition.

Soil erosion - Conventional tillage is being decreased in favour of reduced tillage/no tillage in areas where climate and soil result in erosion from conventional ploughing (Buragiene et al. 2015).

Soil moisture - Intensive tillage reduces soil organic matter (SOM) levels and thus the water-holding capacity of the soil. Conversely, no tillage can cause compaction, which reduces water infiltration to lower layers. Liu et al. (2010) found conventional tillage practices along with removal of crop residue reduced SOM content, causing reduced water retention, as well as affecting soil structure and increasing wind/water erosion. Higher soil moisture levels before sowing were found by Zhang et al. (2015) in no tillage (27.6%) and reduced tillage systems (24.6%) compared to conventional tillage (21.2%) at the 12 leaf growth stage soil moisture was still higher under no tillage (20.9%) compared to 18.9% and 17.8% for reduced and conventional tillage respectively. It was suggested no tillage practices increased soil moisture, which subsequently contributed to higher maize yields by increasing plant height later in the growing season, contributing an average of 468 kg ha^{-1} to yield. Lower soil temperatures during sowing and lower emergence rates found in no tillage and reduced tillage systems did not affect yield, particularly if drilling date was delayed (Zhang et al., 2015).

Nutrient cycling - Zhang et al. (2015) attributed higher maize yields under no tillage and reduced tillage to increased soil organic carbon (SOC) and higher C:N ratios which increases N immobilisation and nutrient retention. Similar results were found by Wei et al. (2014) when examining soil phosphorus levels under different tillage practices.

Economic benefits

Several authors compared the costs of no-tillage/reduced tillage and conventional tillage. Dhuyvetter et al. (1996) reviewed economic analyses of dryland cropping systems in the Great Plains to compare production costs and net returns, among other indicators, and discovered that cropping systems using more intensive rotations with less tillage had higher production costs than a wheat-fallow rotation, but also had increased net returns.

Parch et al. (2001) compared conservation tillage seedbed preparation with conventional tillage main plots with subplots of (i) nonirrigated soybean (Glycine max L. Merr.), (ii) irrigated soybean, (iii) irrigated grain sorghum (Sorghum vulgare L.), (iv) irrigated soybean followed by irrigated grain sorghum, (v) irrigated soybean followed by irrigated corn (Zea mays L.), and (vi) continuous irrigated cotton (Gossypium hirsutum L.). Their study found out that except for cotton, conventional tillage resulted in higher average net returns than conservation tillage. Their study also confirmed the increased variable costs and decreased equipment costs that accompany conservation tillage systems.

Pesticide use and weed control are added concerns when utilising no-till. Some authors (e.g. Jonhson, 1994) found that no-till had the lowest machinery and fuel costs and labour requirements but herbicide and other variable costs increased enough to offset the machine, fuel, and labour savings of no-till, resulting in no-till being less profitable than other tillage systems.

Epplin et al. (2005) analysed the production costs for both conventional tillage and no-till for continuous monoculture wheat production in the southern Great Plains (Northwestern Oklahoma, United States). These authors concluded that even though the price reduction of glyphosate (herbicide) after the original patent expired has improved the relative economics of no-till for continuous winter wheat, for some farm sizes, the total operating plus machinery fixed costs are greater for the no-till system.

Pendell (2006) examined the economic potential (yields, input rates, field operations, prices) of no-tillage versus conventional tillage to sequester soil carbon by using two rates of commercial N fertilizer or beef cattle manure for continuous corn (*Zea mays* L.) production and found out that no-till systems had greater annual soil carbon gains, net carbon gains, and net returns than conventional tillage systems.

A more recent study undertaken by Townsend et al. (2016) found that there were financial benefits for zero tillage when compared against conventional tillage, even with a yield penalty of 0-14.2% across all crops in the zero tillage system. A yield reduction of 14.2% is required for the gross margin of the zero tillage system to equal the gross margin of the conventional tillage system. However, a yield reduction of this size would require a 24% land increase to maintain the same level of food production. Reduced tillage systems had a higher gross margin of 14-25% over conventional tillage systems, where contractors' costs of around £85 ha^{-1} were added to the cost of conventional tillage systems. Even when taking herbicides into account to combat weed problems, the gross margin is still greater for reduced tillage when the higher amount of £85 ha^{-1} is spent on herbicides for all crops. Net margins showed an even greater benefit when implementing reduced tillage practices where reduced requirements for labour, fuel and machinery resulted in a net margin that was £256 ha^{-1} greater in a zero till system than the conventional tillage system. It was concluded that farmers would be able to reduce the intensity of their tillage operations, which would increase their gross margins and net energy while reducing greenhouse gas emissions.

Ercoli et al. (2017) compared the effect that four preceding crops, that included wheat, maize, alfalfa and sunflower, had on the performance of durum wheat using a conventional tillage system (mouldboard ploughing, disking twice, and harrowing) and two reduced tillage (RT) systems; RT1 (chisel ploughing, disking twice, and harrowing) and RT2 (disking twice and harrowing). The study found the total variable cost of conventional tillage was €939 ha^{-1} taking into consideration the costs associated with field management practices, seeds, fertilisers and herbicides. The total variable costs for RT1 and RT2 were reduced by 7% and 12% respectively when compared against the conventional tillage system. Profitability was negative when wheat preceded the durum wheat for RT1 and RT2 and when alfalfa preceded RT2. While profitability decreased when maize and sunflower preceded the durum wheat, the decrease was smaller and the grain yield reduction was not significant.

Potential disadvantages

Increased energy inputs from fertiliser use - Šarauskis et al. (2014) found the greatest energy input in maize cultivation was fertiliser use, accounting for 70% of energy inputs in deep ploughing (conventional tillage) and 78% under no tillage.

2.2 Cover crops (crops, grassland rice)

Reduced carbon dioxide emissions

Carbon dioxide emissions can be managed by use of cover crops (Carbonell-Bojollo, 2011) and by spreading plant residue on soil surface (Al-Kaisi and Yin, 2005).

Cover crops reduce contact between the soil and the environment, limiting microbial activity. The timing of cultivation is important because it can impact CO_2 emissions on a daily and seasonal scale. For instance if rain follows ploughing, then CO_2 emissions will increase (Alvaro-Fuentes et al., 2007). Another study, Buragiene et al. (2015), investigated CO_2 emissions over the course of several seasons. The results showed that CO_2 emissions were higher in autumn than in spring (Fig. 1) and that CO_2 emissions in spring varied considerably between the three years when trials were conducted.

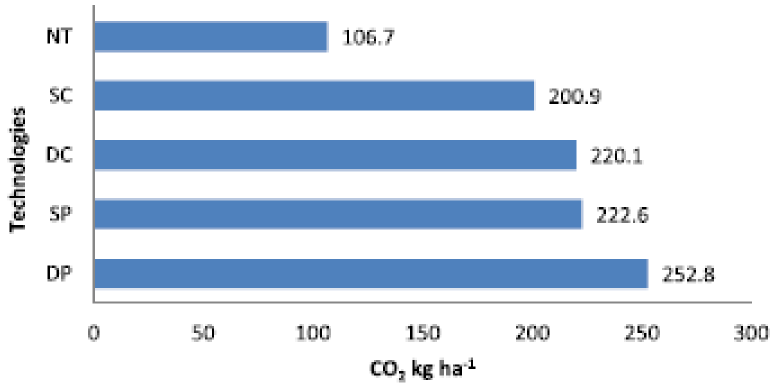

Figure 1. Soil CO2 emissions after autumn tillage in 2011 (DP — deep ploughing, SP — shallow ploughing, DC — deep cultivation, SC — shallow cultivation, and NT — no tillage).

Improved yield

Cash crop productivity - Legume cover crops have been identified as being the most reliable species of cover crop to enhance cash crop yields. The *Brassica* species cover crop produces residues that contain glucosinolate (2-6 Mg ha^{-1}) and they can also inhibit soil-borne diseases and plant-parasitic nematodes (Snapp et al., 2005). A mixed cover crop of rye and hairy vetch have been shown to increase potato yields by 16% and also reduced the amount of fertiliser used by 10% when compared to a bare winter fallow (Snapp et al., 2003).

Soil security

Soil erosion - Soil erosion by wind and water can be reduced through the planting of cover crops. Uncovered sandy soils that are irrigated are particularly susceptible to erosion during colder periods. Growing winter cereals as cover crops, such as wheat and rye, can greatly reduce soil erosion (Kinyangi et al., 2001). Studies have shown that 43% of Michigan potato (*Solanum tuberosum* L.) farmers and 25% of vegetable producers in Western New York use winter cereals to reduce soil erosion (Snapp et al., 2001).

Soil quality and yield stability - Cover crops can be planted before main crops are planted, between main crops, and between trees or shrubs of plantation crops to improve the physical, biological, and chemical properties of the soil. Cover crop utilization can improve soil health, which can subsequently increase yields (Fageria et al., 2005).

The constant use of cover crops will increase the amount of SOM present, improving the quality of the soil by increasing the water holding and nutrient supply capacity, and aeration of the soil. A direct benefit of increased SOM is an increase in yield potential (Snapp et al., 2005). Soil organic matter can be improved rapidly by combining cover crops with reduced tillage. Field studies undertaken in Georgia have shown that hairy vetch is an efficient cover crop for building SOM and providing soil coverage (Sainju et al., 2002).

Cover crops can also provide yield stability; a long-term field study undertaken in Pennsylvania determined that the yield of organic corn, which was planted with a soybean cover crop, was higher during drought years than conventionally produced field crops, which were planted without cover crops (Lotter et al., 2003).

Availability of nutrients - Soils with a higher supply of nutrients will require less fertiliser that could result in a long-term reduction in costs if yield is maintained, which can help recoup the costs of establishing the cover crops (Snapp et al., 2005). Leguminous cover crops have a high capacity for absorbing nutrients from the soil profile when availability is low. In addition, cover crops can also increase the concentration of nutrients within surface soil layers. Legume cover crops can provide primary crops with a large amount of biologically fixed N and they can decompose easily due to their low C:N ratio (Fageria et al., 2005), which can reduce the requirement for N fertilisers for subsequent crops (Singh et al., 2004). Studies have shown that cover crops can add a greater amount of nutrients to the soil prior to crop planting; for example hairy vetch as a winter cover crop supplied between 50 and 120 N ha^{-1} to ensuing tomato crops (Sainju et al., 2002; Yaffa et al., 2000).

Soil rehabilitation - Cover crops can be used to rehabilitate degraded soils. In cooler areas winter cover crops can augment summer cash crops, while in warmer areas summer cover crops can be augmented by winter cash crops (Snapp et al., 2005). This option is cost effective if cover crops are added into a niche that will generally stay fallow after a conventional rotation (Creamer and Baldwin 2000; Snapp and Mutch 2003). In alternate niches, farmers would have to replace a cash crop to enable the growth of a cover crop, which will have a greater economic impact on the farmer (Snapp et al. 2005). Despite this, farmers in New York and Michigan are conducting summer cover crop trials to mitigate degraded soils and constant pest problems (Snapp and Mutch 2003).

Pest, weed, and disease suppression - Cover crops can be used to suppress weeds in a variety of ways, such as creating competition for nutrients, allelopathy, changes in the soil environment, preservation of surface residues, physical effects, and increased weed seed decay (Conklin et al., 2002). The suppression of weeds can reduce the amount of herbicides required, which can lead to a reduction in production costs. Cover crops are also capable of breaking pest and disease cycles through reducing pesticides, fumigation, production costs, as well as offering potential environmental benefits (Snapp et al., 2005).

Economic benefits

Soil conservation - A review by Pimentel et al. (1995) looked at soil erosion from conventional agriculture and the associated economic and environmental on-site costs related to the loss of nutrients, organic matter, productivity of the soil, and soil biota. They estimated that around 160 million hectares of cropland was affected, and the on-site costs were around US$19.7 per tonne (2014 value),which equated to approximately US$46 billion per annum (2014 value). Off-site costs related to soil erosion by wind and water amounted to approximately US$29 billion due to damages caused by floods, contaminated water bodies and damaged water transport facilities. Eshel et al. (2015) found that planting cover crops when growing potatoes led to a 95% decrease in soil erosion, a >60% decrease in runoff, without loss of yield or nutrients, and also inhibited the growth of weeds.

The study by Eshel et al. (2015) determined that the average yearly cost for growing potatoes between 2011 and 2013 was US$13,671 ha^{-1} (Table 1). Additional costs for growing potatoes using conventional farming practices, which includes preparation of the potato beds and various maintenance costs such as road repair and tilling, were US$905 ha^{-1} which resulted in an average yearly cost of US$14,576 ha^{-1}. The costs associated with investing in cover crops was US$719 ha^{-1} which included the purchase of seeds, the extra labour required for planting and growing, and the additional water requirements. This resulted in an average yearly cost of US$14,390 ha^{-1}, which is 1.29% less than the cost of growing potatoes under conventional management. Growing cover crops alongside the potatoes produced a profit margin of US$180 ha^{-1} yr^{-1} with additional benefits, such as reducing the requirement for compost, increasing growers' profits to approximately US$286 ha^{-1}.

Table 1. Costs associated with potato production grown in a Mediterranean climate (Eshel et al., 2015)

	2011	2012	2013	Avg.
Common cultivation costs (US$ ha^{-1})	13,813	13,077	14,124	13,671
Additional costs under conventional practices (US$ ha^{-1})	778	1,050	888	905
Additional costs under cover crop practices (US$ ha^{-1})	773	703	681	719

2.3 Organic manure addition (crops, grassland, rice)

Improved yield

Studies have shown that the addition of organic manure can increase crop yield and water productivity in semi-arid environments. Wang et al. (2017) found that organic manure can be used when growing maize in dryland agriculture to improve the soil environment and water productivity while increasing yield. Organic manure also has the ability to stabilise crop production in semi-arid regions of China that are agriculturally intensive by improving the soil water-nutrient content. Dordas et al. (2008) report that inorganic fertiliser can be replaced by organic manure in northern Greece without a loss of yield; as supported by an increase of 35% in the kernel weight per cob and an increase of 32% in the numbers of kernels per cob.

Soil security

Effects on soil productivity, soil quality and yield - The effect of organic manure addition on soil productivity, soil quality and crop yield appear to vary greatly between studies. Edmeades (2003) determined that manured soils had a higher organic matter (OM) content and an increased population of microfauna compared to fertilised soils. Manured soils also contained greater amounts of P, K, Ca and Mg in topsoils, while subsoils were enriched in N, Ca and Mg. They also had greater porosity, aggregate stability, and hydraulic conductivity, and a lower bulk density than inorganically fertilised soils. However, some studies indicated that there was no significant difference in the long-term effects of crop production between manures and fertilisers and suggest that a large input of manure applied over a number of years is required to improve soil quality in addition to the soils' nutrient content (Edmeades 2003).

Organic manure combined with chemical fertiliser is thought to be a good way to increase SOC while sustaining a high yield (Li et al., 2017a) which will be beneficial in regions where organic manure alone will not have a positive benefit on soil quality or crop yield. Kanchikerimath and Singh (2001) found that a balanced application of manure and chemical fertiliser improved the quality of organic C in the soil in a semi-arid sub-tropical environment, in which wheat, maize and cowpea crops all showed a strong correlation between the build-up of organic C in the soil and an increase in yield. While in India, the use of organic manure alongside chemical fertilisers has the potential to increase the available nutrient content of the soil and soil intervase activities (Manna et al., 2007).

Several studies have determined that the application of organic manure can be used alongside sustainable tillage practices to improve soil quality and increase crop yields around the world (Carr *et al.*, 2013; Ahmad *et al.*, 2013; Parija and Kumar, 2013).

Also see Section 2.3: Improved Yield

Water security

Wang et al. (2017) found that organic manure can be used when growing maize in dryland agriculture to improve the soil environment and water productivity while increasing yield.

Economic benefits

Economic comparison of an organic and conventional farming system (NB: this review covers all organic farming practices, not just organic manure addition) - A study by Pimentel et al. (2005) analysed results from a 22-year study undertaken by the Rodale Institute Farming Systems Trial that compared a grain-based farming system using organic practices to the same farming system using conventional practices. The study looked at several criteria, such as environmental impacts, energy efficiency and soil quality; however, this review will primarily look at crop yields and the economic feasibility of the two systems. The conventional cropping system used synthetic fertiliser, herbicides, and pesticides according to the recommendations set out by the Pennsylvania State University Cooperative Extension. The organic animal-based cropping system applied aged cattle manure at a rate of 5.6 t ha^{-1} prior to ploughing every two out of five years. Nitrogen was also supplied by means of ploughing down legume-hay crops. The total N supplied to the crops was approximately 40 kg per annum, which equated to 198 kg ha^{-1}. No herbicides were applied in the organic animal-based cropping system. An organic legume-based cropping system was also analysed but will not be discussed in this review.

Corn grain yields during the first five years averaged 4222 kg ha^{-1} for the organic animal system while the conventional system yield averaged 5903 kg ha^{-1}. After a period of five years the yields became similar for the two systems. The organic and conventional yields were 6431 and 6553 kg ha^{-1} respectively. Soybean yields between 1981 and 2001 for the organic and conventional systems averaged 2461 and 2546 kg ha^{-1} respectively. Under drought conditions, in a 5-year period between 1988 and 1998, average corn yields were higher for the organic animal system than the conventional system at 6938 and 5333 kg ha^{-1}.

In 1999 extreme drought conditions were experienced which further improved organic yields of corn and soybean, 1511 and 1400 kg ha^{-1}, compared to the conventional yields of 1100 and 900 kg ha^{-1} respectively.

Three economic comparisons were investigated in this study. This review will focus on the third economic comparison that looked at the organic and conventional corn-soybean systems, which took place between 1991 and 2001. The comparison reports prices only for the legume-based cropping system rather than the animal-based cropping system because the net prices for both organic systems were highly similar. The average annual net return for the organic systems was less than ($176 ha^{-1}) the conventional system ($184 ha^{-1}). The revenue comparisons for the organic and conventional systems were $457 and $538 ha^{-1} respectively, with a greater variation in the conventional returns, which makes this option riskier. Total profits within a 10-year timeframe showed a 25% increase with reported profits of $221 ha^{-1} for the organic corn system and $178 ha^{-1} for the conventional corn system.. This was due to the fact that the yield from the organic corn totalled 5843 kg ha^{-1}, which was only 3% less than the conventional corn yield of 6011 kg ha^{-1}, while organic costs ($351 ha^{-1}) were 15% lower than conventional costs ($412 ha^{-1}). Although the organic corn costs were lower, in the organic system a legume crop had to be grown prior to the corn which meant that corn was only grown 33% of the time compared to 60% of the time in the conventional system which results in lower overall production of organic corn over a period of several years compared to the conventional system. A wheat crop was grown prior to the legume crop, therefore, the wheat crop partially compensated for the loss of corn.

2.4 Compost application (crops, grassland, rice)

Improved yield

Experiments conducted by Bedada et al. (2014) determined that the use of compost combined with fertiliser resulted in higher crop harvests when compared to the other treatments. In Ethiopia, fertilisers used by farmers only supply primary plant nutrients. The addition of compost to the fertiliser will restore SOM which in turn can improve the water holding capacity and structure of the soil. The combination of compost and fertiliser has the potential to restore the fertility of the soil, preserve SOM, and improve yield (Vanlauwe *et al.*, 2011; Bedada *et al.*, 2014).

Soil security

Increasing soil fertility - Nutrient depletion causes deterioration in soil fertility, which is a concern for farmers. A study undertaken by Bedada et al. (2016) showed that there was a significant ($P < 0.05$) accumulation of Ca, Mg, K, P, B, Zn and S within the top 10 cm of surface soil when compost was applied at a rate of 2.4 t ha^{-1} dry weight when compared to the control plot. The N balance was negative in the fertiliser (–65 kg N ha^{-1} yr^{-1}) and control (–75 kg N ha^{-1} yr^{-1}) plots but positive in the compost plot (+20 kg N ha^{-1} yr^{-1}). Nitrogen levels in the compost and the half compost–half fertiliser plots were near a steady state when the balance of N was compared to the measured change of N in the soil, while N levels in the fertiliser and controls plots were less than zero. The P balance was negative in the control (-11 kg P ha^{-1} yr^{-1}) and compost (-4 kg P ha^{-1} yr^{-1}) plots and positive in the fertiliser and half compost–half fertiliser plots (+1 kg P ha^{-1} yr^{-1}). This study indicates that the addition of compost, either alone or combined with a mineral fertiliser, can prevent N mining and reduce P mining while improving the nutritional value of the soil. Experiments carried out by Bedada et al. (2014) found that the use of compost combined with fertiliser resulted in higher crop harvests when compared to the other treatments.

In poor farming systems, combining compost with inorganic fertilisers is an affordable way to restore soil fertility (Vanlauwe et al., 2010) as other potential sources of crop nutrients may be required for other uses, such as farmyard manure to be used as fuel or crop residues to be used for animal feed (Haileslassie *et al.,* 2005; Abegaz and van Keulen, 2007).. Castán et al. (2016) found that N and P losses are minimised by utilising low rates of nutrient rich composts, which reduces the value of the compost. The loss of nutrients could be reduced by mixing a nutrient rich compost with one that is nutrient poor, such as those obtained from the organic portion of municipal solid waste, which will preserve the positive effects on SOM.

Also see Section 2.4: Improved Yield

Economic benefits

Economic benefits of composting as a way to reduce fertiliser application - The spreading of compost onto crops can improve SOC and provide nutrients. Additionally, this can reduce the amount of non-organic fertilisers required which will in turn reduce costs (Viaene et al., 2016). A study conducted by Nevens and Reheul (2003) determined mineral fertiliser requirements for silage maize were reduced by 0-43 kg ha^{-1} when compost was applied at a rate of 22.5 Mg ha^{-1} compared to plots that received only mineral fertiliser. According to Wang and Wang (2014) the average cost of N fertiliser in Europe was €0.502 kgN at the time of their study; taking into account the previously mentioned mineral fertiliser reduction of 0-43 kg ha^{-1} (Nevens and Reheul, 2003), this could result in a saving of up to €21.586 kgN ha^{-1}.

Economic benefits of composting as a way to manage solid waste - Composting and vermicomposting are the preferred processes for managing solid wastes, compared to using landfilling, as the composts contain a large amount of organic waste and the processing costs are also lower which makes them suitable options for use in developing countries (Lim et al., 2016). By reducing the amount of waste being sent to landfills through reusing organic waste, waste management costs can be further reduced (Cabanillas et al., 2013). Therefore, composting can be considered to be economically beneficial as it can reduce disposal costs and provide additional income by selling compost for chemical fertiliser production (Proietti et al., 2016). Lim et al. (2016) identified investment costs of approximately €462,646 for an anaerobic sludge composting plant with a capacity of 7.12 x 10^6 kg and an annual running cost between €250,000 and €360,000. The revenue for the plant was obtained by selling compost at a cost of €0.041 kg^{-1}, which is far less than the cost of mineral fertiliser (€0.502 kgN).

2.5 Optimal N application (crops)

Yield

Studies undertaken in China indicated that there was no significant increase in crop yield using current agricultural N practices (550–600 kgN ha^{-1} fertilizer) compared to optimum N application with N savings between 30% and 60%; although the current agricultural N practices resulted in approximately twice as much N being lost to the environment (Ju et al., 2009).

Soil security

Soil biodiversity - Hijri et al. (2006) examined arbuscular mycorrhiza fungi (AMF) population abundance and diversity under organic, intensive, and integrated management systems. Organic fields had the highest abundance of AMF followed by integrated management systems, which plough shallower (15-18 cm) than intensively managed fields (30 cm). Integrated management systems employ fewer chemicals to control pests, weeds and diseases, relying on cultural practices, varietal choice and a long crop rotation whereas intensively managed fields were monocultures. Additionally, an organic field had the lowest levels of AMF diversity and was found to contain high levels of phosphorus from being previously managed under an intensive system (59 mg kg^{-1}), compared to 3.9 mg kg^{-1} at another organic field. Abundance of P reduces the incentive for crops to form symbiotic relationships with AMF. Furthermore, AMF species found in organic and integrated fields were *Paraglomus, Acaulospora* and *Scutellospora*. Whereas in intensively managed fields only *Glomus* Group A was present, implying *Glomus* Group A are less sensitive to chemical application and soil disturbance. By reducing plant species diversity, ploughing could contribute to lower AMF diversity and less competition between AMF species by favouring disturbance-tolerant species, although competition could also be increased due to fewer plant roots to form symbiosis with (Schooner et al., 2010).

Water security

Post-harvest residual soil nitrate (RSN) is thought to be the main source of nitrate that is present in percolating water. Adoption of practices to reduce levels of RSN can minimise the amount of N that is released into the environment (Hong et al., 2007).

Economic benefits

Decreased requirement for N fertiliser to reduce costs - The global application of N fertiliser has greatly increased over the past few decades and application rates are expected to reach 165 Tg N yr^{-1} by 2050 which is a 65% increase from the early 1990's estimate of 100 Tg N yr^{-1}(Galloway et al., 2004). In the Midwest USA it is common practice for farmers to apply a single rate of N fertiliser over entire fields and even farms (Hong et al., 2007) despite studies having shown that crop N requirements can differ greatly between fields and within fields (Scharf et al., 2005). Applying a single rate of N fertiliser can lead to a mismatch between the amount of N in the fertiliser and the amount of N required by the crops, resulting in a build-up of RSN (Mitsch et al., 2001). By applying economically optimal N rates (EONR) when applying N fertiliser, farmers can reduce RSN and generate environmental benefits. EONR can also decrease the requirement for N fertiliser which in turn will reduce costs (Hong et al., 2007).

Also see Section 2.5: Yield

2.6 Nitrification inhibitor

Improved yield

Reduction in N fertilisation and increase in yield – Sutton et al. (2011) estimated that approximately 50% of the world's population is sustained by the use of synthetic N fertilisers. Out of the total amount of N fertiliser applied to croplands, only 47% is transformed into harvested products while 53% of N used in the fertilisation of crops is released into the environment (Lassaletta et al., 2014). The North China Plain (NCP), where 50% of the nation's wheat and 35% of maize are produced, is the location of China's most prominent grain production and a copious amount N fertiliser (Wang et al., 2012). These crops require around 200 kgN ha^{-1} yr^{-1}, however, the current N input of 550–600 kgN ha^{-1} yr^{-1}, which greatly exceeds crop requirements in order to obtain higher yields (Ju et al. 2009; Cui et al. 2010). Higher N application results in a low N utilisation efficiency (Cui et al., 2010), high nitrous oxide (N_2O) and nitric oxide (NO) emissions (Zhou et al., 2016) and loss of N through nitrate leaching (Ju et al., 2006). Nitrification inhibitors (NI) are compounds that work by suppressing NH_3- oxidising bacteria, which leads to a reduction in the bacterial oxidation of NH_4^+ to NO_2^- (Zerulla et al., 2001). A study carried out by Tian et al. (2017) in the NCP determined that combining drip fertigation with NI could potentially decrease annual emissions of N_2O by 66% and NO by 95%. In addition it can also increase maize yield by 26% while reducing the rate of N fertilisation by 30%, which should increase profits while reducing production costs and water requirements.

A common NI is 3,4-Dimethylpyrazole phosphate (DMPP) which is effective at increasing the efficiency of N fertiliser, restricting soil nitrification, and improving crop yield and fruit quality without any toxicological effects (Martinez et al., 2015). Studies found DMPP to be effective at low rates (Zerulla et al., 2001) while increasing the yield of several crops such as barley, wheat and maize (Linzmeier et al., 2001; Pasda et al., 2001). One study, Lasda et al. (2001), found that the marketable yield of carrots and lambs' lettuce was significantly higher when DMPP was used compared to treatments without the use of DMPP.

Soil security

See Section 2.6: Improved Yield

Economic benefits

Cropping systems where NI application is most economically beneficial - The benefits of NI, such as decreasing the amount of N-fertiliser required and the number of applications, as well the potential for increasing yield, can have economic and environmental benefits. It is important to identify the cropping systems in which NI is most able to improve N use efficiency (NUE) and yield to gain the highest costs benefits (Alonso-Ayuso et al., 2016). However, results related to increased NUE and crop yield are contradictory. Studies undertaken by Diez-Lopez et al. (2008) and Liu et al. (2013) noticed an increase in NUE while Arregui and Quemada (2008) determined no increase in NUE was observed in a rainfed crop rotation of wheat and barley. Other studies looked at yield or crop quality, such as Pasda et al. (2001) who determined that cereal and vegetable crop yield and quality was improved through the use of NI rather than conventional fertilisers alone, especially in areas that contained light sandy soils or received large amounts of water by means of irrigation or rainfall. Another study, Martinez et al. (2015), also found that yields from strawberry plants increased after NI application. Other studies found conflicting results. For example, Weiske et al. (2001), Arregui and Quemada (2008) and Ercoli et al. (2013) did not detect a significant increase in yield when N-fertiliser containing a NI was used in winter and summer cereals. Barth et al. (2001) and Wu et al. (2007) both state that these contradictory results, regarding NUE and yield, strengthen the idea that cropping systems and different management practices can influence the effectiveness of NI.

A meta-analysis undertaken by Abalos et al. (2014) found that the application of NI resulted in a mean increase of 12.9% for NUE and 7.5% for crop yield, although this was dependent on environmental factors and management practices. The study determined that the mean effect of NI application was greater in acidic soils with a medium to coarse texture when compared to neutral and alkaline soils with a fine texture. A greater response was also observed in systems that were irrigated and/or where crops received higher rates of N fertiliser. In systems where crops are grown in alkaline soils that are expected to lose large quantities of N by means of ammonia (NH_3) volatilization, then it has been recommended to use N-(n-butyl) thiophosphoric triamide (NBPT), which is a urease inhibitor, to achieve the greatest effect size.

Economic evaluation of NI fertilisers in the Burdekin, Australia - A study by Thompson et al. (2017) evaluated the profitability of NI and controlled release (CR) fertilisers in regard to fertiliser costs and break-even yields (Table 2). The conventional fertiliser, Urea-220, was cheaper per tonne than the NI fertiliser, however, the NI fertilisers were applied at lower rates, which made them marginally less expensive. A variety of treatments were compared in two groups, A and B, including a traditional fertiliser (Urea), a NI fertiliser (ENTEC), and a controlled release fertiliser (CR). In Group A the NI fertiliser, ENTEC-180, cost $3 less per hectare than the Urea-220, therefore a yield reduction of 0.2 to 0.1 tonnes of cane per hectare (TCH) would result in a break-even yield. If there was no loss of yield observed with the ENTEC-180 treatment then it would be slightly more profitable than the Urea-220. In Group B, the NI fertiliser, ENTEC-160, cost $40 less per hectare than the Urea-220, thus a larger yield loss of 1.5 to 1.2 TCH would result in a break-even yield. In comparison, the ENTEC-160 would result in greater profitability compared to the Urea-220 treatment and would allow for a larger margin for yield loss to occur shown in Group B experimentation. However, in both groups, the reduced urea treatments, Urea-160 and Urea-180, as opposed to Urea-220, were not only cheaper than the ENTEC treatments, but a greater loss of yield could be incurred to break-even with the conventional treatment. Therefore, the ENTEC treatments are only less expensive than the conventional treatment fertiliser.

Table 2. Fertiliser costs and break-even yields (Thompson et al., 2017)

	Group A				Group B		
	Treatment	Cost $/ha	Breakeven Yield (TCH)		Treatment	Cost $/ha	Breakeven Yield (TCH)
T1*	Urea-220	537	0	T1*	Urea-220	537	0
T2	Urea-180	480	-2.7 to -1.4	T2	CR25%-220	693	4.4 to 5.6
T3	ENTEC-180	534	-0.2 to -0.1	T3	ENTEC-220	608	2 to 2.6
T4	CR25%-180	608	1.7 to 3.3	T4	Urea-160	451	-3.1 to -2.5
T5	CR50%-180	733	4.8 to 9.1	T5	CR25%-160	566	0.8 to 1
	*Conventional fertiliser treatment			T6	ENTEC-160	497	-1.5 to -1.2

With regards to gross margins, the Group A ENTEC-180 treatment had a higher mean gross margin of $3,367 than the Urea-220 treatment gross margin of $3,317. The Group BUrea-220 treatment had the highest mean gross margin of $2,967 while the ENTEC-160 treatment had the second highest mean gross margin of $2,815.

2.7 Polymer-coated fertiliser

Improved yield

Increase in N use efficiency and yield - Slow-release fertilisers control the rate at which nutrients are supplied to the crop (Chen et al., 2017), which reduces the amount of fertiliser required while increasing the N efficiency use and curtailing environmental pollution (Jat et al., 2012). Several studies have determined that the use of a slow-release fertiliser can greatly increase N use efficiency as well as crop yield (Yang et al., 2011; Haderlein et al., 2001). A study conducted by Li et al. (2017b) suggests that polymer-coated slow-release fertilisers may have the capacity for extensive use, improving the quality of tomato fruit while minimising the risks that soil N has on the environment. The work carried out by Zhu et al. (2012) and Koivunen and Horwath (2005) further support these findings. These studies determined that tomato growth was promoted and tomato yield was increased when polymer-coated fertilisers were applied compared against conventional N fertilisers. Other studies established that coordinating polymer-coated fertilisers with irrigation water levels could reduce the requirement for irrigation while improving tomato quality and increasing yield. It can also minimise the amount of N residue in the soil, which mitigates the risk of leaching (Li et al., 2014; Gao et al., 2008).

There are some issues with polymer-coated fertilisers due to the coating material becoming degraded and secondary environmental contamination. A new C-based, slow-release N fertiliser produced from biochar has the potential to improve the quality and yield of fruit crops while reducing environmental risks. It can also reduce the amount of irrigation required while maintaining normal growth of tomatoes and fruit yield (Chen et al., 2017). Other studies have shown that the use of a C-based, slow-release N fertiliser increased yields of wheat (Gao et al., 2012), rice (Chen et al., 2013) and corn (Lu et al., 2011). Positive results have also been reported on a variety of other crops including pepper, canola, sweet potato, soybean, sorghum, peanut, and Chinese cabbage (Qiao, 2014; Liao et al., 2015).

Water security

See Section 2.7: Improved Yield

Economic benefits

Reduction in time and production costs - Traditional inorganic fertilisers need to be applied regularly, which is time intensive and leads to increased production costs. Slow-release fertilisers only need to be applied once, reducing the amount of fertiliser being applied which saves time and money (Chen et al., 2017). Slow-release N fertiliser will dispense N more evenly, which reduces the amount of N that is lost when the fertiliser is first applied. Therefore, there is a greater supply of N available when the crops N demand is greatest, decreasing the labour requirements that are associated with top dressing application (Carson et al., 2014). A study carried out by Chen et al. (2017) found that the yield of rice was only 3.1% lower with the use of a low-cost polymer-coated fertiliser called 'Xiang Nong Da' (XND), a one-time basal fertiliser that contained 80% N, when compared against the control which was an uncoated compound fertiliser that contained 100% N in a split application. The XND also showed consistently increased values for the partial factor productivity of N when compared to the control. Therefore, it is possible for slow-release fertilisers to partially replace traditional fertilisers to help achieve a sustainable crop yield while reducing production costs.

2.8 Straw addition/Residue return (50%)

Improved yield

Increase in SOC, nutrients and crop yield - A valuable indicator of soil fertility is SOC (SOC), which is linked to crop yield and land productivity (Lal, 2009). Zhang et al. (2017) reported that straw return is a cost-effective and productive means to increase SOC while obtaining a high crop yield. One study conducted in China found that increasing the SOC content by 1 g kg^{-1} could improve crop yield by 0.17–3.74 Mg ha^{-1} yr^{-1} (Kong et al., 2014). Another benefit of straw addition is the release of nutrients, such as N, P, and K into the soil that are required by crops. The addition of straw also increases the amount of C that is added directly into the soil (Zhang et al., 2017). Stagnari et al. (2014) showed that the addition of 1.5 t ha^{-1} of straw mulch was enough to decidedly increase crop yield, although the application of 2.5 t ha^{-1} of wheat straw was required to achieve a greatly positive effect on both soil as well as physical indicators of the crops. The study found that there was a continual improvement in crop performances and soil characteristics until an application threshold of 5 t ha^{-1} of crop residue. The improvement in soil condition, caused by the application of straw, had a positive effect on the crops resulting in increased number of spikes per unit of ground area and increased number of grains per spike and per unit of ground area; both of which led to an increased yield.

Soil security

Improvement in biochemical processes in the soil - The incorporation of straw mulch is capable of modifying the microenvironment in the soil. These modifications can have a positive effect on several biochemical processes that occur in the soil such as a change in the availability of N, residual N accumulation, and N-use efficiency (Gao et al., 2009). Decomposing mulch residue results in a slow release of N, which is more in synch with plant uptake when compared to inorganic N sources. The resulting effect increases the efficiency of N uptake, improving yield and reducing the amount of N lost through leaching (Cherr et al. 2006; Stagnari and Pisante 2010).

Transitioning from conventional agriculture to conservation agriculture - One of the biggest challenges transitioning from conventional agriculture to conservation agriculture in a semiarid environment is the insufficient accumulation of crop residues on the surface of the soil. This issue is caused by a lack of biomass due to the limited production of crops. The incorporation of straw mulch can help the transition by increasing the amount of crop residue until an adequately thick layer has been created, which is commonly associated with stable conservation agriculture systems. The use of straw mulch on the soil surface during the transitional phase also greatly improves the availability of nutrients as well as the retention of soil water (Stagnari et al. 2014).

Economic benefits

Increasing economic return in a rice-based cropping system - A two-year study conducted by Xia et al. (2016) in the Taihu Lake region of China looked at the crop yields, GHG emissions, and economic returns of three different rice-cropping systems: rice-wheat (RW), rice-fava bean (RB), and rice-fallow (RF). Straw was added directly into the soil in the RW and RF systems while the straw was fermented aerobically before it was added to the soil in the RB system. The traditional cropping system in this region is RW. Both the RB and RF systems experienced an increase in crop yield as well as performed better in regards to a reduction in greenhouse gases (GHG) and N-fertiliser application. The RB cropping system was the best performing system compared to the RW system. There was a 29-44% reduction in methane (CH_4) emissions, a 43% reduction in annual N inputs, a 56-69% reduction in N_2O emissions related to N-fertiliser application, and a 5.2% increase in crop yield. Overall, this resulted in an 11-41% decrease in GHG intensity (GHGI) and a 22-94% increase in the annual net economic benefit (NEB). The RF cropping system performed as well as the RW system. There was an increase of 8-30% in GHGI and a decrease of 3-33% in NEB. The study showed that there could be a high economic return by converting RW cropping systems into RF systems where fermented straw is incorporated into the soil, while simultaneously reducing GHG emissions. The use of straw incorporation in the RF system is expected to reduce N-fertiliser requirements, which are currently around 525 kgN ha^{-1}, by 20% which will help increase the annual NEB.

2.9 Multiple drainage: alternate wetting and drying

Improved yield

Crop and yield improvements - Norton et al. (2017) determined that after the implementation of alternate wetting and drying (AWD) the rice shoot and grain mass was decidedly larger during harvest due to the increase in the amount of productive tillers. Alternate wetting and drying (AWD) resulted in a slight increase in tillering as well as the amount of leaf abscisic acid, a plant hormone that helps the plant adapt to stress. The use of AWD decreases the amount of S, Ca, Fe, and As present in the shoots and grains, however, it also increases the amount of Mn, Cu, and Cd. The results of the study showed that growing rice under safe AWD conditions led to an increase in grain mass compared to rice grown under conventional flooding, which may be due to the increased number of productive tillers. In addition, several studies found that yield can be maintained when moving from a conventional flooding systems to AWD (Belder *et al.* 2004; de Vries *et al.* 2010; Yao *et al.* 2012).

Soil security

Soil improvements - Norton et al. (2017) discovered that drainage caused a small hardening of the soil surface that was statistically significant, which can lead to an improvement in lodging resistance.

Water security

Reduction in water use and As levels - By implementing AWD this can reduce the amount of water required by 15-20% without having a significant effect on yield. Experiments on AWD were carried out in China resulted in a reduction of water used by 10-15% without affecting yield. This method is popular in China, especially in lowland rice producing regions, and it is being recommended for implementation in north-west India and regions of the Philippines. Reducing the amount of water used during irrigation allows the soil to become more aerobic which leads to a reduction in the uptake and solubility of As (Global Rice Science Partnership, 2013).

A study undertaken by Linquist et al. (2014) found that moving from a conventional flooding system to AWD improved water-use efficiency by 18-63% while reducing As levels in grains by up to 64%, however, this reduce yield by 1-13%. Yields remained similar when AWD was implemented early during the growing season and followed by flooding the rest of the time. AWD also reduced the amount of water used by 18% compared to conventional flooding, and the amount of As present in the grains were either similar or greater. This study determined that yield does not have to be sacrificed to obtain environmental benefits, although trade-offs may need to be considered.

Reduction in vector-borne diseases - Conventionally irrigated paddy fields can be used as breeding grounds for a variety of vector-borne diseases that can be transmitted to humans. In Africa, puddles in paddy fields prior to transplanting and post-harvest are the most common breeding grounds for the mosquito *Anopheles* gambiae, which is classed as Africa's most potent malaria vector. The impact of vector-borne diseases can be mitigated by a variety of options including AWD. Similarly in Asia, Japanese B-encephalitis virus is closely linked to the production of rice, particularly in China and Vietnam where pigs are commonly raised. AWD can be implemented to help reduce the breeding of mosquito vectors of this viral disease (Global Rice Science Partnership, 2013).

Economic benefits

Economic benefits associated with implementation of alternate wetting and drying - A study by Lampayan et al. (2015) looked at the economics of farms that have adopted the 'safe' AWD management practice for irrigated lowland rice that was devised by the International Rice Research Institute in 2002. This required farmers to follow a simple set of guidelines and implement a perforated 'field water tube' that allowed farmers to irrigate their fields to the required depth. The field water tube is made of an inexpensive material, such as bamboo or plastic pipe, and is easy to use. This allowed farmers to reduce the amount of irrigation water used while maintaining their crop yield. Demonstration trials and training of this management practice have been carried out in eight different countries within Asia, which has resulted in large-scale adoption of AWD in Bangladesh, the Philippines, and Vietnam. This study determined that the implementation of AWD has decreased the amount of irrigation required by 38% without affecting yield, as long as the practice is properly implemented. This led to a reduction in costs associated with water pumping and fuel use, which increased farmers' income by 38%, 32%, and 17% in Bangladesh, the Philippines, and southern Vietnam in comparison to conventional irrigation methods. The study also identified the benefit-cost ratio, using the Philippines as a case study, to determine whether the economic benefits related to the implementation of AWD compensated for the investment costs associated with the research and development of this management practice. The benefit-cost ratio was 7:1 for 1997-2012, which increased to 20:1 for 1997-2016. This shows that the economic benefits are greater than the investment costs of AWD.

The field water tube used in AWD works better where there is a perched water table, due to irrigation and/or rain which is common in heavy clay soils that have a low permeability or in puddled soils, so it can develop an impermeable hardpan at a depth of 15-25 cm (Bouman et al., 2007; Lampayan et al., 2014). The field water tube is less likely to be effective in areas with a deep-water table and where soils have a light-texture and no hardpan (Lampayan et al., 2015).

2.10 Single (midseason) drainage

Improved/no impact on yield

In Japan, floodwater is generally drained over a short period of time during rice cultivation. This helps to aerate the soil in the paddy fields and prevent soil reduction from having a negative effect on rice growth. A form of short-term drainage, known as midseason drainage, is implemented prior to the maximum tiller stage with the aim of prohibiting rank growth and decreasing the amount of inadequate tillers (Itoh et al., 2011). Studies by Ma et al. (2013) and Haque et al. (2016) both found that replacing continuous flooding with midseason drainage had no or little impact on rice production while reducing the impact of greenhouse gasses and having a positive effect on the environment.

Soil security

The implementation of midseason drainage will lead to an increase in the amount of oxygen that is transported within the soil in order to help prevent root rot. It also can increase the hardness of the soil resulting in an improvement in lodging resistance (Itoh et al., 2011). This technique can change soil redox conditions, which can potentially suppress CH_4 emissions (Yan et al. 2005; Minamikawa et al. 2006; Kim et al. 2014).

Suitable for implementation in developing countries

Midseason drainage can be used in developing countries as well as developed countries. Farmers who lack advanced equipment and knowledge of mitigation techniques can easily utilize this drainage practice because the method only requires a simple adjustment in water management (Itoh et al., 2011).

2.11 Ammonium sulphate instead of urea

Improved yield

A study by Qi et al. (2012) found that the application of ammonium sulphate is one of the fertilisation methods that can significantly increase plant growth and grain yield while improving the uptake of N above ground and the apparent N recovery. The study determined that a grain yield greater than 6 t ha^{-1} could be achieved using the dry direct-seeded rice methodology as long as proper N management practices are adopted.

Water security

Improved water-use efficiency - New approaches in rice production systems often also promote the preservation of water resources while maintaining yield to ensure food security. One such approach is ‘dry direct-seeded rice’ that has the potential to reduce the amount of water and labour required while improving the water-use efficiency to benefit areas facing water shortages such as central China (Qi et al., 2012). This method involves incorporating the dry seed into the soil surface through harrowing or ploughing while the soil is dry (Pandey and Velasco, 2002). Qureshi et al. (2006) determined that there was no significant difference between the grain yield obtained from dry direct-seeded rice compared to the grain yield obtained from traditionally transplanted flooded rice.

Reducing the risk of NH_3 toxicity - Ammonium sulphate is a type of N fertiliser that is less prone to volatilization. Therefore it can be used as one of the accepted N management practices that can lessen the risk of NH_3 toxicity (Dobermann and Fairhurst 2000; Haden 2010).

2.12 Optimal N application (rice)

Improved yield

A 10-year study by Peng et al. (2010), which took place between 1997 and 2007 in six Chinese provinces, determined that optimal N application increased grain yield by 5% while reducing fertiliser requirements by 32% compared to traditional N practices. The increase in yield was also attributed to the reduction in damage inflicted on the rice crops by insects and disease.

Soil security

Optimal N application can improve lodging resistance of rice crops by hardening the surface of the soil (Peng et al. 2010).

Economic benefits

Reducing N fertiliser rates resulting in reduced costs - Chen et al. (2011b), in the Jiangsu Province, calculated economically optimum and ecologically optimum N rates for the dominant rice varieties: conventional *indica* and *japonica*, and the hybrid *indica*. The cost of N fertiliser for the *indica* double rice-based, *indica* single rice-based, and *japonica* single rice-based cropping systems was found to be US$632 t^{-1}, US$635 t^{-1}, and US$619 t^{-1}, while the rice price was calculated as being US$185 t^{-1}, US$188 t^{-1}, and US$195 t^{-1}, respectively. The present N rate is ∼390 kg ha^{-1} and the economically optimum N rate was found to be 180–285 kg ha^{-1} with a corresponding rice yield of 6.1–8.9 t ha^{-1}, while the ecologically optimum N rate was 90–150 kg ha^{-1} with a corresponding rice yield of 5.5–8.8 t ha^{-1}. By applying economically and ecologically optimum N rates, the amount of N fertiliser applied could be reduced by 26% and 61% which equates to a saving of 189×10^3 and 442×10^3 metric tonnes each year while marginally improving yield compared to farmers' current practices.

2.13 Best technology (rice)

Improved yield

A study undertaken by Huan et al. (2005) in Vietnam found that reducing inputs, such as the amount of N fertiliser used in rice production, the seed rates used in crop establishment, and the amount of pesticides sprayed during the season, had little impact on yield but increased income.

Reduced susceptibility to pests and diseases - Trying to maximise yield by increasing inputs can make rice plants more vulnerable to pests and diseases. This can occur particularly when the increased inputs are not necessary (Ma et al. 2014; West et al. 2014). A study carried out by Huelgas and Templeton (2010) found that early spraying of insecticides to destroy pest predators could result in a revival of pest issues, which would require an increase in the amount of insecticides sprayed.

Water security

Resilience against climate change and water scarcity - Technologies that will reduce inputs (seeds, fertilisers, water) increase incomes in a manner that is sustainable and environmentally friendly, and thus can increase farmers' resilience against the negative effects of climate change and future water shortages (Stuart et al. 2017).

Economic benefits

Decreased inputs and increased income - The income during the winter season was approximately US$58 ha^{-1} while the summer/autumn seasons saw an income of nearly US$44* ha^{-1} (*figure corrected by Huelgas and Templeton, 2010). The greatest saving was obtained from a reduction in pesticides, which accounted for about 80% of the increased income. Pesticide reductions also led to a decrease in labour requirement and reduced exposure to pesticide poisoning. Huelgas and Templeton (2010) reported that the study undertaken by Huan et al. (2005) involving 951 farmers showed that a marginal increase in yield could still be obtained when fertilizers, seed rates, and insecticides were reduced by 13%, 40%, and 50% respectively. These reductions amounted to an increase of US$17 to US$85 ha^{-1} per season in the farmers' gross margins (Huan et al., 2005).

Huelgas and Templeton (2010) identified the unit cost between adopters and non-adopters of the 'Three Reductions, Three Gains' crop management technology in the Mekong River Delta in Vietnam. The technology promotes the reduction of fertilisers, pesticides and seed rates. Adopters of this management technology are thought to have a lower average unit cost than non-adopters. The study found the mean difference to be US$4.42 t^{-1} during the dry season and $12.41 t^{-1} during the wet season between adopters and non-adopters across the province, which was determined to be statistically significant.

Stuart et al. (2017) compared three best management packages in Thailand, based on Cost Reducing Operating Principles (CROP), against standard farmer's practice (FP) over a period of three seasons. The packages included CROP recommendations, CROP + drum seeder (DS) technology, and CROP + AWD. Fertiliser input was reduced through the application of CROP recommendations by a mean of 50-64% each season. This had no impact on the yield amount which resulted in a mean net income increase by 26% across the three seasons compared to FP. Seed rates were reduced by 60-67% when applying the CROP + DS treatments which increased the mean net income by 29-46% each season in comparison to FP. Each of the treatments used AWD due to a shortage in water during the dry season. A high yield was still obtained even though the water supply was limited. Overall, farmers' costs were reduced by 6-36% (mean = 17%) while their net income increased by 21-131% (mean = 79%) when compared against the same season from the year prior.

Also see Section 2.13: Improved Yield

Reduced labour requirements - Labour undertaken by family members tends to be unpaid so by reducing labour requirements this can free up time for these workers to find employment off the farm or undertake non-rice related activities to increase their income (Huelgas and Templeton, 2010).

2.14 Agroforestry – silvopasture

Improved yield

Increased biomass - Mussery et al. (2013) discovered that the planting of *A. victoriae* increased the biodiversity within the silvopasture plots which will be beneficial to the animals grazing in the woodland as different species eat different types of vegetative fodder as well as differing amounts. The amount of biomass gradually decreased with increasing distance from the tree trunk, which was especially pronounced during periods of drought.

Rehabilitation of degraded dryland and drought resistance - In arid, semi-arid, and sub-humid regions, over one billion hectares of dryland are degraded in large part due to overgrazing (Malagnoux, 2007). Afforestation is considered to be a solution through silvopasture that uses browsable dryland trees (Wilkie, 2010). Planting trees that are drought resistant and have an edible canopy biomass can improve nutrient cycling and water-use efficiency that will promote the growth of flora (Leu et al., 2011). Sustainable silvopasture within arid environments can help prevent degradation and desertification while supplying enough fodder for livestock during periods of drought. By increasing the amount of fodder available this can aid the long-term sustainability of dryland exploitation by increasing the amount of livestock that can be fed during extended dry periods. It was determined that *A. victoriae* woodlands have the potential to feed a herd of goats through two drought years with the increase in available tree biomass while only a small percentage of the same sized herd could be fed in a shrubland during a single drought period (Mussery et al., 2013).

Increased grazing capacity - A study conducted by Mussery et al. (2013) determined that woodland consisting of *A. victoriae* doubled the grazing capacity for sheep and goats compared to the adjacent plot consisting of sustainably managed shrubland. The grazing capacity was four times greater in the woodland when compared against degraded shrubland.

Mussery et al. (2013) applied a mathematical model to calculate the biomass availability for grazing using both a single tree and the entire plot. The model concluded that at least 10-20 additional grazing days could be achieved each year by planting *A. victoriae* trees by increasing the amount of edible tree biomass, providing twice as much herbaceous biomass and supplying tree litter which could also be used as fodder.

Soil security

Increased nutritional value - Studies in Australia, where the *A. victoriae* originates from, highlight the high nutritional value of *A. victoriae* and its benefit to livestock (Ladiges et al., 2006). This tree species can also increase the amount of available N, phosphate, and P within the woodlands, which will improve the mineral content within arid soils (Leu et al., 2011).

Water security

Planting trees that are drought resistant and have an edible canopy biomass can improve nutrient cycling and water-use efficiency as well as promote the growth of flora (Leu et al., 2011).

Economic benefits

Economic analysis of silvopasture practices to restore longleaf pine - Stainback and Alavalapati (2004) compared the economic viability of silvopasture in the south-eastern US to traditional forestry and traditional ranching. They determined that silvopasture was the most profitable practice due to a higher Land Expectation Value (LEV) even without a carbon payment (Table 3). An increase in carbon price leads to an increase in the LEV for both silvopasture and traditional forestry as more C is being sequestered. This in turn increases the profitability as well as the optimal rotation age and tree density. As silvopasture is more profitable than traditional forestry, regardless of carbon price, this could make silvopasture and economically attractive option for farmers that are interested in planting longleaf pine on their land in the south-eastern US.

Table 3. Land expectation values (\$ ha^{-1}) under different management regimes and carbon prices (\$ t^{-1}) for longleaf pin in the south-eastern US* (Stainback and Alavalapati, 2004)

Management regime carbon price	p	tf	sp	tf (rot=60)	tf (rot=80)	sp (rot=60)	sp (rot=80)
0	1700.18	2088.04	2804.64	1507.34	1186.10	2471.05	1927.42
10	1700.18	3088.81	3805.42	2644.02	2372.21	3558.31	3014.68
20	1700.18	4151.36	4843.26	3756.00	3558.31	4695.00	4200.79
30	1700.18	5201.56	5893.45	4867.97	4744.42	5806.97	5386.89
40	1700.18	6276.47	6956.01	5979.94	5905.81	6918.94	6572.99
50	1700.18	7376.08	8055.62	7116.62	7091.91	8043.27	7882.65

p = traditional pasture, tf = traditional forestry, sp = silvopasture, 'rot' = fixed rotation (60 or 80 years)

2.15 Best technology (grassland)

Improved yield and biodiversity

By increasing the richness of plant species in unproductive grasslands, there is the potential to increase the yield of dry matter (Hector and Loreau, 2005). Grasslands that consist of more intricate forage mixtures, rather than a grass monoculture, could also be more profitable

(Sanderson et al., 2006). This may due to the increased yield in herbage from forage mixtures when compared against monoculture grasslands (Frankow-Lindberg et al., 2009).

Increased biodiversity - An increased diversity of plant species may add to the stability of ecosystems according to the plant biodiversity theory. Increasing the stability of herbage production would be advantageous for managed grasslands such as pastures (Sanderson 2010). A greater diversity in plant species may also help prevent pest invasion in grasslands (Biondini 2007). The abundance and richness of species of grassland fauna, including birds (Söderström et al. 2001a), bumblebees (Söderström *et al.* 2001b), and butterflies (Franzén and Ranius 2004), are greatly increased when vegetation is higher and has a heterogeneous structure (Öckinger et al. 2006). This is usually the result from low-intensity grazing due to varied grazing, trampling, and defecation from livestock. This management method is thought to allow more species to co-exist when compared to mowing which results in the homogenisation of the grasslands (Redecker et al., 2002). Grazing is considered to be a cheaper management practice as the cost of mowing can be quite high and can be detrimental to the maintenance of traditionally managed grasslands (Schreiber and Briemle, 2009). Low to medium intensity grazing, < 0.5 animal unit ha^{-1}, combined with annual rotation of pastures can result in an increased richness in plant species when compared against annual mowing (Vadász et al. 2016). A study by Öckinger et al. (2006) found that species richness for plants and butterflies were higher when cattle or horses grazed in the grasslands compared to sheep.

Soil security

An increase in SOC can help improve grassland productivity if primary C production exceeds the C losses (Moinet et al. 2017), while increasing the area of grasslands can help prevent soil erosion and N losses (Gocht et al.,2016) and increase soil C sequestration (De Deyn et al., 2011). After reviewing over 100 experimental studies from around the world, Conant et al. (2001) determined that converting arable land into grassland was an efficient method of sequestering C.

Grasslands are being damaged by intensive management practices such as ploughing and the use of inorganic fertilisers and reseeding (Stewart and Pullin 2008). Species diversity has been found to decrease if high amounts of N fertiliser are applied (Maurer et al. 2006). This may be due to the fact that many grassland plant species have adapted to nutrient conditions that are low to medium; therefore, large applications of N fertiliser can be detrimental to the plants (Jacquemyn et al., 2003). Less intensive management practices may also be more cost efficient.

Economic benefits

Costs associated with increasing grassland in the European Union - A study conducted by Gocht et al. (2016) calculated that increasing grassland area by 5%, which equates to 2.9 Mha, would amount to an average cost of €238 ha^{-1} or a total cost of €417m for the entire European Union. This amounts to an average net abatement cost of €97 t^{-1} CO_2e based on premium payments. The study found that 28% of the total C sequestered by increasing the grassland area could be achieved at a reduced cost of €50 t^{-1} CO_2e. The regions that C sequestration would be most productive are Germany and the Netherlands, as well as parts of France, Italy, and Spain. Farming systems that have the greatest potential for mitigation at comparatively low costs are larger farms that focus on 'mixed-crop livestock', 'mixed-field cropping', and 'cereals and protein crops'. Not only will increasing grasslands lead to an increase in the amount of C being sequestered but the other benefits, such as greater biodiversity and reduction of soil erosion and loss of N, can also reduce abatement costs.

Supplying forages for livestock - Grasslands contribute to a wide variety of agronomic services such as the supply of forage for livestock, which in turn has an effect on the quality of milk and meat produced (Huyghe, 2008).

III. Co-benefits of mitigation options in livestock systems

3.1 Manure storage cover with straw or natural crust

Manure handling/quality/cost reduction

Reduced odours from stored manure - One of the most common complaints with regards to livestock farming is related to the odours that are emitted by the anaerobic decomposition of wastes such as manure, bedding materials, and wash water. Emissions from the storage of manure include odorous gases such as NH_3, hydrogen sulphide (H_2S), and volatile fatty acids, which generally are released when the manure is agitated, either during windy conditions or when the manure is stirred or pumped prior to land application. Odours from manure stores can be reduced by means of a cover or the formation of a natural crust. These solutions create a physical barrier that prevents the release of various gases from the liquid (Bicudo et al., 2004). Straw covers are thought to reduce NH_3 emissions by forming an aerobic region at the top of the store and allow the occurrence of nitrification (Dennehy et al., 2017).Permeable covers are the most commonly used and are comprised of materials such as straw or geotextiles. A straw cover is usually created by applying a thick layer of straw, around 30 cm deep, to the manure store by means of a straw blower. An area of around 46 m^2 can be covered using a single round straw bale with a diameter of approximately 3.5 m. Straw covers generally last for between two to six months. Duration depends on variables such as how much straw has been applied, the size of the basin, how evenly the straw has been applied, and the wind conditions during application. Emissions are greatly reduced with increasing thickness of the straw layer. A 10 cm layer of straw reduces odours, H_2S, and NH_3 by 60%, 69%, and 61% respectively. Emissions are further reduced, with reductions ranging between 70-90%, when the straw layer was increased to a thickness of 20-30 cm. Natural crusts are also considered as permeable covers and they typically form on dairy manure due to the high content of fibrous material within the manure. While natural crusts also reduce odorous emissions, researchers have had difficulty in quantifying the reductions, although it is thought that the reductions will be similar to those of straw covers (Bicudo et al., 2004). Slurries must have a dry matter content of >1% to allow the formation of a natural crust (Smith et al. 2007).

3.2 Manure storage with straw (to aid composting)

Manure handling/quality/cost reduction

Environmental and economic benefits - Petric et al. (2009) determined that the best conditions for composting were achieved by a mixture of 83% poultry manure and 17% wheat straw. In areas, such as Bosnia and Herzegovina, straw accounts for around half of the cereal crop yields. Therefore, there will not be transportation costs associated with this mitigation option. There are many benefits from composting poultry manure with wheat straw, such as reducing the volume and moisture content of the manure, which in turn reduces the storage space required and transport costs, odour reduction, the eradication of weeds and pathogens, the stabilisation of microbes, and the creation of a good quality fertiliser.

Costs associated with addition of straw to manure - Cooper et al. (2011) identified the cost of high C:N materials to mix with compost using autumn 2011 prices in the UK. Wheat straw is the cheaper option at £55 t^{-1} while barley straw is more expensive at £80 t^{-1}. They estimated that a tonne of fresh slurry would require around 100 tonnes/bales of straw.

Increasing C content and aeration to aid composting and reduce associated energy costs - Carbon accounts for approximately 40% of the mass of the straw while around 0.5% of its mass is N. The high C content of straw aids aerobic decomposition (Yamulki, 2006). Forshell (1993) found that 2.5 kg straw cow^{-1} day^{-1} should be added to the manure to produce a compost that does not required to be turned or undergo forced aeration. Cooper et al. (2011) estimated that forced aeration requires around 0.5 L of diesel fuel per tonne of compost being turned. As a result the addition of straw to the stored manure could reduce the associated energy costs.

Reduced emissions - The addition of straw to manure has several benefits due to the high C content of the straw. It impacts the dry matter content and C:N ratio, and also aerates the manure. The resulting effects aids in the reduction of GHG emissions (Yamulki, 2006).

Soil security

Composting poultry manure with wheat straw can eradicate weeds and pathogens (Petric et al., 2009).

3.3 Compost

Manure handling/quality/cost reduction

Economic analysis of on-farm manure composting processes - A study by Pergola et al. (2017) looked at the sustainability of producing one tonne of compost using manure from dairy cattle and buffalo and a variety of bulking agents (Table 4) in two on-farm composting facilities in the south of Italy. The cost of composting ranged from €9.9 to €31.5 t^{-1} of compost (Table 5), while the energy requirements associated with compost production ranged from 233 to 756 MJ tonne of compost (Table 6). Overall, when bulking agents comprised of maize straw or pruning residues were used this resulted in the lowest costs, energy requirements, and environmental impacts. Wood chips resulted in the greatest costs and energy usage, and was determined to be the least sustainable option. On-farm composting greatly reduces the overall price. Prices in Italy were as high as €250 t^{-1} for one tonne of commercial compost when taking the cost of transport to the final destination into account.

Table 4. Composting alternatives for Castel Volturno Plant (CV Plant) and Stigliano Plant (ST Plant). The alternatives differed for the use of diverse bulking agents and for their combination in stables and in the composting plants (Pergola et al., 2017)

Alternatives		Stable	Plant
CV Plant	A	CS + MS	WC
	B	CS + MS	MS
	C	WC	WC
	D	MS	MS
ST Plant	E	PR	CS
	F	WC	CS

CS: conventional straw; WC: wood chip from Short Rotation Forestry; PR: pruning residues; MS: maize straw

Table 5. Operating costs in the examined composting scenarios within each composting plants (Castel Volturno Plant - CV Plant; Stigliano Plant - ST Plant). Values are expressed as € t-1 of compost (Pergola et al., 2017)

Composting Operations	CV Plant				ST Plant	
	Alternatives					
	A	B	C	D	E	F
Material Processing and Transport	12.6	5.5	22.4	2.2	4.9	21.5
Stable management and manure collection	0.5	0.5	0.5	0.5	1.1	1.1
Composting process	7.3	7.3	7.3	7.3	8.8	8.8
Total costs	20.3	13.3	30.1	9.9	14.8	31.5

Table 6. Energy consumption in the examined composting scenarios within each composting plants (Castel Volturno Plant - CV Plant; Stigliano Plant - ST Plant). Values are expressed as MJ t-1 of compost (Pergola et al., 2017)

Composting Operations	CV Plant				ST Plant	
	Alternatives					
	A	B	C	D	E	F
Material Processing and Transport	409	203	598	75	118	525
Stable management and manure collection	20	20	20	20	52	52
Composting process	139	139	139	139	107	107
Total costs	568	362	756	233	276	684

Composting benefits to offset cost - The cost associated with composting can be offset by the benefits of applying compost to farmland, such as the reduction in nutrient leaching when compost is compared against inorganic fertiliser and/or raw manure (Petric et al., 2009). Several studies investigated these benefits. Dick and McCoy (1993) determined that compost could increase the fertility of the soil and also crop yield. Another study, Hoitink and Boehm (1999), found that there was a reduction in diseases that were spread by plant pathogens within the soil when compost was applied to agricultural land. Additionally, spreading costs are also reduced as the composting process results in a decreased mass of the solid manure (Cooper et al., 2011).

Improved crop yield

Dick and McCoy (1993) determined that compost could increase the fertility of the soil and also crop yield.

Soil security

Reduction of diseases - See Section 2.3: Manure handling/quality/cost reduction (Composting benefits to offset cost).

Reduction in N loss - The loss of N can affect the quality of the compost and cause pollution through nitrification (Yamamoto et al., 2012). Composting can stabilise the inorganic N present in manure and reduce the risk of N being lost through excess soil N mineralisation (Cooper et al., 2011).

3.4 Aeration (in composting)

Manure handling/quality/cost reduction

Active composting vs passive composting - Active composting involves forcing air through the manure pile to ensure aerobic conditions, Active composting is achieved by using blowers or intermittent mechanical turning, while passive composting is dependent on the temperature within the pile to generate passive aeration. Stable compost is generated more quickly when active composting is applied (Szanto et al. 2007), although up to 25% of N within the manure can be lost through the volatilisation of NH_3 and N_2O emissions when compost is actively aerated (Osada et al. 2000).

Agricultural benefits of forced aeration - A study by Janzekovic et al. (2005) determined several agricultural benefits related to aeration. Liquid manure that has been aerated can be spread more uniformly on agricultural land as it runs off the plants and enters the soil to root depth more rapidly, reduces the risk of contamination or burning of meadow plants. Odours in aerated liquid manure were greatly reduced. The resulting manure contains less NH_3 and is partly sterilised, therefore, it can be used during vegetation that can extend the period that manure can be applied. This in turn reduces the amount of storage space that is required thus cattle do not have to wait as long to graze due to the reduced odours compared to the spreading of liquid manure that has not been aerated. Deposits do not form in aerated uniform liquid manure, which means that it is easier to pump and to transport. While aeration can be expensive due to the investment, operating, and maintenance costs involved, it is still a cheaper option than mechanical liquid manure mixing.

Naturally aerating manure during composting is a low-cost option that requires a low-energy input and is suitable for implementation in small to medium sized farms. It is a cost-effective way to improve the recycling of N within a farmyard, resulting in a better-quality fertiliser and reductions NH_3 emissions (Oudart et al. 2015). As long as the initial mixture is suitable, a naturally aerated compost pile results in the same final product as a forced-aeration compost at a lesser cost (Solano et al. 2001).

Reduced emissions - Sommer and Møller (2000) found that there were no CH_4 or N_2O emissions from manure piles that contained a higher straw content in deep litter pig management systems due to the decreased litter density, while emissions were detected in the piles that were more anoxic. This may be due to the typically larger pore spaces within the piles mixed with straw, which will improve aeration (Thompson et al., 2004). Passive composting or compost piles that are poorly aerated produce greater temperatures and may result in anoxic areas within the pile that can lead to increased emissions of NH_3 and N_2O (Park et al., 2011).

Reduced odours - Janzekovic et al. (2005) found that the odour from the aerated liquid manure was greatly reduced when sprinkled. Odour reduction is caused by the oxidation of the NH_3, which promotes the performance of the aerobic bacteria and thus reducing the decomposition of organic matter within the manure.

3.5 Mechanical intermittent aeration during storage (in composting)

Manure handling/quality/cost reduction

Benefits of intermittent aeration - While mechanical intermittent aeration is thought to be a more expensive option, there have been studies that have focused on reducing the cost and energy expended in the production of compost. Airflow reduction can cause a temperature increase in the compost that can lower the oxygen concentration within the pile, which will decrease the rate of composition. However, a higher temperature will lead to a decrease in fan costs. A reduction in airflow can reduce odour emissions as long as aerobic conditions are maintained (Keener et al., 2005).

Reduced emissions - Intermittent aeration results in a reduction of greenhouse gas emissions when compared to continuous aeration (Keener et al., 2001).

3.6 Solid separation/manure separation

Manure handling/quality/cost reduction

Reduction in management costs - Solid-liquid separation can potentially reduce the costs linked to the management of pig manure. Liquid pig manure contains high levels of N and should not be applied to land that contains an N limit of 170 kgN ha^{-1} yr^{-1} according to the EU Nitrates Directive (1991) (Dennehy et al., 2017). Unseparated pig manure is also not suitable for spreading on land with a high P content, which can limit the areas in which the pig manure can be spread (Hansen et al., 2006). If pig manure is unsuitable for spreading on nearby land then this may require the farmer to travel a great distance to dispose of the manure (Møller et al., 2000) resulting in greater costs related to the management of the manure (Deng et al., 2014). Solid-liquid separation can be used to separate the solid, nutrient rich portion of the pig manure from the liquid portion, thus the solid manure can be transported to land away from the farm that has a requirement for nutrients while the liquid manure can be spread closer to the farm without violating the set limits for P or N (Dennehy et al. 2017) reducing management costs (Burton 2007).

Further uses for the solid and liquid components - Dennehy et al. (2017) reported that solid-liquid separation could make manure suitable for further treatments such as composting or biological wastewater treatment. Additionally, Henriksen et al. (1998) found that the solid portion of the manure can be used to produce compost or used in anaerobic dry digestion.

Recycling of materials within the separated manure - Reusing certain components of treated manure can reduce management costs. Recycled water obtained from the liquid portion of the manure can be used for floor washing and/or manure flushing while the large fibres obtained from the solid portion can be reused as cow bedding (Gooch et al., 2006). Leach et al. (2015) determined that using recycled manure solids as bedding material can be advantageous for UK farmers with regards to convenience, availability, and economics.

However, risks can be associated with this practice so farmers should be cautious if implementing this option and follow the recommended strategies for mitigating risk.

Reduced storage costs - Møller et al. (2000) determined that solid-liquid separation can greatly reduce the size of the storage vessels for the manure which can result in a significant cost saving.

Reduced odours - By removing the coarse particles from the manure during solid-liquid separation, coarse particles experience decelerated deterioration, which can decrease the capacity for odour generation from animal manure during storage. By removing these particles, the oxygen transfer will have a greater efficiency resulting in a more stabilised liquid manure (Ndegwa, 2004). Furthermore, a past study by Ndegwa (2003) found that very fine particles may need to be removed from the manure to significantly reduce odours during the storage of manure.

3.7 Manure acidification

Manure handling/quality/cost reduction

Bacteria reduction - Zhang et al. (2011) determined that pathogenic bacteria present in the liquid pig manure was greatly reduced when the manure was diluted either 16 or 64 times, after 20 and 21 days of acidification. Manure that has been acidified should have a diminished effect on environmental pollution as well as containing less pathogens that are harmful to humans.

Reduced NH_3 emissions - Manure can undergo acidification to reduce NH_3 emissions, the acidic environment keeps the NH_3 in its soluble form of ammonium. (McCrory and Hobbs, 2001; Cocolo et al. 2016).

Aids solid-liquid separation – Cocolo et al. (2016) found that acidification reduced the size of the particles within the manure, which makes it more susceptible to solid-liquid separation.

Economic feasibility and related benefits of on-farm manure acidification - Foged et al. (2012) investigated the economic feasibility of on-farm manure acidification in Denmark. At present EU regulations state that slurry tanks are not permitted to be built <300 m away from sensitive habitats such as raised bogs, heaths, or grassland. However, slurry tanks that contain acidified slurry are exempt. Sulphuric acid is added to the slurry to lower the pH to around

5.5, which results in N being bound to the slurry rather than being evaporated to reduce NH_3 volatilization. Therefore, N sensitive agricultural land that is used to rear livestock is at less risk of N precipitation. Another benefit is the greater N content in the acidified slurry that increases the value of the fertiliser.

Investment costs (2005 prices) were calculated with and without subsidies (Table 7). The subsidies obtained from a national state programme that invested in environmental technology covered approximately 40% of the costs of the acidification unit and amounted to €32,000.

Table 7. Investment costs of the slurry acidification plant, with and without subsidies (Foged et al., 2012)

	Without subsidies (€)	With subsidies (€)
Total investment	125,000	93,000
Depreciation, 6.75%, 15 years	8,438	6,278
Real interest rate payment, 3.25%	4,063	3,023
Annual capacity costs	12,500	9,300
Annual capacity cost per m^3 treated biomass	1.25	0.93

Costs involved with the running of the acidification plant include the electricity to run the unit, acid required for acidification, and costs related to maintenance (Table 8). While the amount of electricity required is dependent on variables such as the length of the slurry pipes and the amount of slurry to be pumped, it was estimated that the energy required would be around 1,500 kWh per month or 18,000 kWh per annum. This amounts to an energy requirement of 1.8 kWh per m^3 of slurry. Around 5-7 kg of sulphuric acid is required per 1,000 kg of livestock slurry to reduce the pH from 7.0 to between 5.5 and 6.0. This study found that 4-5 kg of sulphuric acid was used per tonne of slurry at a cost of between €0.10 and €0.24 kg^{-1} of acid, which amounts to approximately €0.72 t^{-1} of slurry.

Table 8. Operational costs categories (Foged et al., 2012)

	€ yr^{-1}
Energy consumption	1,680
Acid consumption	7,200
Maintenance and service contract	2,870
Total costs	11,750
Total costs/m^3 treated slurry	1.18

The increased N content in the acidified manure can result in an increase in crop yield of approximately 0.2-0.3 tonnes of grain ha^{-1}, resulting in an increase in income (Table 9). In addition, the sulphuric acid increases the amount of sulphur within the treated slurry and therefore negates the requirement for the purchase of sulphuric fertiliser.

Table 9. Income categories (Foged et al., 2012)

	Theoretical income, €/year

Value of higher yields/ha due to higher N application according to the acidification of slurry*	1.45
Treated amount of slurry (t yr^{-1})	10,000
Total income (€ yr^{-1})	14,500
* estimation based on scientific literature and experiments (€ t^{-1} slurry)	

Taking into the account the money required for investment and the increased income due to a greater crop yield, it was possible for Foged et al. (2012) to determine the net cost per unit which was €6,500 and €9,750, with and without subsidies (Table 10).

Table 10. Net cost per unit (€), without and with subsidies (Foged et al., 2012)

Net cost/unit	Without subsidies (€)	With subsidies (€)
Capacity costs	12,500	9,300
Operational costs	11,750	11,750
Income	14,500	14,500
Net costs, total per annum	9,750	6,500
Net cost at 10,000 tonne treated slurry per annum (€ m^3)	0.98	0.66
Net cost at 47,200 kg N-total treated per annum (€ kgN-total)	0.21	0.14

Reduced odours - Acidification also controls H_2S emissions, which was one of the main causes of farmyard odours as well as CH_4 emissions (McCrory and Hobbs, 2001; Cocolo et al., 2016).

Biogas production - Acidified liquid pig manure can create organic compounds that have a low molecular weight which are ideal materials for use in the biogas industry. During anaerobic treatment, acetic acid and hydrogen are produced by the degradation of butanoic acid, propanoic acid and valeric acid by means of hyrdogen producing acetogenic bacteria. The more organic acids that are contained within the liquid pig manure results in a greater amount of CH_4 produced by methanogens in a wastewater treatment system (Zhang et al., 2011) as methanogens produce CH_4 by utilizing the acetic acid and hydrogen (Ren and Wang, 2004).

Improved crop yield

Foged et al. (2012) found that acidified manure resulted in a higher crop yield due to the higher N content in the manure.

3.8 Decreasing temperature and/or storage time

Manure handling/quality/cost reduction

Reducing risk of manure degradation - The degradation of the organic fraction within the manure is directly influenced by storage time; therefore solid-liquid separation should be carried out as soon as possible to ensure optimum efficiency (Kunz et al. 2009). Storage time and temperature, as well as the initial quality of the manure, can also change the efficiency for solid-liquid separation because of the biological activity that occurs in the manure during storage that can change the composition of the manure (Ndegwa et al. 2002).

Reduction in microbial activity and reductions - When manure is stored in a facility below ground level, the resulting lower storage temperature reduces microbial activities (Alberta Agriculture and Forestry, 2005). A study by Massé et al. (2008) found that manure initially stored at a temperature of 20°C starting emitting CH_4 right away, while the manure that was stored at an initial temperature of 10°C did not emit CH_4 until after a lag phase of around 250 days when the temperature had increased to 20°C, which is generally longer than the majority of storage periods between two land applications.

Reduction of odours - An increased storage time is thought to be responsible for the production and volatilization of compounds that are accountable for the creation of odorous emissions (Lo et al., 1994).

Biogas production - Organic matter in stored slurry breaks down with increasing temperature and storage time. A study undertaken by Browne et al. (2015) compared biogas production from manures that were stored over varying times and temperatures. The manure that was stored at 20°C over a period of 26 weeks resulted in a biogas production that was 32% of the manure that was stored at 9°C over the same timescale. Slurry that was stored at 20°C showed no impact on biogas production until week 8 which suggests that there is a depletion of substrates that are available for digestion. This result is similar to that of Steed and Hashimoto (1994) where they found that the biochemical methane potential (BMP) of cattle manure that was stored for 5 months at 20°C had been reduced by 55% when compared against the BMP of cattle manure that had been stored at 10°C for the same length of time.

3.9 Litter stacking

Manure handling/quality/cost reduction

Use as a fertiliser - A study by Sagoo et al. (2007) found that crop N recovery was increased in broiler litter that was sheet-stored over the winter period and incorporated into the soil within 4 or 24 hours after spreading. The results were compared to conventionally stored broiler litter that was spread on the surface. The crop N recovery was up to 20% and 7.6% respectively as a percentage of total N within the store. By maximising crop N recovery, there was less mineral N available that could be lost in the soil, which reduces the amount of N that could be lost to the environment. An increase in N recovery would result in a greater amount of N within the manure that would increase the value of the fertiliser while reducing the requirement for inorganic N fertilisers. Hamdar and Rubeiz (2000) determined that poultry litter could be used in greenhouses growing strawberry plants as an economically attractive source of N. Composted poultry litter has the potential to improve the quality of the crop while improving the quality of the soil.

Use as a feed ingredient - Broiler litter that has undergone deep stacking contains high amounts of protein and minerals, making it suitable for use as a feed ingredient for ruminant livestock. It is already widely used by sheep and cattle farmers due to its inexpensive nature. While deep stacking of broiler litter had no effect on its chemical composition, it did destroy pathogens such as *E. coli* and *Salmonella*, which were deemed to be at an acceptable level. Litter that has been deep stacked was also devoid of fecal and total coliforms (Elemam et al., 2010). This option is of particular interest to developing countries where feed cost amounts to around 70-75% of the overall production costs. These are costs that are far greater than the 50-60% in developed countries (Nwogu et al., 2003). There are high levels of calcium, N, and P in poultry manure, which make it an ideal feed ingredient; and ruminants are known for their ability to digest feedstuffs that are not suitable for other livestock. By utilizing deep stacked poultry litter as a feed ingredient, it reduces the amount of waste requiring to be disposed of while supplying farmers with a low-cost protein-rich feed (Talib and Ahmed, 2008).

Improved crop yield

Composted poultry litter has the potential to improve the quality of the crop while improving the quality of the soil (Hamdar and Rubeiz, 2000).

Soil security

See Section 3.9: Manure handling/quality/cost reduction (Improved crop yield)

3.10 Anaerobic digestion

Manure handling/quality/cost reduction

Production of a more efficient fertiliser - Möller and Müller (2012) conducted a review that found anaerobic digestion of manure resulted in an increase of 10-25% of N availability in digestate when compared to untreated manure. This produces manure that is more efficient, which reduces the requirement for chemical fertilisers.

Economic feasibility of on-farm anaerobic digestion - Meinen et al. (2014) determined that eliminating the requirement for an on-farm post-digestion storage construction increased the economic feasibility of anaerobic digestion. This was achieved by creating underfloor manure storage pits underneath the pigs' living space. The storage pits were used to store the pig manure until it was ready to be collected for use in the digester and also then stored the post-digested manure.

The project costs totalled $242,033.83 ($55.01 pig space^{-1}). Grant funding from various sources amounted to $199,613.53, which left the producer with a loan of $42,420.30 ($9.64 pig space^{-1}). This resulted in a monthly payment of $478.54 over a period of 8 years at a rate of 2% interest.

The amount of electricity purchased from the grid equalled 606,161 MJ over a 24-month steady-state period that amounted to 25,257 MJ month. The purchase of this electricity, at a cost of $0.0187 MJ^{-1}, resulted in an income of $11,450 which was slightly higher than the energy costs that totalled $11,333.94 over 24-months ($472.25 month^{-1}). The electricity produced by anaerobic digestion supplied 50.3% of the electricity required to power the manure treatment system as well as the swine buildings.

The monthly electric production amounted to $477.10, which was similar to the monthly debt of $478.54. Therefore, this option will only be economically feasible with external funding and a low-interest loan.

Biogas production – Anaerobic digestion results in the production of biogas that can be used to replace fossil fuels, which is why this option is classed as one of the most sustainable methods of treating waste and/or wastewater (Passos et al., 2017). This option produces a carbon-neutral energy source that also reduces CH_4 emissions (Sommer et al., 2002). The biogas can be used for a variety of uses, after some refinement, such as heating application, the running of vehicles, and the production of electricity, all of which reduce the requirement for fossil fuels (Neshat et al., 2017).

Improving biogas recovery - One problem with generating biogas from poultry manure is the restriction presented by the low C:N ratio and the N- and NH_3-rich compounds (Tian et al., 2015). A higher yield of biogas can be obtained through co-digestion of the poultry manure with an energy-yielding substrate, resulting in a greater microbial diversity (Khoufi et al., 2015). To improve the biomass recovery the lignocellulosic biomass in the co-digestor should be treated to improve the digestion efficiency (Abudi et al., 2016), as the cellulose-hemicellulose-lignin matrix is resistant to biodegradation by anaerobic microorganisms (Jaffar et al., 2016). Dahunsi et al. (2017) investigated the co-digestion of poultry manure with *Arachis hypogaea* hulls. A higher biogas yield was obtained by using a thermo-alkaline pre-treatment before anaerobic digestion at a solid loading of 35 gTS L^{-1} that resulted in a net electrical energy of 303 kWh t^{-1} TS. An economic benefit can be achieved by injecting the energy directly into the national grid or by selling it at a certain rate.

3.11 Feeding nitrate supplementation

Improved diet/efficiency/yield

Source of nitric oxide - Studies have found advantages to including nitrate in livestock diets, as dietary nitrate is a source of NO, which has valuable pharmacological benefits in humans (Lundberg et al., 2008; Gilchrist, 2010). Nitric oxide is formed when microbes within the mouth reduce ingested nitrate to nitrite, which is then reduced to NO through the acidic conditions in both the mouth and the stomach. Some of the benefits associated with NO include the destruction of acid-producing organisms such as pathogens, the stimulation of advantageous nitrated lipids which play an important role in cell-signalling, and the protection against gastrointestinal ulcers and infections (Lee and Beauchemin, 2014).

Reducing toxicity related to nitrate supplementation - The addition of nitrate to livestock feed can result in nitrate poisoning, however, the risk of nitrate toxicity can be reduced by gradually acclimatising the livestock to the nitrate or feeding nitrate at lower levels (Lee and Beauchemin, 2014). In vivo studies conducted by van Zijderveld et al. (2011) and Li et al. (2012) managed to reduce enteric CH_4 emissions through nitrate supplementation without any clinical signs of toxicosis.

Reduced CH_4 emissions - A study by Sun et al. (2017) found that the CH_4 yield was reduced by 31.1% when nitrate was added to the diet of cattle. Results were reported as 15.7 g CH_4 kg^{-1} dry matter intake (DMI) when nitrate was added and 22.8 g CH_4 kg^{-1} DMI from the control diet. In addition to mitigating CH_4, the nitrate also increased the digestibility of dietary crude protein. Other benefits of nitrate supplementation include increased daily weight gain and improved productivity from a low-N diet (Nguyen et al., 2016) as well as a greater concentration of milk protein (van Zijderveld et al., 2011). In Australia using nitrate to mitigate CH_4 emissions from livestock can be used by farmers to earn carbon credits as part of Australia's Carbon Farming Initiative (Department of the Environment and Energy, 2013).

Economic benefits

Decreased requirement for expensive protein supplements - The addition of nitrate to livestock feed can have nutritional benefits related to protein nutrition (Yang et al., 2016). The reduction of nitrate is advantageous with regards to thermodynamics (Guo et al., 2009) and in certain microbial species nitrate reduction is associated with the synthesis of adenosine triphosphate by means of electron transport-linked phosphorylation (Yoshii et al., 2003). This will result in an improved circulation of microbial protein as a result of rumen fermentation and a greater growth yield of nitrate reducing organisms. Additionally, nitrate additives will lead to a reduction in the amount of protein supplements that are required due to the improved N content within the diets of ruminant livestock. However, it is noted that this option will reduce the efficiency of N utilisation if the livestock are either grazed on tropical forages or if excessive N is supplied to the rumen (Yang et al., 2016).

3.12 High fibre and/or low protein diet

Improved diet/efficiency/yield

Benefits related to animal health and welfare - There are health benefits to using dietary fibre in pig production. Fibrous feedstuffs will decrease energy levels which is beneficial for gestating sows, as it will circumvent massive weight gain that can impede production performance. It can also decrease aggressive behaviour by reducing feeding motivation (Philippe et al., 2008). There are benefits to intestinal health in fattening pigs and weaned piglets. Dietary fibre can reduce gastric ulcers and protect against bacterial pathogens by strengthening the protective barrier within the intestine (Hermes et al. 2009; Laitat et al. 2015). Diets that are high in fibre can reduce NH_3 emissions, which have health benefits (Philippe et al., 2008), as these emissions can irritate pigs' respiratory tracts (Krupa, 2003). Pigs have a greater metabolizable energy efficiency when they are fed a diet that is low in crude protein (CP) due to the increased starch content. The increase in net energy content results in a greater amount of energy that will be available for fat deposition (Galassi et al., 2010). Reducing the amount of dietary CP in dairy cows diets also has health benefits. For instance, too much CP can harm reproduction and be partly responsible for lameness while reducing the amount of dietary CP to approximately 140 to 150 g CP kg^{-1} dry matter (DM) has not shown to have any adverse effects on either reproduction or lameness. A low protein diet can also increase the efficiency of urea recycling in ruminants (Sinclair et al., 2014).

Reduction in N excretion and increased milk N efficiency - Around 65% to 75% of N is lost in excretion while the rest is captured and stored within the milk (Broderick, 2003). A study by Sinclair et al. (2014) found that the capture of N was more efficient when CP levels were reduced to approximately 140 g CP kg^{-1} DM in the diet of dairy cows, resulting in less N being loss to excretion. Galassi et al. (2010) found that the amount of N excreted in urine was reduced by 6 g day^{-1}, or around 25%, when pigs were fed a high fibre diet with a reduction in CP. A diet low in CP reduced total N excretion by around 20% compared to a diet high in CP. The reduction increased with increasing fibre content. The study undertaken by Philippe et al. (2015) reported that growth performance of fattening pigs was adversely affected by a high fibre diet. However, a high fibre/low protein diet for heavy pigs reduces the amount of N excreted without threatening performance (Galassi et al., 2010).

Manure handling/quality/cost reduction

A high fibre/low protein diet for heavy pigs reduces the amount of N excreted without threatening the performance of fattening pigs (Galassi et al., 2010).

Economic benefits

Broderick et al. (2006) found that the cost of milk production was greater due to the large amounts of N being lost to the environment through excretion compared to the amount of N that was secreted in the milk. Protein supplements are expensive. Since such a large quantity of N is lost through excretion it would be more cost effective to feed dairy cows a low protein diet, which would result in an increased profit margin (Broderick, 2003). A study by Corea et al. (2017) determined that reducing the amount of CP to 155 g kg^{-1} DM from 170 g kg^{-1} DM resulted in a reduction in the cost of feed that increased income as well as N excretion and milk urea N (MUN). The reduction in CP did not affect milk yield or the milk components and increased the efficiency of N secretion in the milk. Roseler (1990) determined that the cost of feeding excess protein to dairy cows in the New York State dairy industry resulted in an annual cost of around $23.6 million, which amounted to a cost of $0.09 cow^{-1} day^{-1}. It was thought that the concentration of MUN could be used to determine if livestock diets contained too much protein that could result in a saving of around \$3.96 cow^{-1} if this approach was implemented. Although Buza et al. (2014) thought that the quality of the feed may affect profit margins and income over feed cost more than the cost of the ingredients as increased production was associated with high feed costs; therefore, an increase in production and profitability may be achieved by means of more favourable feed formulation rather than low-cost strategies such as a reduction in dietary CP.

3.13 Higher forage digestibility

Improved diet/efficiency/yield

Oba and Allen (1999) found that the digestibility of neutral detergent fibre (NDF) from forage greatly improved milk yield and DMI. An increase of in vitro or in situ NDF digestibility by one-unit resulted in a 4% fat-corrected milk increase of 0.25 kg and a DMI increase of 0.17 kg. Krämer-Schmid et al. (2016) determined that improved NDF digestibility resulted in an increase in DM digestibility and organic matter as well as an increase in milk yield and live weight gain. When the coefficient of NDF digestibility of maize silage was increased by 0.01 the daily milk yield increased by 0.082 kg while daily weight gain increased by 0.012 kg. According to Salinas-Chavira et al. (2013) total tract NDF digestibility was not affected by the source of forage, although it was found that NDF digestion was better for 80 g kg-1 of forage NDF compared to 40 g kg-1.

3.14 Feed processing

Improved diet/efficiency/yield

Enhanced starch digestibility and utilisation - Ruminants are fed grains as they have a high starch content which facilitates a high energy density that supports production. Feed processing can improve the digestibility of starch by means of thermal or mechanical processing procedures. Although ruminal starch degradation can be sped up with extensive grain processing, which can increase the risk of rumen fermentation ailments. Substances such as sodium hydroxide (NaOH) and formaldehyde can be used in feed processing. NaOH promotes whole grain degradation in the rumen that can save money by removing the need for grinding while formaldehyde impedes the degradation rate of starch and proteins in the rumen. While these treatments can improve digestibility and reduce the risk of fermentation ailments, they can also be highly corrosive and pose health risks (Humer and Zebeli, 2017).

Enhanced nutritive value of grains - Chemical grain processing methods, such as mild organic acids, like lactic acid, have been found to enhance utilisation of P, which is organically bound. In addition to starch, grains also provide protein and essential minerals, particularly P, in ruminant diets. Chemical treatment increases the availability of P for rumen microbes that can increase the nutritional value of the grains and reduces the requirement for inorganic P, which in turn reduces the amount of P lost through excretion in high producing ruminants (Humer and Zebeli, 2015).

Prevention of possible mycotoxin contamination of feed - Feed processing can help prevent feed becoming contaminated with mycotoxins. Mycotoxins are able to enter the feed chain quite easily as they are hard to eradicate (Jard et al., 2011). Post-harvest removal strategies are being investigated, as preventative measures, to combat the formation of mycotoxins in the field are generally unsuccessful. Several chemicals such as NaOH, NH_3, and formaldehyde react with mycotoxins that either destroys them or reduces them to a compound that is less toxic (Kabak et al. 2006). The quantity of mycotoxins in animal feeds can potentially be reduced through the use of mild organic acids such as citric or lactic acids (Jalili et al., 2011; Humer et al., 2016).

Reduced degradation of nutrients - Ammonia can also reduce degradation of ruminal nutrients, starch, and proteins. Ammonia has the benefits of increasing the amount of crude protein in the treated grains while preserving whole high moisture grains. Organic acids and their respective salts can improve the digestibility of nutrients in ruminants while also improving their energy balance in a manner that is considered to be safe (Humer and Zebeli, 2017).

Manure handling/quality/cost reduction

See Section 3.14: Improved diet/efficiency/yield (Enhance nutritive value in grains)

3.15 Plant bioactive compounds

Improved diet/efficiency/yield

Improved animal health and productivity - The addition of plant bioactive compounds (PBC) to ruminant feed can aid animal health by improving the efficiency of rumen fermentation. Health benefits can include a reduction in the production of CH_4, decreased nutritional stress that is induced by bloating or acidosis, or improving advantageous elements of N metabolism (Salem, 2012).

Improved productivity - A study by Hu et al. (2006) found that daily supplements of 3 g day-1 of tea saponins improved the efficiency of feed conversion and daily weight gain in goats. Condensed tannins (CT) found in temperate forages were found to reduce the degradation of CP in ruminants at a lower amount of 20-40 g kg-1 DM, another benefit was the greater absorption of amino acid within the small intestine which improved productivity (Min et al., 2001). The addition of tannins were found to have several potential benefits in ruminants, such as increases in milk yield, weight gain, and wool growth as well as improving reproductive performance (Patra and Saxena, 2011); however, tannins included in dairy diets could have an adverse impact on diet digestibility (Cieslak et al., 2012). Rochfort et al. (2008) found that tannins affected feed intake when they reached a certain level, although this was dependent on the species of animal studied. Forages such as *L. corniculatus* were found to increase the milk yield of ewes throughout the spring and summer months. They contained 44.5 g kg-1 DM CT, which is near the limit that has been reported for a favourable effect for ewes.

Improved meat quality - A decline in meat quality is caused by lipid oxidation that occurs during the processing and storage of meat. Lipid oxidation results in drip loss, discolouration of meat, adversely affects the smell and flavour, can change the nutritive value, and decrease the shelf-life of the product (Nissen et al., 2000). A study by Zhong et al. (2009) found that the quality of goat meat was improved through the addition of a tea catechin (TC) supplement, which is thought to be an encouraging natural antioxidant. A suitable amount of dietary TC can prevent lipid oxidation that would result in an improved meat colour while reducing the drip loss of fresh meat. The effects of TC supplementation were dependent on a dosage of 3000-4000 mgTC kg-1 feed and a feeding period of 40 to 60 days.

Potential to reduce *Escherichia coli* - The purple prairie clover (PPC) is a native legume that can be found in the prairies of North America. The PPC contains a large amount of CT that have been shown to protect against *E. coli* O157:H7 without negatively affecting digestion (Jin et al., 2012). A 2-year grazing experiment conducted by Jin et al. (2011) found that cattle contained reduced fecal counts of generic *E. coli* when they were grazed on native pasture that contained PPC when compared with cattle that grazed on pastures that did not contain PPC.

Alternatives to synthetic chemicals - In 2006 the use of antibiotics in animal feed was banned by the European Union. The use of PBC is being researched to determine whether they can improve animal health, particularly that of ruminants. Replacing synthetic chemicals with PBC would not only benefit the environment, and possibly animal health (Rochfort et al., 2008), but they could provide an alternative option that is sustainable and generally inexpensive. However, more research is required before PBC could be endorsed for use in animal production systems (Durmic and Blache 2012).

IV. Conclusion/recommendations

The negative effects of climate change have resulted in the necessity of identifying GHG sinks and sources, and the reporting of GHG emissions in national databases. Greenhouse gas calculators are becoming increasingly popular as they allow the user to calculate emissions associated with a variety of activities, including those in the AFOLU sectors. The CCAFS-MOT is a GHG calculator that identifies emissions related with current agricultural management practices and provides a list of mitigation options that are ranked according to potential. By implementing management practices that focus on mitigation, carbon and other emissions can be removed from the atmosphere and sequester them in the soil. The CCAFS-MOT is a freely available excel-based tool that can be used worldwide by a variety of users such as policy makers, researchers, farmers, and educational institutions.

While the mitigation of GHG emissions is the primary aim of the CCAFS-MOT, this report has investigated the co-benefits associated with each of the mitigation options listed in the tool. It has been determined that co-benefits can include increased crop and livestock yield, improved soil health and fertility, and reduced production costs, compared to current agricultural management practices. An increase in crop and/or livestock yield can aid food security while reduced production costs can help alleviate poverty in developing countries by increasing household incomes.

Implementing agricultural practices that can reduce GHG emissions with little to no adverse effects is crucial in aiding food security and improving resilience against the negative effects of climate change.

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