Economic assessments of practices and policies to address climate change and sustainable development for agriculture at global, regional and farm population scales

A Dissertation submitted by

Benjamin B. Henderson, M. Sci.

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UNE Business School

University of New England

Armidale, NSW, Australia

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Certification of Dissertation

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

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Signature of candidate   Date

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Signature of Supervisor/s   Date

Abstract

The objective of this thesis is to address knowledge gaps, which can assist policy makers in preparing the agriculture sector for the challenges of addressing climate change. A range of methodologies are employed at different scales for these purposes. These include a global bio-economic analysis and a global computable general equilibrium model to assess the global scale abatement potential of the ruminant sector (inclusive of cattle, sheep and goats), and the economic consequences of policies employed to achieve this potential. With the inevitable emergence of climate change policies and growing consumer expectations for improved environmental performance, these global analyses reveal that there is reasonable potential for the ruminant sector to contribute to global greenhouse gas (GHG) mitigation efforts, with the associated effectiveness and economic impacts varying widely depending on the choice of policy. The global scale analyses are complemented by a range of modelling assessments at the region and farm population scale in different smallholder production contexts, which reveal that there are also opportunities to exploit synergies between agricultural development, and climate change mitigation and adaptation objectives. It should be noted, however, that the global scale models are not formally linked to the smaller scale models (i.e. changes in the price and quantity variables in the global models are not used to update any of the variables in the smaller scale models).

It was shown that the global abatement potential for the ruminant sector indicated by the marginal abatement cost curves constructed in this thesis, could be substantially amplified by a global carbon tax. However, due to its disproportionately harmful impacts on ruminant production in low income countries, the overall merit of this policy option is questionable. In contrast, the use a producer subsidy to compensate producers for their tax expenses could effectively address these issues, albeit for a much reduced global mitigation potential. Another key insight of this research is that a carbon tax could restructure the global cattle sector, increasing the share of cattle meat supplied by the dairy sector relative to the beef sector.

Closing yield gaps for mixed smallholder farmers in several parts of Sub Saharan Africa, without the introduction of new technologies, could provide marked benefits for smallholder incomes and food supply, and reduce GHG emission intensities of production. Similarly, the intensification of beef production in Eastern Indonesia with improved feed from tree-legumes could deliver large

increases in production and smallholder incomes and also lower the emission intensity of beef products. This innovation also has good potential for scaling up and is likely to benefit multiple value chain participants. It was also found that the costs of climate change could be partially offset by interventions based on increased fertilisation and the retention of crop residues for a population of mixed smallholder farmers in Sub Saharan Africa. Significantly, vastly different conclusions about the economic desirability of these practices were apparent when assessing their performance through the lens of the aggregate population, compared to considering the impacts on individual farms within the population.

Despite the large variation in scales and methods utilised in this thesis, a number of cross-cutting themes emerged from the analyses. For instance, the economic advantages of targeting sectors and producers with practices that can contribute to climate change mitigation and adaptation for the least cost or highest return, were apparent at different scales of analyses. Related to this, positive synergies between producer profits and mitigation or adaptation outcomes were also found across the analyses, for a range of improved practices and policies. Further, benefits from the integration of crop and livestock enterprises were apparent in the different analyses, although some practices were shown to generate trade-offs between these enterprises. Finally, all the studies in this thesis touched upon the challenges associated with barriers to the adoption of improved practices.

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Chapter 1: Introduction

1.1 Background

Agriculture as a sector contributes substantially to climate change, with 5.0-5.8 $GtCO_2eq$ of emissions per year during 2000-2010, representing 10-12% of global anthropogenic greenhouse gas (GHG) emissions. There were a further 4.3-5.5 $GtCO_2$-eq of emissions from land use and land changes during this period (Smith et al. 2014), much of which was caused indirectly by agriculture. Moreover, global emissions from agriculture are increasing. Developing countries are the largest and the fastest growing source of direct and indirect agricultural emissions. Between 2000 and 2010, OECD countries as a whole have experienced a slight reduction in emissions, as productivity growth has contributed to a 2% fall in the emission intensity of agricultural output (MacLeod et al. 2015).

The main sources of agricultural GHG emissions are nitrous oxide (N_2O) emissions from soils, fertilisers, manure and urine from grazing animals; and methane (CH_4) emissions from ruminant animals (e.g. cattle, sheep and goats) and paddy rice cultivation. Both of these gases have a significantly higher global warming potential than carbon dioxide. Among the various agricultural sectors, 80% of these non-CO_2 emissions come from livestock (Havlik et al. 2014). Tubiello et al. (2013) provide a breakdown of global GHG emissions from different agricultural sources, based on Tier 1 emission equations specified by the Intergovernmental Panel on Climate Change (IPCC, 2006). According to their calculations the sources of livestock emissions, in order of importance, in 2010 were: enteric fermentation (2,018 $MtCO_2$-eq), manure deposited on pasture (764 $MtCO_2$-eq), manure management (353 $MtCO_2$-eq), and manure applied to soils (116 $MtCO_2$-eq). Ruminants account for all of the first of these two emission sources, which comprise 86% of all livestock emissions, and they make a partial contribution to the last two. Of the 2,782 $MtCO_2$-eq of emissions from enteric fermentation and manure deposited on pasture in 2010, the following percentage contributions from different animal types were provided by Tubiello et al. (2013): non-dairy cattle (56%); dairy cattle (19%); buffaloes (11%); Sheep (7%); goats (5%); and others (3%). The growth of emissions from ruminants and the use of synthetic fertiliser has been the most rapid in the agriculture sector between 1990 and 2014 (Blandford and Hassapoyannes 2018).

In order to tackle climate change effectively and efficiently, agriculture must do its part. This will become increasingly important over time, given that agriculture has received less consideration in GHG mitigation policies compared with energy and other sectors (Bajzelj et al. 2014). Scenarios show that non-CO_2 emissions, mainly from agriculture, will become the largest source of global emissions as other sectors are projected to mitigate their emissions much more effectively by mid-century (Gernaat et al. 2015; Wollenberg et al. 2016).

Following the Paris Agreement at the 21st session of the Conference of the Parties (COP 21) to the United Nations Framework Conventions on Climate Change (UNFCCC), support for stronger mitigation efforts to slow down global warming has been growing. Importantly, there also appears to be trend towards inclusion of agricultural emissions in national mitigation plans. The Paris Agreement, which has been ratified by 195 Parties to the UNFCCC, aims to strengthen global mitigation efforts and keep global warming to well below 2°C above pre-industrial levels this century. The growing trend towards the inclusion of agriculture in national mitigation plans, is reflected by the vast majority of signatories to the Paris Agreement including agriculture in their Nationally Determined Contributions (NDCs) to mitigation. Of the Parties that include mitigation targets in their NDCs, 103 include targets related to agriculture, however, only nine Parties provided specific percentage goals for reducing agricultural emissions. Furthermore, pledges were limited to technical options, usually targeting improvements in efficiency and productivity, without specifying how these targets will be pursued (Richards et al. 2015). Despite the recent progress in commitments to reduce emissions, the national pledges under the Paris Agreement are not sufficient to achieve the global target of keeping global warming below 2°C by the end of the century (UNEP 2017, Kitous et al. 2016).

In the absence of specific details on targets and policy options both nationally and internationally, there is the opportunity in this thesis to explore how policies in agriculture could contribute to global mitigation efforts. To reduce agricultural GHG emissions in the same proportion as emissions from other sources to meet the less than 2°C target, agricultural emissions would need to be reduced by two-thirds, while at the same time increasing total food supply by 70% in response to higher global demand by consumers by 2050 (Adhya et al. 2014). Most of this increase in production will come from livestock, mainly due to the changes in consumption patterns associated with growing per capita incomes in developing countries (Bennetzen et al. 2016). Wollenberg et al. (2016) identify a more reasonable contribution of 1 $GtCO_2e$ yr^{-1} of non-CO_2 emissions (~10% of direct agricultural GHGs) per year in 2030 for the 2°C target, taking into consideration agriculture's mitigation costs relative to other sectors in the economy and the importance of not worsening existing rates of food security. However, the authors show that relying on carbon prices of 20 USD per tCO_2e and available practices to lower non-CO_2 emissions could only reduce emissions by up to 0.40 GtCO2e yr^{-1}. Therefore, both higher carbon prices and mitigation from additional sources, such as the sequestration of soil carbon on agricultural land, would also be needed.

With awareness about agriculture's contribution to climate change increasing, the sector will eventually have to adjust to emerging carbon policies and consumer concerns. The overriding challenge for the sector is to meet these demands in the context of increasing competition for resources and changing climatic conditions, without compromising food security and livelihood improvement priorities for farmers in low-income countries. Given their dominant contribution to global GHG emissions, mitigation opportunities associated with ruminant livestock production will be one of the main focus areas of this thesis. Further, with most of these emissions and the negative impacts from climate change generally being located in low-income countries, the thesis will also focus on the contribution of sustainable development options to climate change mitigation, adaptation and the improvement of farm incomes.

1.2 Abatement opportunities and adaptation challenges

There are five categories of options available to reduce GHG emissions from livestock production, which target: 1) the reduction of animal emissions from enteric fermentation; 2) the reduction of animal emissions from manure handling, storage, and management; 3) the enhancement of carbon stocks in the soils of grazing lands; 4) the prevention of carbon stock losses from the clearing of naturally vegetated land for grazing; and 5) all the above sources of mitigation by improving production efficiency. The first category includes a range of dietary additives and feed digestibility improvements that can lower CH_4 emissions per ruminant animal and can also increase productivity. Several chemical compounds, including ionophores, proprionate precursors, electron receptors (such as nitrates), dietary lipids, and plant bioactive compounds have shown promise and have been tested as options for suppressing enteric CH_4 emissions (Hristov et al. 2013). Among these additives, dietary lipids and nitrates stand out as the most effective and feasible options (Hristov et al. 2013, Henderson et al. 2015). Other measures, including vaccines against rumen methanogens have shown promise, but are still under development (Gerber at al. 2013a). Increasing the digestibility and energy content of livestock feeds and forages is another effective approach for reducing enteric CH_4, particularly in developing countries where feed quality is low. Measures for increasing the digestibility of forages and fodder include replacing grass silage with corn silage, introducing legumes into grass pastures, and treating straws with urea (Hristov et al. 2013; Gerber et al. 2013a). Another approach is to introduce concentrate feeds, including cereal grains, into ruminant rations (Herrero et al. 2016; USEPA, 2013). The second broad category of mitigation options covers improved manure management methods to lower CH_4 from manure stored under anaerobic conditions and reduce N_2O emissions from manure applied to agricultural land . Most of these methods focus on reducing CH_4 emissions from manure stored in slurries, by covering them with permeable or impermeable membranes and in some cases the accumulated CH_4 is combusted to produce electricity of heat (Hristov et al. 2013). Anaerobic digestion of stored manures to lower CH_4 emissions and generate electricity or heat is also a recommended mitigation practice, with a range of digester options available to suit different production systems in developed and developing countries (UESPA 2016). However, there are limited opportunities for these manure management and treatment options in most ruminant production systems because most manure is deposited in fields while animals are grazing and/or collected once dried (Smith et al. 2008). There is arguably larger mitigation potential associated with measures that aim to reduce N_2O from manures applied to croplands, including the matching of manure applications with plant N demands and the timing of application to avoid heavy rains (Smith and Conen, 2004), as well as the use nitrification inhibitors (Snyder et al. 2009). According to Herrero et al. (2016) and Hirstov et al. (2013), the first two broad categories of measures that target emissions from enteric fermentation and manure have the potential to mitigate up to 1 $GtCO_2$-eq yr^{-1}. In addition, there is a range of measures for raising animal and herd productivity, including improvements to animal fertility, health, genetics and nutrition, all of which can lower the size of the herd, their associated GHG emissions, and the land and resource footprint needed to generate a given level of output (Gill et al. 2009; Mottet et al.

2016). Herrero et al. (2016) estimate that these practices could lower livestock emissions by a further 0.2 $GtCO_2$-eq yr^{-1}. There are also opportunities to sequester atmospheric CO_2 emissions into soil carbon in grazing lands, including the optimisation of grazing management to maximise forage production and thereby increase carbon inputs to soil (Conant and Paustian, 2002; Holland et al. 1992) and the cultivation of grasses and legumes with high sequestration potential (Smith et al. 2014; Lal 2004). According to Herrero et al. (2016) these measures have the potential to mitigate up to around 0.8 $GtCO_2$-eq yr^{-1}. Finally, there are also substantial indirect mitigation opportunities from the avoidance of clearing native vegetation to supply additional grazing land. An important approach for achieving this is through the sustainable intensification of production, including through the closing of yield gaps, to lower agriculture's land use requirements (Smith et al. 2013).

Although the technical potential of GHG mitigation practices in agriculture has been relatively well studied, only a handful of studies have assessed the cost effectiveness of the various supply-side mitigation options described above. These include studies at the country level for the UK (Moran et al. 2011), Ireland (Schulte et al. 2012), Australia (Whittle et al. 2013) and France (Pellerin et al. 2013), and at the global level (US EPA 2013; USEPA 2006; Beach et al. 2015; McKinsey & Co 2009; Smith et al. 2007; Smith et al. 2008). According to these studies, a global mitigation potential of between 0.2 and 0.6 $GtCO_2$-eq yr^{-1} is possible for a carbon price of \$50 tCO_2-eq^{-1}. This is considerably lower than the total mitigation potential of the livestock sector, revealing that a major portion of this potential cannot be attained cost effectively. Some genetic and breeding measures appear to be cost effective across different countries, including genetic improvements to improve cattle productivity and fertility (Moran et al. 2011; Schulte et al. 2012). In contrast, the cost effectiveness of some feeding and grazing strategies that aim to increase the production efficiency of cattle herds provide much more mixed economic outcomes across different global regions (USEPA 2006). Given the above paucity of studies, more economic assessments are clearly needed to better inform policy makers about cost-effective mitigation potential of the sector.

In addition to its significant global GHG contribution, agriculture is also one of the main sectors affected by climate change. Higher temperatures, changes in the distribution of rainfall and more frequent extreme weather events associated with climate change threaten agricultural production and productivity throughout much of the world. For livestock production, these changes can have direct impacts by increasing heat stress and water scarcity, as well as indirect impacts from increased scarcity of feed and fodder, greater prevalence of livestock disease and more intense competition between sectors for resources (Thornton 2010; Thornton et al. 2009; Thornton and Gerber 2010; FAO 2009). The impacts of climate change will also be felt strongly for crops, with the area suitable for growing most staple crops in the tropics shrinking over time (Thornton et al. 2017). A possible reduction in the area suitable for growing staple crops in Sub Saharan Africa of 30-50% as a result of climate change is reported by Ramirez-Villegas and Thornton (2015).The impacts of climate change are expected to be somewhat more muted at the global average level. Nelson et al. (2013), which rely on an assemblage of climate, crop and economic models, project a mean global decline in crop yields of 17% by 2050, although after considering endogenous economic responses, the size of this yield reduction shrinks to 11%. However, when coupled with a projected increase in crop area of 11%, there is only a 2% mean decline in global production. Using a similar suite of global models, van Meijl et al. (2018) estimate a similarly small decline in agricultural production (crop and livestock) of between 0.5% and 2.5% by 2050. However, climate change is expected to present challenges to smallholder mixed farming systems in the future that could be severe in some locations, exacerbating existing challenges for the adoption of more productive practices and land consolidation (Thornton et al. 2017). Nevertheless, the flexibility of these farming systems can offer multiple options for adapting to climate change. Switching to crop types better suited to the evolving climate is one important option, as is the development of crops varieties with improved resilience to drought, salinity and pests (Thornton et al. 2017). In addition, the use of no-till combined with the retention of mulched crop residues is a widely recommended conservation agricultural practice which can improve soil health, and help conserve water (Thornton et al. 2017; Rusinamhodzi 2015). However, in a mixed production context this option can generate trade-offs where the retained residues would have otherwise been used as ruminant feed. In contrast, other options such as the addition of fertiliser in low input systems can provide synergies between crop and livestock enterprises by increasing crop yields and residue production (Rigolot et al. 2016). Finally, there may also be some beneficial impacts from climate change, such as reductions in cold stress for animals reared outside in the cooler higher latitude climates, as well as from savings in the heating costs of confined animal systems (FAO 2009; Henderson et al. 2011). Similarly, precipitation changes induced by climate change may result in higher crop yields in some parts of the world, depending on latitude and the capacity of producers to take advantage of these changes by investing in irrigation (Kang et al. 2009).

With the exception of the assessment in Chapter 6, the quantitative analyses in this thesis focus on policies and measures to reduce GHG emissions and improvements to farm performance, without simultaneously quantifying the impacts of climate change. This reflects the reliance on mainly static analytical methods in the majority of the studies in this thesis. While this is a limitation of the research is also true that if ambitious mitigation efforts are implemented, they would be likely to place a larger burden on food production and producer costs than climate change itself, by 2050 (Meijl et al. (2018); Hasegawa et al. 2015).

1.3 Synergies with development

Productivity improvements are central to most of the GHG mitigation options available to the agricultural sector, but the scope for these improvements is highly variable among regions and sectors. For example, in most OECD countries where productivity is already high due to higher levels of development and commercialisation, additional improvements will be more reliant on new innovations (Gerber et al. 2013b). There is arguably much larger potential for increasing productivity in the more traditional production systems of many low income countries. In situations where there is sufficient access to markets and capital, these improvements could come from the transfer of more advanced practices and technologies (Henderson et al. 2011; Ugalde et al. 2008). It is likely that some productivity improvements could increase manure emissions on a per animal basis, and cause higher N_2O and CO_2 emissions related to the use of fossil fuels and the cultivation of feed. However, there is evidence in some ruminant production systems that their overall emission intensity of output is reduced as production intensifies (Gerber et al. 2013b). The impacts of intensification on the emission intensity of crops is less clear, as more intensive use of fertiliser can either reduce or increase cropland emission intensities, depending on the yield response which is both crop-specific and climate-specific (Carlson et al. 2016). In contrast, the closing of yield gaps through improvements in production efficiency, which enables the production of the same or more output with fewer production inputs, can provide more assured opportunities for simultaneously delivering mitigation and development benefits (Gerber et al. 2013b).

1.4 Summary and thesis outline

Agriculture faces several future challenges related to addressing climate change and improving farmer livelihoods. Not least are the challenges the sector will inevitably confront in adjusting to emerging GHG mitigation policies and consumer expectations for its improved environmental performance . This thesis explores a range of economic options to address these issues, primarily for the ruminant sector, which is the largest GHG emitting sector in agriculture. The thesis will also focus on the contribution of options to exploit synergies between agricultural development and either climate change mitigation or adaptation objectives. In the remainder of this section, a summary of the thesis outline, including a description of the interrelationships between the various thesis chapters, is provided.

The research in this thesis is based on a number of economic assessments of measures and policies to address climate change and sustainable development for agriculture at a range of scales. The first two papers in Chapters 2-3 focus on the ex-ante economic assessment of the GHG mitigation potential of the ruminant sector at the global scale. In Chapter 2, the marginal abatement costs of a selection of mitigation practices that target soil carbon sequestration and enteric CH_4, are assessed. These marginal abatement costs are then incorporated into a global computable general equilibrium (CGE) model, in Chapter 3, to assess the global mitigation potential and economic impacts of different mitigation policies. Here it is shown that the market effects of pricing carbon can significantly add to the total mitigation potential of the ruminant sector, but at the cost of lowering production and consumption levels, particularly in the more emission-intensive sectors of low-income countries. The methods used in the global assessments are highly complementary, as the marginal abatement costs constructed in Chapter 2 are used directly to parameterise the abatement responses in the CGE model in Chapter 3. These methods were chosen due to their suitability for global level assessments and together they shed light on the different roles that technical interventions and market interactions, induced by different policy choices, can play in lowering ruminant GHG emissions.

While the global scale analyses in Chapters 2-3 are useful for determining the different impacts and potentials of mitigation policies between low-income and high-income countries, the focus shifts to smallholder agriculture in developing countries in Chapters 4-6, to obtain more detailed insights about different measures that could address development goals and climate change at the same time. There is more urgency and utility in focusing on low-income countries because these countries account for the largest global share of agricultural GHG emissions and they will also account for all of the future growth in this global emission source. These countries are also expected to suffer a disproportionately large share of the negative impacts from climate change. Reflecting the priorities of these countries, the emphasis in Chapters 4-6 is on the adoption of practices that have farm productivity and profit improvement as their main objective, and climate change mitigation and adaptation as their secondary objectives. The three methods that were applied in these chapters were each selected to cover separate, but equally important and complementary research questions, instead of being directly linked to address one major issue, as was the case in Chapters 2-3. In Chapter 4, the potential of closing yield gaps to improve farm performance and lower GHG emission intensities is assessed for sample populations of mixed smallholder farmers in six different Sub-Saharan African countries. For this type of assessment, which required an empirical method that could utilise the observed heterogeneity within farm populations, the stochastic frontier analysis method was considered to be the most suitable option to estimate the extent to which output could be increased for a given set of inputs and existing practices.

The addition of the ex-ante methods used in Chapters 5-6 help to provide a more complete appraisal of technical options for addressing climate change and improved economic performance. In Chapter 5, the ex-ante potential for intensifying beef production on Sumbawa Island, by introducing a household feedlot production system based on the *Leucaena leucocephala* (leucanea) tree legume as an improved source of feed, is assessed. For this a system dynamics approach is used to model the entire value chain, accounting for herd dynamics, demand dynamics and seasonality. The system dynamics model was the most flexible of the methods employed and this attribute was important for exploring the potential for: scaling up the adoption of sustainable beef production; modelling value chain linkages; and for explicitly incorporating herd dynamic behaviour.

In Chapter 6, the ex-ante potential of residue retention and fertilisation measures to sustainably increase productivity and adapt to climate change is assessed. This is done using a positive mathematical programming (PMP) model, which captures decision making at the farm level for a sample population in Northern Burkina Faso for the 2010 to 2045 simulation period. As with the frontier efficiency method in Chapter 4, the PMP method in Chapter 6 also utilises the heterogeneity within the farm population in one of the sites also covered in Chapter 4, but in this case to provide insights about the potential adoption rate and impacts of new practices as opposed to the gains from using existing practices more efficiently. It should be noted that none of the resulting price and production changes from the global-scale assessments conducted in Chapters 2 and 3 are linked to the model variables in the farm population and sector scale models in Chapters 4-6.

In Chapter 7, the main findings of the thesis are summarised, and a series of common policy–relevant themes among the various research chapters are outlined. This chapter then concludes by identifying limitations of the research conducted in the thesis and by also offering future research suggestions that could address these limitations.

The geographical focus of the assessments within this thesis include a mixture of global and developing country regions. The regions were selected according to their suitability for the analyses, data availability, and the availability of research resources. For the Chapter 4 yield gap study, sites spanning a range of Sub Saharan African countries were chosen because this is the most impoverished global region with the greatest need for development, and the closing of regional yield gaps provides one feasible pathway for improving farmer livelihoods and food security. The IMPACTlite database (Rufino et al. 2013) provided highly suitable data for this purpose given its geographical breadth and blend of economic data and socio-economic indicators. The study site in Northern Burkina Faso in Chapter 6 was selected for the assessment of options to address the impacts of climate change, due to its suitability as an area with mixed farming systems and because this research is likely to achieve relatively high impact in this region. The reason for this is that the Climate Smart Agriculture program coordinated by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), has been achieving good traction in this region, raising the possibility that further relevant research could add to this momentum. The selection of the Sumbawa beef sector in the Chapter 5 study was more serendipitous, providing the opportunity to fulfil the requirements of the Applied Research and Innovation Systems in Agriculture (ARISA) research project (more details are provided in Chapter 5). Nonetheless, the study is highly complementary to the thesis, because it covers a key GHG emitting agricultural sector, considers the mitigation outcomes of a technical intervention with high potential for uptake, and extends the focus of the thesis into downstream branches of the value chain.

Finally, it should be noted that this thesis is by publication. Chapters 2-5 have been published as journal articles, and Chapter 6 has passed a first round of review and has been resubmitted after minor revisions. It is expected that this paper will be accepted for publication very soon. Each chapter in the thesis contains its own reference section, however, to improve the readability of the thesis the chapter appendices are presented at the end of the document.

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Chapter 2: Marginal costs of abating greenhouse gases in the global ruminant livestock sector

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Chapter 2: Marginal costs of abating greenhouse gases in the global ruminant livestock sector

Abstract

Livestock [inclusive of ruminant species, namely cattle (*Bos Taurus* and *Bos indicus*), sheep (*Ovis aries*), goats (*Capra hircus*), and buffaloes (*Bubalus bubalis*), and non-ruminant species, namely pigs (*Sus scrofa domesticus*) and chickens (*Gallus domesticus*)] are both affected by climate change and contribute as much as 14.5% of global anthropogenic greenhouse gas (GHG) emissions, most of which is from ruminant animals (Gerber et al. 2013). This study aims to estimate the marginal costs of reducing GHG emissions for a selection of practices in the ruminant livestock sector (inclusive of the major ruminant species—cattle, sheep, and goats) globally. It advances on previous assessments by calculating marginal costs rather than commonly reported average costs of abatement and can thus provide insights about abatement responses at different carbon prices. We selected the most promising abatement options based on their effectiveness and feasibility. Improved grazing management and legume sowing are the main practices assessed in grazing systems. The urea ($CO(NH_2)_2$) treatment of crop straws is the main practice applied in mixed crop–livestock systems, while the feeding of dietary lipids and nitrates are confined to more intensive production systems. These practices were estimated to reduce emissions by up to 379 metric megatons of carbon dioxide (CO_2) equivalent emissions per year ($MtCO_2$-eq yr^{-1}). Two thirds of this reduction was estimated to be possible at a carbon price of 20 US dollars per metric ton of CO_2 equivalent emissions (\$20 tCO_2-eq^{-1}). This study also provides strategic guidance as to where abatement efforts could be most cost effectively targeted. For example, improved grazing management was particularly cost effective in Latin America and Sub-Saharan Africa, while legume sowing appeared to work best in Western Europe and Latin America.

Keywords: Carbon sequestration; Grazing; Climate change mitigation; Feed additives.

2.1 Introduction

Climate change is arguably the most serious environmental challenge humanity has to face and reducing greenhouse gas (GHG) emissions is becoming ever more urgent (Stocker 2013). Livestock [inclusive of ruminant species, namely cattle (*Bos Taurus* and *Bos indicus*), sheep (*Ovis aries*), goats (*Capra hircus*), and buffaloes (*Bubalus bubalis*), and non-ruminant species, namely pigs (*Sus scrofa domesticus*) and chickens (*Gallus domesticus*)] are both affected by climate change and are a significant contributor to GHG emissions. This contribution is mainly from methane (CH_4) generated by ruminant digestion (enteric fermentation) as well as from emissions related to manure management and indirect emissions from feed production, energy use, and the processing of animal products. Livestock supply chains are estimated to account for 14.5% of total human-induced emissions (Gerber et al. 2013).

The global annual GHG abatement potential of the livestock sector is estimated to be a substantial 0.3 to 2.4 metric gigatons of carbon dioxide (CO_2) equivalent emissions per year ($GtCO_2$-eq yr−1) (Gerber et al. 2013; Smith et al. 2007; Herrero et al. 2015; US EPA 2013). The overwhelming majority of this potential is in ruminant production systems owing to their dominant share of global livestock GHG emissions. Ruminants account for over 90% of all direct GHG emissions (CH_4 from enteric fermentation and manure, and nitrous oxide (N_2O) from manure and urine) from livestock globally (Gerber et al. 2013).

While the technical potential of GHG mitigation practices in agriculture has been relatively well researched (FAO 2013), far fewer studies have assessed the costs and benefits of these practices at the country (Moran et al. 2011; Schulte et al. 2012; Whittle et al. 2013; Pellerin et al. 2013) or global (US EPA 2013; Beach et al. 2008; McKinsey & Company 2009; Smith et al. 2007) level. According to these studies, the global GHG abatement potential for livestock at a carbon price of \$50 tCO_2-eq^{-1} is between about 0.2 and 0.6 $GtCO_2$-eq yr^{-1}. This is much lower than the total abatement potential of the sector, suggesting that much of this total potential is not cost-effectively attainable.

This study aims to address two important shortcomings of previous studies. First, by including soil carbon (C) sequestration in grazing systems, a source of abatement that is either missing (e.g., US

EPA 2013; Beach et al. 2008) or poorly handled in other abatement cost studies. Second, by incorporating heterogeneity in the effectiveness, costs, and benefits of abatement practices within different regions and production systems. This approach enables the construction of marginal abatement cost (MAC) curves, which show how the costs increase with each additional unit of emissions that are reduced for either an individual practice or a group of practices. Most existing abatement cost studies in agriculture ignore this heterogeneity and estimate average rather than marginal abatement costs.

MAC curves provide valuable information for policy makers because they reveal the emission reductions that are likely for a region or sector in response to different carbon prices. Carbon prices can be introduced via various market-based instruments such as a carbon tax, emission trading scheme, or an abatement subsidy. These instruments are being increasingly applied in various countries. A good example is the Carbon Farming Initiative which allows farmers in Australia to create credits for sequestering carbon, which can be purchased by the government (Department of Environment 2015). The MAC curves summarized in this study are essential to help policy makers understand the potential effectiveness of these types of policy instruments. For example, the soil C sequestration potential and costs of improved grazing management will vary according to agro-ecological conditions, baseline grazing pressure, and its impact on forage production within a region. By capturing this heterogeneity, a MAC curve can indicate what the adoption rate of the practice for a given carbon price is likely to be. Those producers with marginal abatement costs below the carbon price will have an incentive to adopt the practice, while the remaining portion of producers will not.

Conversely, the usual approach of estimating average abatement costs cannot provide useful insights about the potential effectiveness of policy instruments that use carbon price incentives. In summary, this study aims to estimate the marginal costs of reducing GHG emissions for a selection of practices in the ruminant livestock sector globally. We selected the most promising abatement options based on their effectiveness and feasibility in different regions and production systems given management and regulatory considerations. These findings will assist policy makers in understanding the cost effectiveness of abatement interventions in the sector and, therefore, the likely contribution that abatement policies could make in global initiatives to address climate change.

2.2 Methodology

A series of MAC curves are constructed in this study, which describe the incremental changes in the costs and benefits of reducing each unit of GHG emissions for either an individual practice or a group of practices. These curves are constructed by arranging these incremental changes from lowest to highest cost, to show how costs rise as more emissions are reduced. Rising costs reflect the fact that carbon price incentives result in the cheapest opportunities for abatement being exhausted first, followed by increasingly expensive opportunities. The analytical approach used in this study involved five stages. First, production systems were selected based on the importance of their contribution to the livestock sector's [inclusive of ruminant species such as cattle (*Bos Taurus* and *Bos indicus*), sheep (*Ovis aries*), goats (*Capra hircus*), and buffaloes (*Bubalus bubalis*) and non-ruminant species such as pigs (*Sus scrofa domesticus*) and chickens (*Gallus domesticus*)] total output of GHG emissions and the corresponding potential for reducing these emissions. Second, abatement practices were selected according to agreement in the literature and among experts about their reliability and effectiveness in reducing emissions. Third, the analytical framework was designed and biophysical models to support the analysis were chosen on the basis of their suitability (i.e., accuracy, acceptance by experts, and global coverage). Fourth, the selected abatement practices were specified within the analytical framework. This involved making decisions about the applicability of these practices in different production systems and regions based on considerations about their feasibility and suitability (e.g., practices with detrimental impacts on food security were considered to be unsuitable in developing regions). For the abatement potentials of practices that were not explicitly derived from the biophysical models, emission reduction factors were derived and assembled from the literature. In the fifth and final stage, economic data were combined with the biophysical model outputs to estimate the costs and benefits of each practice at the pixel level to construct corresponding MAC curves.

2.2.1 Selection of production systems and GHG abatement sources

We focused on assessing the potential for reducing emissions from ruminants because they contribute to more than 90% of livestock GHG emissions, globally. Ruminants include all dairy-based and meat-based cattle (*B. taurus* and *B. indicus*) and small ruminant [sheep (*O. aries*) and goat (*C. hircus*)] herds. The dairy-based production systems encompass all animals in the herd that are required to support the production of milk, including the milked animals, breeding animals (cows, bulls, and replacement animals), and animals that are fattened for meat production as by-products of the dairy herds. Similarly, the meat-based herds include animals for fattening as well as the breeding animals required to support their production. The breeding part of ruminant herds tends to be more extensively managed than both the milking and fattening cohorts which, as discussed latter, has important implications for the applicability of different abatement practices. These systems are also further disaggregated into mixed and grazing systems. Mixed systems are defined according to Gerber et al. (2013) as those in which crop by-products and/or stubble comprise more than 10% of dry matter fed to animals or where non-livestock farming activities comprise more than 10% of the value of production. Grazing systems are defined as those in which farm produced feed comprises more than 10% of dry matter fed to animals and where average stocking rates are less than ten livestock units per hectare. With regard to GHG abatement sources, this assessment includes CO_2 removals from soil C sequestration and all direct animal emissions (enteric CH_4, manure CH_4, manure/urine N_2O).

2.2.2 Selection of abatement practices

The abatement practices selected in this assessment target enteric CH_4 and soil C sequestration (although changes in all direct ruminant GHG emissions are captured) because these are the largest sources of abatement for ruminant production systems (FAO 2013; Gerber et al. 2013; Soussana et al. 2010; Smith et al. 2007). According to Smith et al. (2007), these sources account for 98% of the global livestock sector's total abatement potential. For guidance on selecting the most feasible and effective practices for abating enteric CH4 emissions, we mainly relied on the findings from FAO (2013)—a comprehensive review of the literature by a large team of the world's leading experts on abatement practices for livestock. We also relied on findings from the European project AnimalChange (An Integration of Mitigation and Adaptation for sustainable Livestock production under climate CHANGE). Recommendations were also drawn from Henderson et al. (2015), Gerber et al. (2013), Smith et al. (2007), and Conant (2010) for guidance on selecting the most promising practices for the large-scale sequestration of soil C in grazing lands.

The five practices that were selected, based on agreement in the literature about their effectiveness, are summarized in Table 2.1. They include three practices that target enteric CH_4 emissions: feeding of dietary oils, feeding of nitrates, and the urea treatment of crop straws fed to animals. Other additives which are effective but banned in some countries are not included in this assessment due to controversy surrounding their use and uncertainty about their global applicability. These include growth promoters such as monensin, which are banned in the European Union, and recombinant bovine somatotropin, which can boost dairy productivity, but is banned in Canada, Japan, the European Union, Australia, and New Zealand (FAO 2013). With regard to soil C sequestration, improved grazing management and legume sowing were considered to be the best available practices.

The practices differ in their coverage of production systems and regions, although there is some overlap (Table 2.1). Dietary oils and nitrates were not applied in developing regions because it was assumed that these products could be more appropriately used to directly improve food security (i.e., by using oils in human diets and nitrates for growing crops), which is a high priority objective in these regions. By contrast, the urea treatment of crop residues was confined to mixed crop–livestock systems in developing countries and emerging countries (defined here as countries in East Europe, Latin America, and East Asia), but applied to all herd cohorts (i.e., both breeding and fattening animals). This practice was deemed to be suitable for these countries because it improves the nutritive content and digestibility of feeds, which frequently constrain production due to their poor quality. More details about these practices including their emission reduction potentials, the decisions about the production systems to which they are applied, and the approaches used to implement them, are provided in Section 2.2.4.

Table 2.1 Summary of abatement practices assessed indicating the regions, animal types, and production systems to which they are applied, their main sources of abatement, and the models underlying the estimation of their impacts

Mitigation practice	Applicability	Animal productivity increase	Main abatement source	Models used
Dietary oils	Developed/emerging country fattening & milked animals, with high concentrate diets	No	Enteric CH_4	GLEAM
Nitrates	Developed/emerging country fattening & milked animals, with high concentrate diets	No	Enteric CH_4	GLEAM
Urea treatment of straws	Developing/ emerging country mixed crop-livestock systems	Yes	All ruminant GHGs	GLEAM
Grazing management	All rangelands & pasturelands, and all regions	No	Soil C	Century, GLEAM
Legume sowing	All pasturelands, and all regions	Yes	Soil C, All ruminant GHGs	Daycent, GLEAM

2.2.3 Analytical framework and data

2.2.3.1 Analytical framework

In this study, the Global Livestock Environmental Assessment Model (GLEAM: Gerber et al. 2013) was the main analytical tool used to assess the various abatement practices and to integrate data on emission reduction potentials and economic variables from different sources. GLEAM is a spatial model of livestock production systems that represents the biophysical relationships between livestock populations (FAO 2007; FAO 2011a), production, and feed inputs (including the relative contribution of feed types—forages, crop residues, and concentrates—to animal diets) for each livestock species, country, and production system. The production parameters and data in GLEAM have been drawn from an exhaustive review of the literature and validated through consultation with experts during several joint projects and workshops. The relationships between GHG emissions and production have also been cross validated for ruminants across a range of regions and studies, and published reports on GLEAM have also been through rigorous peer review (Opio et al. 2013; Gerber et al. 2013). The GLEAM framework is used to characterize the baseline production and GHG emission output of all major livestock production systems across the world around the year 2005. The abatement potentials for each practice and their associated economic impacts were calculated by estimating the changes from the baseline GHG emissions, soil C stocks, and net income, following the application of each practice. To specify each abatement practice within GLEAM, it was necessary to incorporate emission reduction factors along with data on their associated additional costs and benefits to producers. These data were obtained from a range of literature sources and databases as elaborated in Sections 2.2.4 and 2.2.3.2.

For the practices that sequester soil C, we relied on outputs from an extensive modelling exercise by Henderson et al. (2015), which used the grassland and ecosystem dynamics (Century) model and the daily version of the Century model, known as Daycent (Parton et al. 1987; Parton et al. 1998). The Century model was originally developed to describe ecosystem processes in grassland systems. Daycent is a version of the Century model, which uses a daily time step to more accurately model nitrogen (N) cycling in agro-ecosystems. The Century and Daycent models are commonly used for project- and national-level GHG accounting because they have been extensively validated against field observations of changes in forage production, soil C stocks, and N_2O fluxes in response to changes in grazing land management (Henderson et al. 2015). As indicated in Table 2.1, we rely on outputs from the Century and Daycent models to assess the mitigation potential of improved grazing management and legume sowing. The changes in soil C stocks, forage consumption, and soil N_2O emissions from these models were incorporated into GLEAM to ascertain their implications for animal production and animal GHG emissions. To model the abatement practices that target enteric CH_4 (urea treatment of straws, dietary oils and nitrates), it was necessary to incorporate data on emission reduction factors, obtained from the literature, into GLEAM. Similarly, data on the costs and benefits of each practice, from various literature and database sources, were also incorporated. Details about these data sources and the approaches used to specify the abatement practices within GLEAM are provided in Sections 2.2.3.2 and 2.2.4.

The spatially explicit GLEAM model framework allows the incorporation of heterogeneity in emission reductions, production responses, and, subsequently, in net income on a pixel-by-pixel basis (3 arc minutes, or ca. 5×5 km at the equator). In each pixel, the change in net income is divided by the emission reduction associated with each practice to derive a measure of either the cost (if net income declines) or benefit (if net income increases) per unit of GHG emissions reduced. This measure is expressed in US dollars per ton of CO_2 equivalent emissions reduced (\$ $tCO_2\text{-eq}^{-1}$). Global warming potentials of 25 and 298 were used to convert CH_4 and N_2O emissions in CO_2-

equivalent emissions (IPCC 2007). The MAC curves presented in this study were constructed by arranging the pixel-based \$ tCO_2-eq^{-1} abatement estimates in GLEAM from least to most costly, for each practice. In addition, an aggregate MAC curve combining all of the assessed practices was also constructed. Details about the construction of this aggregate curve are provided in Section 2.2.5.

2.2.3.2 Data sources

The large volume and range of data used in this study can be divided into three categories. The first is the input data used to populate and specify GLEAM, the main analytical model of this study. The second is the input data used in the Century and Daycent models. The final category is the additional information on the GHG emission reduction potentials, resources requirements, and associated costs and benefits for the assessed abatement practices. A detailed description of the data used in GLEAM can be found in Opio et al. (2013). These data are too multitudinous to outline in detail in this paper; however, a summary of the main data sources is provided here: animal population data came from the Food and Agricultural Organization's statistical database FAOSTAT (2013) and FAO (2007), animal product yields were derived from literature and FAOSTAT (2013), feed composition data was from literature reviews and databases from the International Food Policy Research Institute (You et al. 2010) and lifecycle inventory databases from the Netherlands and Sweden (Flysjö et al. 2008), and herd performance parameters were derived from an extensive review of the literature. Tier 2 equations from the Intergovernmental Panel on Climate Change were used to estimate all animal GHG emissions (IPCC 2006) in GLEAM.

As with GLEAM, the data sources for the Century and Daycent models are too extensive to explain in detail here. Instead, we have summarized the main data used in this assessment drawing largely from Henderson et al. (2015). The Century model used monthly climate from the Climate Research Unit of the University of East Anglia (Mitchell and Jones 2005). Soils data came from the FAO Soil Map of the World, with modifications by Reynolds et al. (2000). For rangelands, information on native vegetation came from the Potsdam model intercomparison study (Melillo et al. 1993). The Daycent model runs required daily climate data, which also came from the Climate Research Unit, but otherwise Daycent used the same soil, plant, and grazing data as the Century model. The Global Agro-Ecological Zone data layers produced by FAO and the International Institute for

Applied Systems Analysis Global (IIASA/FAO 2012) were used to define and scale the grazing land areas assessed in Century and Daycent. Further details and descriptions of the plant communities, fire frequency, land types, and general assumptions of grazing seasonality used in the Century model can be found in Henderson et al. (2015).

In its standard form, GLEAM does not include the economic data needed to specify baseline net income. For this purpose, data on the production costs, revenues, and producer prices were sourced from a range of international databases including FAOSTAT (2013), the Global Trade Analysis Project database (Narayanan and Walmsley 2008), and the International Labor Office (ILO) database. These economic data are based on year 2005 US dollars to match the production year specified in GLEAM. The emission reduction potentials of the abatement practices that target enteric CH_4, which were also added to the standard version of GLEAM, were obtained from various literature sources, as detailed in Section 2.2.4.

2.2.4 Methods and data specific to each abatement practice

In this section, the approaches used to specify the abatement practices within the model framework are outlined. An overall guiding principle for specifying each practice is the maximization of their abatement potentials. For all of the practices, apart from legume sowing, this involved holding animal production constant.

2.2.4.1 Improved grazing management

Improved grazing management is based on the premise that ruminant grazing pressure can be adjusted, either up or down, to increase forage production. With more forage being produced, more plant litter can be returned to the soil and, consequently, more organic carbon incorporated into the soil (Frank et al. 2012; Pineiro et al. 2010). In grazing lands that have experienced the excessive removal of vegetation from sustained periods of overgrazing, historical carbon losses can be partially reversed by reducing grazing pressure. On the other hand, forage productivity and soil C stocks can be enhanced by increasing grazing pressure in areas that are only lightly grazed (Holland et al. 1992). Improved grazing management was applied to all grazing lands, including native rangelands and pasturelands. As described in Henderson et al. (2015), native rangelands are defined as land on which the native vegetation is predominantly grasses, grass-like plants, forbs, or shrubs, primarily managed through the manipulation of grazing, whereas pasturelands are those areas on which there is some cultivation of grasses and other agronomic inputs such as irrigation and fertilization.

Details about the approach used to implement this practice in Century are described in Henderson et al. (2015). The main steps are outlined again in this section, along with the additional steps used to accommodate the objectives specific to this study. The Century model was run for a set of grazing scenarios to estimate the changes in soil C stocks that might be possible by shifting to an optimal grazing management regime that maximized forage production. This involved conducting a set of global runs for a range of forage removal rates by ruminants (ranging from 0 to 100% in 10% increments) and selecting the rates that maximized forage production averaged between 1987 and 2006. All grazing activity was limited to the forage growing season, excluding the month in which plant growth initiated. The results from this assessment were considered to reflect future sequestration potential based on the assumption that climate change-induced changes in GHG fluxes and forage production over the next 20 years would be modest in comparison to the impacts from the changes in grazing management.

As shown in Henderson et al. (2015), improved grazing management resulted in net increases in forage consumption and, therefore, in corresponding increases in the number of ruminant animals in all regions and production systems. The animal emissions associated with this increase in ruminant numbers were shown to easily exceed the carbon sequestration benefits of this practice. However, as noted in that study, since this practice leads to both increases and reductions in forage consumption, it could still deliver net abatement benefits if it was scaled back in some of the areas in which forage production increased. Following this recommendation, we sought to maximize the abatement potential of this practice by balancing the increases and reductions in forage removals within areas defined by region (25 global regions), ruminants (three groups—dairy-based cattle, meat-based cattle, and small ruminants), and agro-ecological zone (three agro-ecological zones—temperate, humid, arid), within GLEAM. For example, for meat-based cattle production in the humid agro-ecological of Brazil, we selected all of the pixels in which forage consumption fell. Following this, we incrementally selected pixels in which forage consumption increased, giving priority to those pixels with the highest rates of carbon sequestration until we approximately matched the quantity of reductions and increases in forage consumption. As a consequence of this balancing procedure, we assumed ruminant production and emissions were held constant. These changes in forage consumption from the Century model were translated into changes in ruminant livestock production, by using a fixed relationship between forage intake, animals, and animal production, taken from GLEAM, at the pixel level. The economic costs and benefits of these pixel-level changes in production were then estimated according to their impacts on net income. This was done by first calculating the revenue associated with ruminant outputs, such as meat and milk, and by multiplying these outputs by their corresponding country-level producer prices from FAOSTAT (2013). Following this, the net income shares of these revenues were derived from the Global Trade Analysis Project database (Narayanan and Walmsley 2008), based on the difference between revenue and costs of intermediate inputs (such as concentrate feeds, fuel, transport, and other services), labor and capital, for each region and production system. Naturally, where improved grazing management led to increased production, net income levels increased, and where production fell, net income also fell. These changes in net income were then divided by the quantity of carbon sequestered in each pixel to derive a level abatement cost or benefit expressed in $\$tCO_2\text{-}eq^{-1}$.

2.2.4.2 Legume sowing

Legume sowing was only considered to be applicable in pasturelands which are more amenable to agronomic inputs than native rangelands because of their agro-ecological conditions (e.g., soil moisture availability) and accessibility. As outlined in Henderson et al. (2015), the Daycent model was used to simulate forage production, soil C sequestration, and N_2O emissions from pasturelands under the baseline scenario and with legume sowing. Legumes were assumed to be over-sown on grass to achieve a cover of approximately 20%. The impact of the legume sowing scenario was compared with a “no-legume” baseline. As explained in Henderson et al. (2015), a severe lack of global data precluded the representation of existing distributions of legumes in the baseline. Due to this simplified baseline assumption, the effectiveness of this practice is likely to have been overestimated in some places because legumes will have been present in some of the areas which are modeled. However, it was not possible to quantify the extent of this overestimation. The net GHG impacts of this practice were estimated by subtracting increases in soil N_2O emissions from the quantity of soil C sequestered in CO_2-equivalent terms. In contrast to improved grazing management, legume sowing invariably resulted in higher forage consumption by ruminants. Therefore, it was necessary to allow animal numbers and production to also increase to obtain the soil C sequestration benefits of this practice. The Daycent outputs were combined with parameters on animal productivity improvements for this practice within GLEAM to assess its impact on ruminant production and to estimate abatement and net of changes in animal emissions for each region and production system. Animal productivity was assumed to increase as a result of legume inclusion in grass swards because of the higher nutritive value of legumes, including higher digestibility and crude protein contents (Rochon et al. 2004; Min et al. 2003). We reviewed and synthesized results from several studies covering a range of species and regions to derive assumptions about these productivity improvements (Rochon et al. 2004; Coates and Mannetje 1990; Mannetje and Jones 1990; MacLeod and Cook 2004; Hernandez et al. 1995; Nyambati et al. 2003; Min et al. 2003; Jones 1994). Based on these findings, we assumed a 15% increase in animal growth rates for all species, a 10% increase in milk production, and a modest 1% increase in dry matter digestibility. These performance improvements are realistic and generally conservative compared to experimental results in the referenced literature. Further, the impact of additional dietary N intake on N_2O emissions was also estimated within GLEAM.

The economic benefits from this practice come from increases in forage production, consumption, and animal productivity improvements. As with improved grazing management, increased forage consumption was translated into increased animal production and animal numbers, based on feed conversion factors in GLEAM. As with improved grazing management, increases in revenue were estimated by multiplying the increases in ruminant livestock products by their respective producer prices in FAOSTAT (2013), and the associated net incomes were again based on data from the Global Trade Analysis Project database (Narayanan and Walmsley 2008). In addition, a literature review was conducted to ascertain the typical resource and investment requirements for legume sowing (e.g., fertilizer, seed, labor, herbicide, and machinery requirements), and a combination of these studies (Nutt 2012; DPI Department of Primary Industries and New South 2012a, b; MacLeod et al. 1991, 1993; Elbasha et al. 1999; Miller and Stockwell 1991; MacLeod and Cook 2004; Holmann 1999; Undersander and Laboski 2013; Biermacher et al. 2012; Choufang and Shurong 2013) and global and regional price databases (including FAOSTAT 2013; ILO (International Labour Organization) 2013; Index Mundi 2013; and CUSA (Uruguayan Chamber of Agricultural

Services) 2013) were used to estimate the costs of these inputs. Investments in legume establishment were assumed to occur periodically at 5-year intervals over the assessment period, and the investment costs were annualized using a 10% discount rate. Finally, as with all assessed practices, the changes in net income were divided by the quantity of GHG emissions abated at the pixel level.

2.2.4.3 Dietary oils

There is a large body of evidence showing that lipids suppress enteric CH_4 production in ruminants. Beauchemin et al. (2007) found that enteric CH_4 emissions were reduced by about 12% when supplemented with lipids [sunflower (*Helianthus annuus*) seed and oil animal fat] at 3.4% of dietary intake. In another study by Beauchemin et al. (2009), the inclusion of crushed oilseeds in the diet of lactating cows at between 3.1 and 4.2% (crude oil content) of dietary dry matter decreased CH_4 emissions by an average of 13% without affecting feed intake or animal productivity. There have also been a number of literature reviews and meta-analyses demonstrating the abatement potential of dietary lipids. Based on a dataset of 17 studies with beef cattle, dairy cows, and lambs, Beauchemin et al. (2008) found that CH_4 emissions (in grams per kilogram of dry matter intake) was lowered by 5.6% with every 1% of supplemental lipids added to ruminant diets. However, the authors found large variations among lipid sources. Grainger and Beauchemin (2011) analyzed 27 studies and concluded that, within a practical feeding rate of less than 8% fat in the diet, a 10 g/kg increase in dietary fat would decrease the CH_4 yield by 1 and 2.6 g/kg of dry matter intake in cattle and sheep, respectively. Other meta-analyses by Rabiee et al. (2012)) and Moate et al. (2011) also found a negative relationship between CH_4 production and dietary fat concentration in dairy cows. We assumed that dietary lipids were administered in the form of crushed oilseeds (that are commonly available within each region), and we restricted their addition to 3% (in terms of crude oil) of dietary dry matter to prevent suppression of dry matter intake and, consequently, animal production. Based on the evidence in the literature, we assumed that enteric CH_4 emissions were reduced by 3% with every 1% addition of dietary lipids, and we also assumed that there were no changes in animal productivity (Beauchemin, personal communication) mainly because we kept total feed intake per animal fixed by requiring the substitution of dietary concentrates with the crushed oils in dry matter equivalent terms.

As indicated in Table 2.1, this practice was only considered to be applicable to fattening and milked animals in developed and emerging countries because it was assumed that oilseeds would be more appropriately used for human consumption in developing countries. The application of this practice was further restricted to more intensive production systems where there is a high degree of control over animal diets. This requirement was deemed to be met if the fraction of concentrates (e.g., grains, brans, oilseed meals) in animal diets was greater than or equal to 20%, based on the feed database within GLEAM. These restrictions were applied because it is unlikely that producers would have enough control over animal diets in grazing situations to closely manage oil intake levels. Since this practice is only applied to fattening and milking animals that are already being fed a significant level of concentrate feed, the only costs considered for implementing this practice were the costs of the oilseeds, which were based on country-level producer prices obtained from FAOSTAT (2013). Suitable oilseeds that were most common in each region, based on FAOSTAT (2013) production data, were selected. Oilseed prices were converted to oil equivalent prices based on their typical oil contents. Marketing margin of 25% was assumed to cover the costs of crushing the oilseeds and other costs such as freight and handling. Importantly, since the crushed oilseeds are assumed to replace a portion of grain concentrates, the costs of these concentrates were estimated based on FAOSTAT (2013) producer price data.

2.2.4.4 Nitrates

According to the comprehensive FAO (2013) review of abatement practices for livestock, nitrates were identified as promising enteric CH_4 mitigation agents providing that animals were properly adapted to these chemicals to avoid nitrite toxicity. The review includes some encouraging results, with nitrates shown to decrease enteric CH_4 production by up to 50%. According to research by van Zijderveld (2011), with the addition of 1% of nitrate in the dry matter of ruminant rations, a reduction in enteric CH_4 emissions of approximately 10% can be achieved. To minimize the potential for nitrate toxicity, nitrate addition to ruminant diets was limited to 1% of total dry matter intake. As with dietary oils, we only applied this measure to fattening and milking animals that have a 20% or greater share of concentrates in their diets. In this case, with the possible risks of nitrite toxicity, the need to control animal dietary intake is particularly important. We also restricted its application to developed and emerging countries since nitrates could arguably be used more beneficially as crop fertilizers. Nitrate was assumed to be applied in the form of either calcium-nitrate, potassium-nitrate, or sodium-nitrate, and mixed into prepared feed. And, as with dietary oils, we assumed that there are no productivity benefits or losses associated with this practice. FAOSTAT (2013) producer prices for nitrate fertilizers were used to cost the nitrates added to ruminant diets for each region. The prices were converted into nitrate-equivalent prices on the basis of their nitrate content, and a marketing margin of 20% was assumed to cover costs such as freight, handling, and related marketing costs. This is slightly lower than the margin for oilseeds, which also included the costs of crushing the oilseeds. Finally, since this practice was applied in systems where there was a relatively high degree of dietary manipulation and control, we assumed there would be no additional costs associated with labor and other inputs related to feeding.

2.2.4.5 Urea treatment of straws

A number of chemical treatments for straws have been developed, with the aim of increasing digestibility by disrupting the cell wall structure and increasing the availability of hemicellulose and cellulose fractions for rumen digestion (FAO 2013). Urea ($CO(NH_2)_2$) is the most widespread option advocated among the available chemical treatments, and it is particularly well suited to mixed ruminant production systems in developing countries (FAO 2013). Typically, straws are mixed with a urea solution and stored under airtight conditions, while ammonia NH_3 is formed from the urea and alkaline conditions compromise the cell wall structure and improve digestibility. Feed value is also improved by the provision of additional N to diets (FAO 2013). As urea is hydrolyzed to NH_3 in a short time span, a large portion of urea N is lost to the air as NH_3 when opening bags and silos (Makkar and Singh 1987; Makkar et al. 1999). To account for this process, we assumed that 50% of the added urea N was lost as NH_3. Additional N_2O emissions associated with the additional N ingested by ruminants were also calculated in GLEAM. Improved feed digestibility directly lowers enteric CH_4 emissions per animal and, by improving animal productivity, the number of animals required to produce the same level of output is reduced. Based on results in reviewed literature (Biswas et al. 2010; Kayastha et al. 2012; Uddin et al. 2002, Tsega et al. 2012; Sharma et al. 2004; FAO 1997; Nianogo et al. 1999; Brown and Adjei 1995; Islam and Huque 1995; Wanapat et al. 2009; Chemjong 1991; Alhassan and Aliyu 1991; Saadullah et al. 1982; Perdok et al. 1982, 1984; Hamid et al. 1983; Kumarasuntharam et al. 1984; Waiss et al. 1972), this practice was conservatively assumed to increase ruminant growth rates by 40%, milk yields by 25%, and dry matter digestibility by 10%. As this practice depends on the availability of crop straws, it was only applied to ruminants in mixed crop–livestock systems. It was also only applied in developing and emerging countries. As mentioned, this practice was deemed more suitable in these regions where low-quality forage is frequently a major constraint to productivity. The improvements were applied on a pro-rata basis according to the amount of straws in the animals' diets. Several studies outlining detailed budgets for the urea treatment of straws were used to identify the input requirements for this practice which include straws, urea, plastic sheet, and labor (PCC Philippine Carabao Center Urea-molasses treatment of rice straw. Technology brief series no. 10. Available via PCC. http://www.pcc.gov.ph/TransparencySeal/Urea.pdf. Cited 4 December 2012; FAO 1997; Uddin et al. 2002; Tsega et al. 2012; Schiere and Nell 1993; Islam and Huque 1995, Jabbar et al. 2009; Prasad et al. 1998; van Man and Wiktorsson 2001; Sharma et al. 2004, Chemjong 1991). Country-specific prices were used where possible. For urea, we relied on FAOSTAT (2013) for country-level prices (inclusive of a 20% marketing margin); for labor, we relied on the International Labor Office database of agricultural wages; and for plastic sheets, we relied on the above cited literature. Cost savings, based on productivity improvements and the associated reductions in animals required to produce a given level of output, were also incorporated into the abatement cost calculations.

2.2.5 Constructing the aggregate MAC curve

Once the GHG abatement quantities and the changes in net incomes were calculated, the MAC curves for the single abatement practices were constructed using the simple procedure, described earlier. However, as a consequence of overlaps with regard to the animals and grazing land areas to which each abatement practice can be applied, the construction of an aggregate MAC curve incorporating all of the assessed practices was a much more challenging exercise. Ideally, where these overlaps occur, interactions between the overlapping practices should be taken into account. However, in the absence of scientific studies quantifying these interactions, we mainly dealt with this issue by exclusively selecting the most cost-effective practice where these overlaps occur. This is a conservative approach because the overlapping practices are likely to be additive to some degree (i.e., the combined abatement potential of two practices should exceed the potential of either practice applied on its own).

With regard to the practices that target soil C sequestration (improved grazing management and legume sowing), there was a very small overlap in the grazing land areas to which they could both be effectively applied. On these small areas, we selected legume sowing because it tended to have much higher per hectare net mitigation potential and lower abatement costs. In the resulting areas where improved grazing management was applied, it was however possible to also apply one of the additional practices that target enteric CH_4 (i.e., dietary oils, nitrates, and urea treatment). This is because grazing management was assumed to have no effect on animal productivity or dietary intake and composition, and under this assumption, the interactions between grazing management and abatement practices that target enteric CH_4 could be ignored. However, where there were overlaps between legume sowing and these practices, legume sowing was again exclusively applied because it directly abated enteric CH_4 and was estimated to be more cost effective than all other assessed practices. With regard to the abatement practices that specifically target enteric CH_4, nitrates and dietary oils had complete overlap, as both were applied to the same groups of animals (fattening and milk animals with high concentrate diets) in the same regions. In this case, due to the similarities in applicability and effectiveness, priority was given to the most cost-effective practice on a pixel-by-pixel basis. On the other hand, the urea treatment of straws was generally applied to a different set of regions, with overlaps between urea treatment and either nitrates or oils only occurring in what we describe as emerging country regions. Where overlaps occur in these regions, urea treatment was selected due to its generally higher cost effectiveness compared with oils and nitrates.

2.3 Results

2.3.1 Grazing management

The total abatement potential of improved grazing management is 91 metric megatons of CO_2 equivalent emissions per year ($MtCO_2$-eq yr^{-1}). As shown in Figure 2.1, about half of the global potential for this practice is estimated to be achievable at no cost. Beyond this point, where the curve crosses the horizontal axis, the marginal costs initially increase quite slowly, with around three quarters of the total potential for costing less than \$10 $tCO_2\text{-eq}^{-1}$ to producers. Costs increase quite steeply thereafter, as the affordable opportunities for sequestering soil C are exhausted. The portion of the curve with very steep marginal costs represents pixels with very low per hectare sequestration rates and/or very high per hectare opportunity costs from forfeited livestock production.

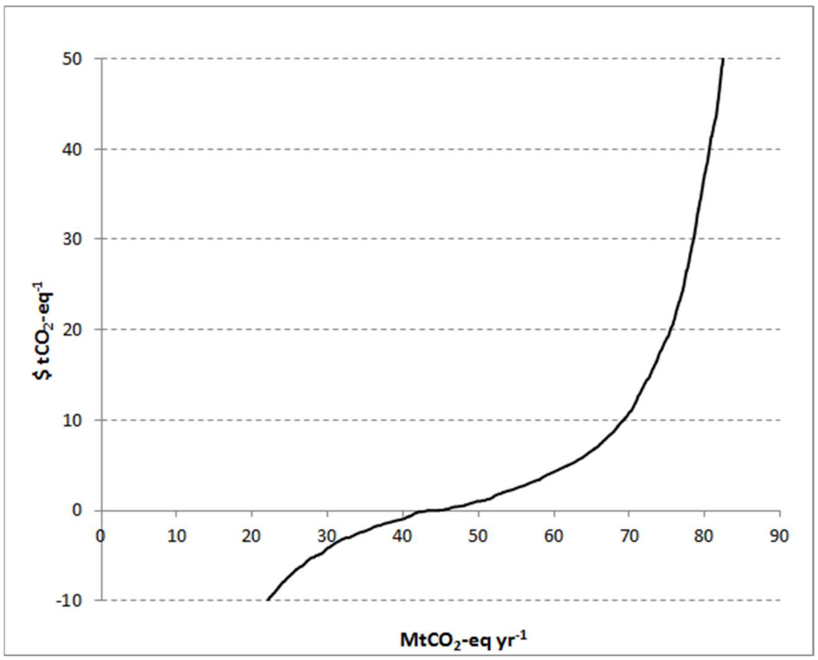

Figure 2.1 Global MAC curve displaying the incremental increases in the cost of sequestering each unit of soil C with the improved grazing management practice

The region-specific MAC curves displayed in Figure 2.2 reveal large differences in abatement potential between the world's regions, aggregated into ten regional groups of countries. The abatement quantities at all positive carbon price levels are significantly higher for Latin America and Sub-Saharan Africa than for any other region, which reflects the much higher overall sequestration potential found in these regions. This higher potential is, in turn, explained by the relatively high sequestration rates and large areas over which the practice can be effectively applied in these regions (Henderson et al. 2015).

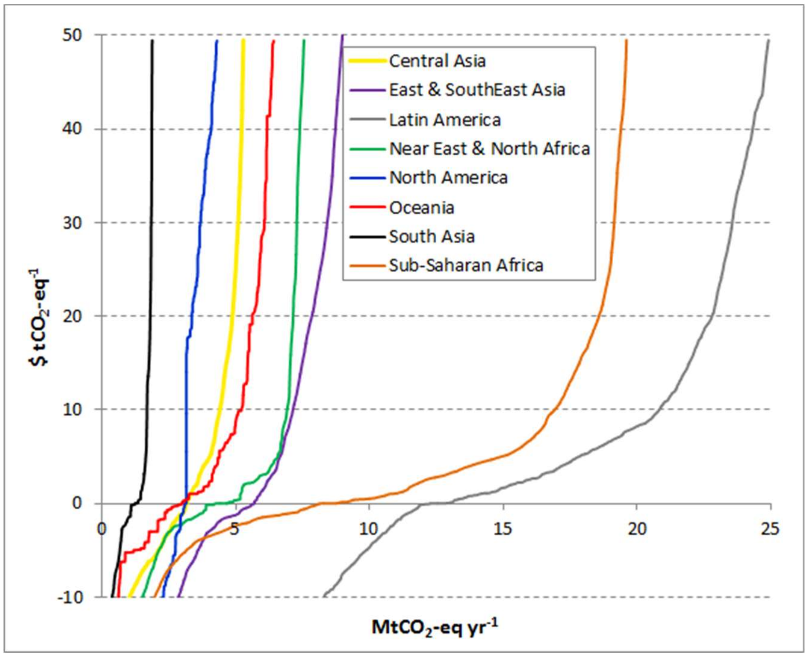

Figure 2.2 MAC curves displaying the incremental increases in the cost of sequestering each unit of soil C with improved grazing management for ten aggregate global regions. This figure is a regionally disaggregated version of Figure 2.1

2.3.2 Legume sowing

The total global abatement potential of this practice is 115 $MtCO_2$-eq yr^{-1}, which is higher but similar to the total potential estimated for improved grazing management. The MAC curve shown in Figure 2.3 reveals further similarities with improved grazing management, with around half of its abatement potential estimated to be costless. However, the marginal abatement costs for legume sowing are lower, with a greater proportion of the practice's total abatement potential achievable at any given carbon price. For example, 85% of the total technical potential of this practice is achievable at a carbon price of \$10 tCO_2-eq^{-1} compared with 75% for improved grazing management. The abatement potential for legume sowing is also cheaper in absolute terms, with a higher quantity of abatement possible at any given price. While legume sowing has relatively high upfront and periodic investment costs, these are offset in many cases by the additional returns associated with higher forage production and animal productivity.

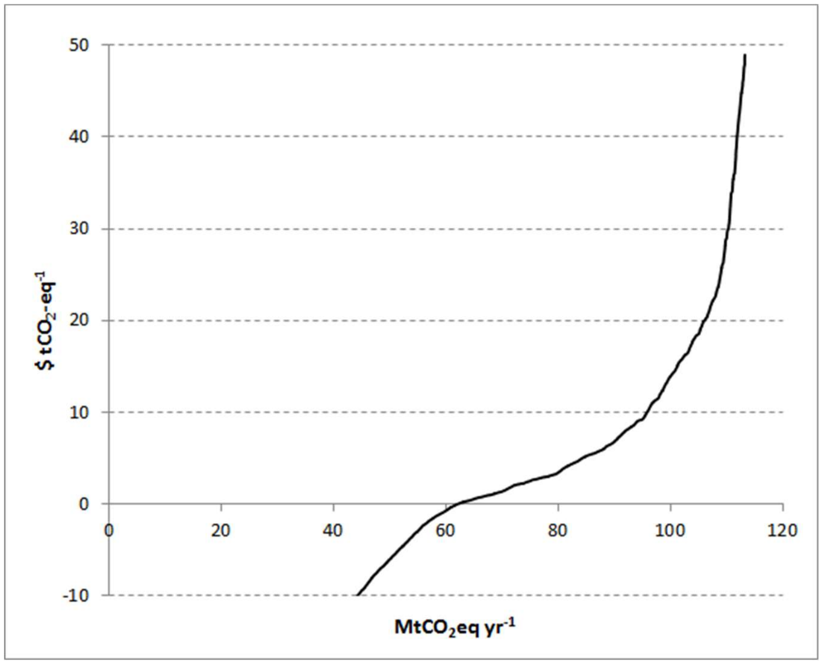

Figure 2.3 Global MAC curve displaying the incremental increases in the cost of abating each unit of GHG emissions with the legume sowing practice. These emissions are abated through the sequestration of soil C, net of additional GHG emissions from soil N_2O emissions, and animal emissions

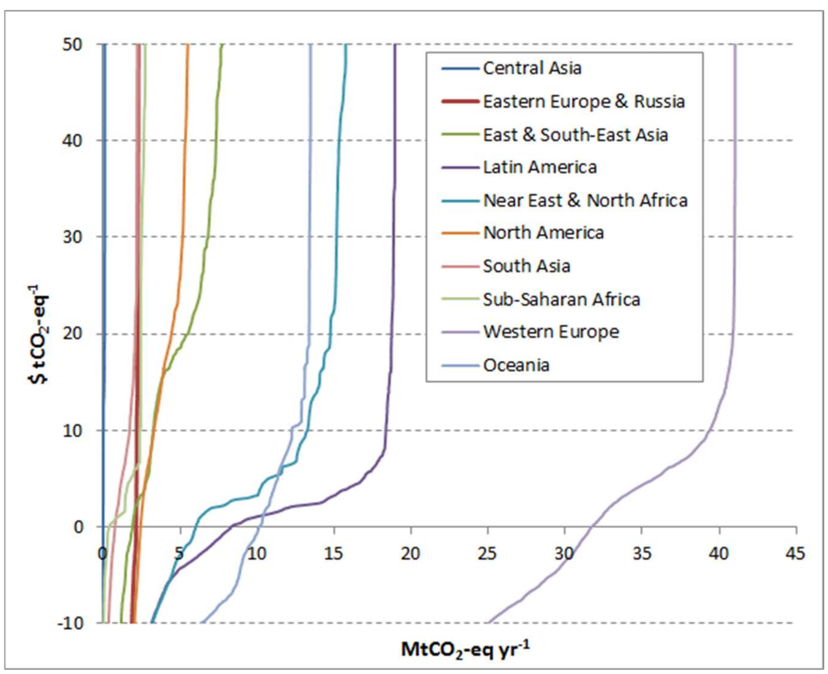

Figure 2.4 MAC curves displaying the incremental increases in the cost of abating each unit of GHG emissions with legume sowing for ten aggregate global regions. This figure is a regionally disaggregated version of Figure 2.3

As shown in the region-specific MAC curve in Figure 2.4, a small number of regions dominate in terms of their contribution to the global MAC curve. Western Europe stands out in terms of its dominant share of global abatement at all CO_2 prices, which can be explained by the large area over which this practice is amenable (15.5 million ha) and the relatively high per hectare abatement potential in this region (2.6 tCO_2-eq ha^{-1} yr^{-1}). Abatement by this practice is also relatively profitable in Western Europe due its high proportion of dairy which, as explained in Section 2.3.5, tends to attract higher return from legume sowing than other production systems.

2.3.3 Dietary oils and nitrates

The total annual abatement potential from feeding dietary oils to ruminants is 34 $MtCO_2$-eq yr^{-1}. Unlike improved grazing management and legume sowing, the marginal costs of this practice are high at all levels of abatement due to the high costs of oilseeds and the lack of animal productivity improvement. While crushed oilseeds are substituted for grain concentrates in ruminant's baseline diets, this does not result in net savings because of the much higher price of oilseeds relative to grains.

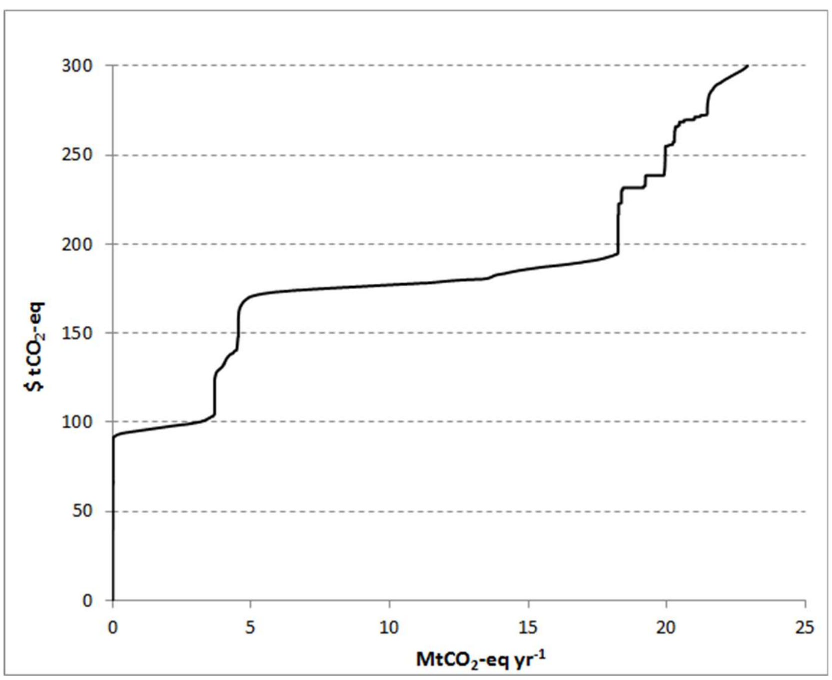

Figure 2.5 Global MAC curve displaying the incremental increases in the cost of abating each unit of GHG emissions with the dietary oils practice

As shown in Figure 2.5, abatement costs begin at close to \$100 tCO_2-eq^{-1}, with marginal costs rising fairly steeply from about 4 $MtCO_2$-eq yr^{-1} onwards. Around 23 $MtCO_2$-eq yr^{-1} is estimated to be possible at \$300 tCO_2-eq^{-1}, which is equivalent to about two thirds of the total abatement potential for this practice. The total abatement potential of feeding nitrates is 30 $MtCO_2$-eq yr^{-1}. As with dietary oils, this practice does not result in any productivity improvements and it is therefore also a relatively expensive abatement option, with marginal abatement costs also beginning at close to \$100 tCO_2-eq^{-1} (Figure 2.6).

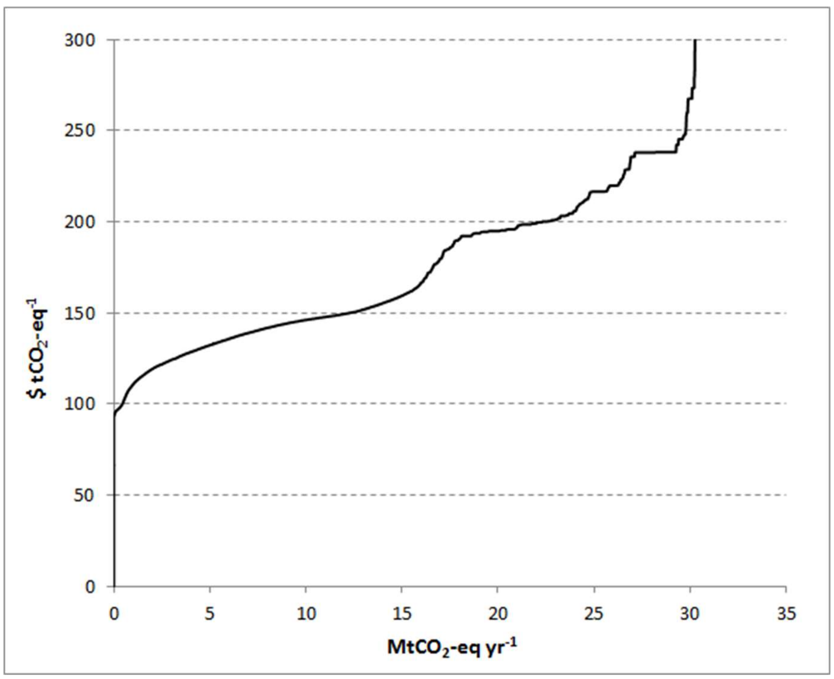

Figure 2.6 Global MAC curve displaying the incremental increases in the cost of abating each unit of GHG emissions with the nitrates feeding practice

2.3.4 Urea treatment of straws

Due to the widespread applicability of urea treatment, the urea treatment of straws generates a relatively large total annual abatement potential of 183 $MtCO_2$-eq yr^{-1}. However, according to the global MAC curve in Figure 2.7, only a small share of this total potential is costless. This suggests that urea treatment costs exceed their productivity-related economic benefits for the vast majority of producers. On the other hand, over 40% of this practice's total potential is estimated to be possible at low to moderate CO_2 prices of up to \$25 tCO_2-eq^{-1}. Beyond this point, costs increase relatively steeply, particularly at abatement levels in excess of 160 $MtCO_2$-eq yr^{-1}. These findings about the general lack of profitability for the urea treatment of straws are in agreement with other studies and on-ground reports about the modest uptake of this practice, despite years of trials and development projects. Walli (2010) describes outcomes from farm trials in a number of Asian countries, which show that most farmers stopped using the treatment following the completion of the trials due to high upfront costs of materials, labor constraints, and unavailability of clean water.

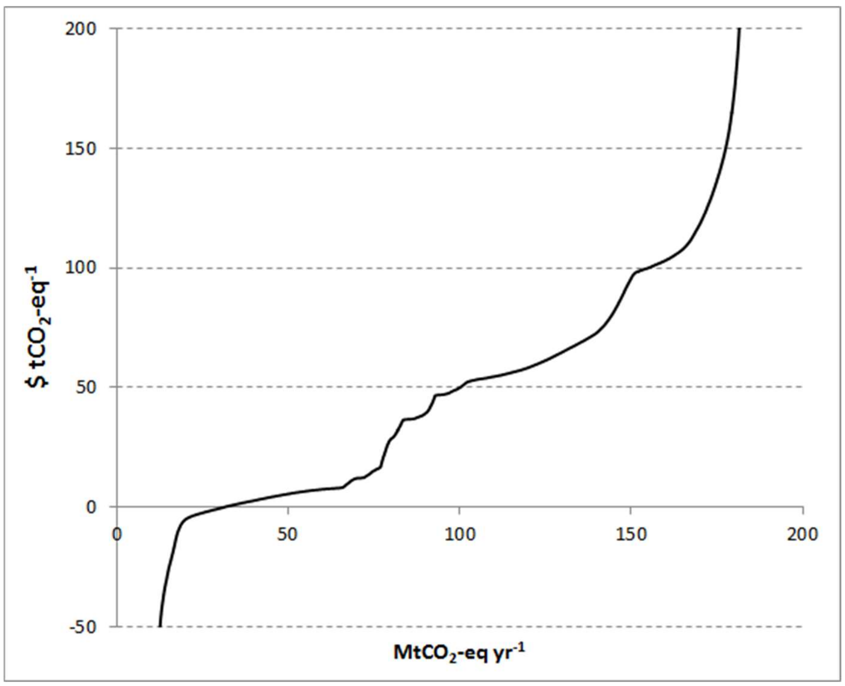

Figure 2.7 Global MAC curve displaying the incremental increases in the cost of abating each unit of GHG emissions with the urea treatment of straws practice

2.3.5 Global composite MAC curve

When summed together, the singularly applied abatement options are estimated to abate a total of 453 $MtCO_2$-eq yr^{-1} GHG emissions. However, after eliminating overlaps between practices, using the approach described in Section 2.2.5, this annual total falls to 379 $MtCO_2$-eq yr^{-1}. Over one third (36%) of this combined potential is estimated to be costless to producers, while two thirds can be abated at a relatively moderate rate of \$20 tCO_2-eq^{-1} (Figure 2.8). The marginal costs become increasingly steep beyond this point. Naturally, the composition of abatement practices differ as the marginal costs increase (Table 2.2), which provides strategic insights with regard to the targeting of practices. Legume sowing, which was estimated to be the most affordable practice at producer level, contributes the most between \$0 and \$50 $tCO_2\text{-}eq^{-1}$, while improved grazing management contributes second most between \$0 and \$20 $tCO_2\text{-}eq^{-1}$. Urea treatment of straws, on the other hand, makes the third largest contribution at these prices. However, as the carbon price increases to \$100 $tCO_2\text{-}eq^{-1}$, it becomes the main contributor to global abatement. In contrast, dietary oils and nitrates contribute very little to global abatement at all carbon price levels.

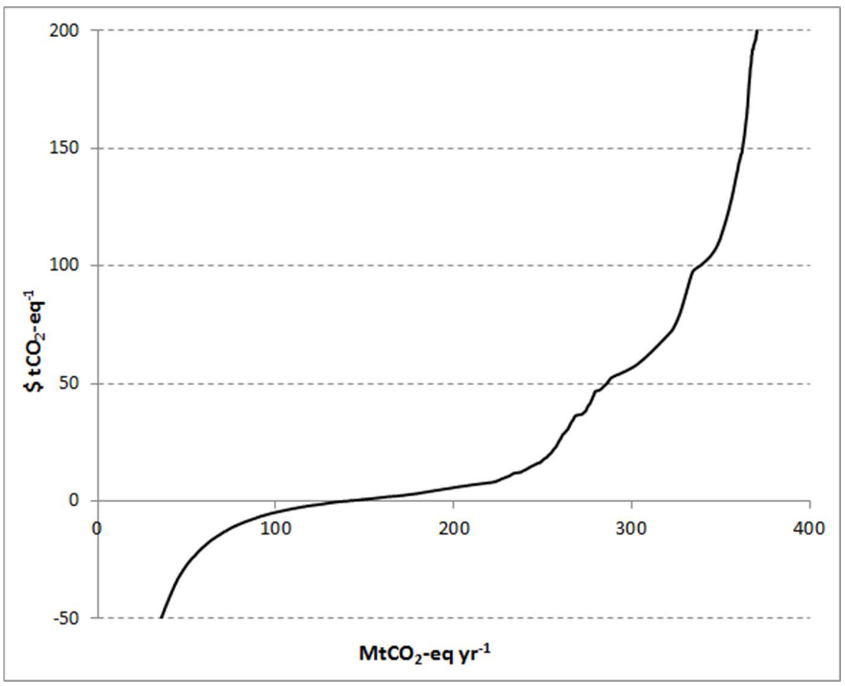

Figure 2.8 Global composite MAC curve, displaying the incremental increases in the cost of abating each unit of GHG emissions associated with the combined application of each of the five abatement practices. At any given point on this curve, there is a blend of practices being applied, as shown in Table 2.2

Just as the contributions of each practice vary as marginal costs increase, so too do the contributions from the different ruminant production systems (Table 2.3). While the total abatement potentials for the cattle beef and dairy subsectors are similar, the marginal abatement costs tend to be much lower for dairy cattle, as reflected by its dominant contribution to global abatement at low marginal cost levels (Table 2.3). This is mainly due to the dairy subsector's capacity to obtain a higher payoff from investment into legume sowing and urea treatment. This higher payoff stems from the dual benefits of higher milk yields and growth rates, in response to improvements in forage quality.

Table 2.2 The percentage contribution of each practice to global GHG abatement, when all of the practices are combined

Marginal cost ($\$tCO_2\text{-eq}^{-1}$)	Total abatement ($MtCO_2\text{-eq}\ yr^{-1}$)	Improved grazing (%)	Legume sowing (%)	Urea treatment (%)	Dietary oils (%)	Nitrates (%)
-50	32	20	45	35	0	0
0	136	33	46	21	0	0
20	249	30	43	27	0	0
50	282	29	40	31	0	0
100	335	26	34	40	0	0
150	360	24	32	43	0.1	0.8
Total	**379**	**24**	**30**	**42**	**0.2**	**3.4**

Note: This table shows the blend of practices across the range of carbon prices displayed in the composite MAC curve in Figure 2.8

Table 2.3 The percentage contribution of ruminant subsectors to the global GHG abatement, when all of the practices are combined

Marginal cost ($\$tCO_2\text{-eq}^{-1}$)	Beef cattle ($MtCO_2\text{-eq}\ yr^{-1}$)	Dairy cattle ($MtCO_2\text{-eq}\ yr^{-1}$)	Small ruminants ($MtCO_2\text{-eq}\ yr^{-1}$)	Beef cattle (%)	Dairy cattle (%)	Small ruminants (%)
-50	3	25	3	8	81	11
0	32	78	25	24	57	19
20	65	130	55	26	52	22
50	76	145	61	27	51	22
100	116	153	66	35	46	20
150	137	155	68	38	43	19
Total	**147**	**162**	**70**	**39**	**43**	**18**

Note: This table shows the shares of abatement contributed by each subsector, across the range of carbon prices displayed in the composite MAC curve in Figure 2.8.

2.4 Discussion and conclusions

2.4.1 Global significance and comparison with other studies

As discussed, livestock make a massive contribution to global anthropogenic GHG emissions (14.5%). Despite its importance, this study is one of only four global studies (US EPA 2013; Beach et al. 2008; McKinsey & Company 2009; Smith et al. 2007) that assess the costs and benefits associated with reducing GHG emissions from livestock. Consequently, this study provides information which is sorely needed for understanding the global economic potential of abatement practices in the livestock sector. Although this study only focuses on the ruminant portion of the sector, this is where the overwhelming majority of emissions are generated.

We estimate that the most promising practices for reducing enteric CH_4 emissions and for sequestering soil C in grazing lands could abate up to 379 $MtCO_2$-eq yr^{-1} of emissions, which is equivalent to 11% of annual global ruminant GHG emissions. A sizeable portion of this potential is estimated to be affordable, with around two thirds of this potential possible at a carbon price of $20 tCO_2-eq^{-1}, a price level that has been observed in Kyoto-compliant carbon markets in the past. Nevertheless, while our results are broadly aligned with those of previous global studies, they are more modest and thereby temper some of the optimism aroused by the previous assessments (Table 2.4).

For grazing land measures that aim to sequester soil C, Smith et al. (2007) estimate abatement potentials of 160, 403, and 813 $MtCO_2$-eq yr^{-1}, by 2030, at a carbon price of $20, $50, and $100 tCO_2-eq^{-1}. Our corresponding abatement potentials at these prices are 182, 196, and 201 $MtCO_2$-eq yr^{-1} (Table 2.4). There are several reasons for this large discrepancy in sequestration potentials. Foremost, Smith et al. (2007) used a statistical approach to derive sequestration potentials from a group of experimental studies and assumed these potentials could be applied to 2.4 billion hectares of the world's grazing lands. We, on the other hand, applied process-based models (Century and Daycent) to represent the variety of agro-ecological conditions observed in the world's grazing lands. Based on these model outputs, the assessed practices were only found to be effective on a much smaller area of 0.8 billion hectares.

Regarding direct animal emissions, our estimated abatement potentials are still lower but more closely aligned with those from other global studies. Smith et al. (2007) estimate that 135, 189, and 246 $MtCO_2$-eq of global annual livestock emissions (from ruminants and non-ruminants) could be abated by 2030, at carbon prices of $20, $50, and $100 tCO_2-eq^{-1}, respectively (in 2000 US dollars). More recently, the US EPA (2013) estimated that global livestock emissions could be reduced by 83, 136, 193, and 228 $MtCO_2$-eq yr^{-1}, by 2030, at carbon prices of $0, $20, $50, and $100 tCO_2-eq^{-1}, respectively (in 2010 US dollars). By comparison, we estimate lower abatement levels of 31, 78, 100, and 159 $MtCO_2$-eq yr^{-1} at these prices (Table 2.4). While a small portion of this difference is because we focus on abating ruminant enteric CH_4 emissions, whereas Smith et al. (2007) and US EPA (2013) also consider reductions in manure CH_4 emissions from dairy cattle and pigs, the main reason is we also apply more restrictive conditions on the inclusion and application of abatement practices. For example, we exclude some practices, such as the feeding of additional grain concentrates to animals in developing countries, given its likely detrimental impact on food security. Furthermore, both the Smith et al. (2007) and US EPA (2013) assessments are based on higher animal numbers and emissions in 2030, whereas our assessment is calibrated to the 2005 production year specified in GLEAM.

Table 2.4 A comparison of the global abatement responses in different studies, from practices that sequester soil carbon in grazing lands and reduce animal GHG emissions

	Carbon price (tCO_2-eq^{-1})	Soil C sequestration ($MtCO_2$-eq yr^{-1})	Abatement of animal emissions ($MtCO_2$-eq yr^{-1})
Present study	0	107	31
	20	182	78
	50	196	100
	100	201	159
Smith et al. (2007)	0	0	0
	20	160	127
	50	403	169
	100	813	204
US EPA (2013)	0	n.a.	83
	20	n.a.	136
	50	n.a.	193
	100	n.a.	228

Note: The carbon prices are in 2005 US dollars for the present study, 2000 US dollars for Smith et al. (2007), and 2010 US dollars for US EPA (2013).

As described in the Section 2.1, we also employ a different overall approach to other global studies in assessing abatement costs. Whereas US EPA (2013), Smith et al. (2007), and McKinsey & Company (2009) rely on average representative farms for each region and production system, we incorporate heterogeneity in the effectiveness and costs of abatement practices to estimate marginal costs. Approaches that rely on average costs can overestimate abatement responses because they tend to assume full regional adoption of a practice as soon as the carbon price exceeds its average cost of adoption.

2.4.2 Policy and strategic implications

As the political will to include agriculture in global efforts to address climate change gathers momentum, policy makers will be eager to understand the potential effectiveness of market-based instruments, such as emissions trading schemes and carbon offset schemes (e.g., the Clean Development Mechanism), for incentivizing GHG abatement. For this purpose, estimates of marginal abatement costs are especially useful because they indicate the likely abatement responses of a sector for a range of carbon prices. As mentioned, this study is the only global assessment that provides this essential and policy-relevant information on marginal costs for the ruminant livestock sector. This information can also be used for several strategic purposes. While the global nature of this study places limits on the inferences that can be made at more local scales, it provides broad guidance as to where abatement efforts could be targeted and have the greatest impacts at lowest cost. For example, improved grazing management and legume sowing were estimated to be the most affordable practices. Grazing management was particularly effective in Latin America and Sub-Saharan Africa, while legume sowing appeared to work best in Western Europe and Latin America. Urea treatment of straws tended to be less attractive at low carbon price levels, but at relatively high carbon prices of \$100 tCO_2-eq^{-1}, it was the most effective practice globally. This study also provides strategic guidance as to the production systems that abatement policies could target, with abatement found to be most cost effective in the dairy cattle subsector.

In addition to the targeting of practices and intervention areas, the marginal abatement costs provided by this study can also provide very useful insights about the range of policy instruments that could promote the adoption of various abatement practices. This is because the suitability of policy instruments depends very much on the economic attractiveness of the practices to producers, which can vary significantly within a farm population. For example, since extension and capacity building programs may be sufficient to encourage the uptake of practices that are profitable, it could be argued that around half of the abatement potential for improved grazing management and legume sowing, and around one fifth of the potential from urea treatment, could be achieved with these policy options. However, barriers to adoption including a lack of awareness, technical capacity and access to credit, aversion to change, and perceived risks of new practices can help explain why profitable abatement opportunities are not exploited, particularly in the absence of more powerful incentives. A further 146 $MtCO_2$-eq yr^{-1} (38% of the total abatement potential) is estimated to cost between \$0 and \$50 tCO_2-eq^{-1}. For this more costly portion of abatement, stronger policy incentives would be required to stimulate abatement. These incentives could be provided by a range of market-based instruments including abatement subsidies, offset schemes, tradable permit schemes, a carbon tax, or the imposition of emission quotas. While \$50 tCO_2-eq^{-1} appears to be high in comparison to recently observed carbon market prices, it is lower than the carbon price needed to encourage significant reductions in economy-wide global GHG emissions (Edenhofer et al. 2014) and much lower than the \$85 tCO_2-eq^{-1} marginal social cost of carbon estimated by Stern (2007).

While this study helps to further our understanding about the global effectiveness of abatement policies in the livestock sector, in order to implement these policies, more accurate and affordable methods for measuring carbon sequestration and emission reductions are needed. For example, the measurement of carbon stocks through direct soil sampling can be prohibitively expensive (FAO 2011b). Methodologies for estimating soil C stocks, based on the monitoring and measurement of management activities, have been developed to improve the affordability landscape scale measurements (VCS 2014). However, further research and piloting of these methodologies is needed before producers and carbon market participants can confidently invest in practices that sequester soil C in grazing lands.

2.4.3 Caveats and considerations

The effectiveness of improved grazing management and legume sowing depends very heavily on the a priori identification of areas amenable to these practices. As discussed in Henderson et al. (2015), more work is needed to develop indicators, based on management and biophysical characteristics of grazing lands, to assist with this requirement. It is also worth emphasizing that the detailed biophysical models on which this assessment was based are deterministic in nature and therefore do not incorporate uncertainty and or quantify errors related to the various abatement estimates. This weakness reflects, to a large extent, the current state of research on the economics of abatement in agriculture. All global and country-level studies on abatement costs in agriculture that we are aware of, and cited in this study, are deterministic assessments. While this is a weakness that should be addressed in future research, it is worth noting that this study does at least account for spatial variance in the costs, benefits, and effectiveness of abatement practices.

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STATEMENT OF AUTHORS' CONTRIBUTION

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	Author's Name (please print clearly)	**% of contribution**
Candidate	Benjamin Henderson	80
Other Authors	Alessandra Falcucci	10
	Anne Mottet	2
	Lonisa Early	3
	Beate Werner	2
	Henning Steinfeld	1
	Pierre Gerber	2

Name of Candidate: **Benjamin Henderson**

Name/title of Principal Supervisor: **Prof. Oscar Cacho**

[redacted]

06 / 04 / 2018

Candidate　　　　Date

[redacted]

09/04/2018

Principal Supervisor　　　　Date

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We, the PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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Name of Candidate: **Benjamin Henderson**

Name/title of Principal Supervisor: **Prof. Oscar Cacho**

[redacted]

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Candidate Date

[redacted]

09/04/2018

Principal Supervisor Date

Chapter 3: The power and pain of market-based carbon policies: a global application to greenhouse gases from ruminant livestock production

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Chapter 3: The power and pain of market-based carbon policies: a global application to greenhouse gases from ruminant livestock production

Abstract

The objectives of this research are to assess the greenhouse gas mitigation potential of carbon policies applied to the ruminant livestock sector [inclusive of the major ruminant species—cattle (*Bos Taurus* and *Bos indicus*), sheep (*Ovis aries*), and goats (*Capra hircus*)]—with particular emphasis on understanding the adjustment challenges posed by such policies. We show that market-based mitigation policies can greatly amplify the mitigation potential identified in marginal abatement cost studies by harnessing powerful market forces such as product substitution and trade. We estimate that a carbon tax of US$20 per metric ton of carbon dioxide (CO_2) equivalent emissions could mitigate 626 metric megatons of CO_2 equivalent ruminant emissions per year ($MtCO_2$-eq year^{-1}). This policy would also incentivize a restructuring of cattle production, increasing the share of cattle meat coming from the multiproduct dairy sector compared to more emission intensive, single purpose beef sector. The mitigation potential from this simple policy represents an upper bound because it causes ruminant-based food production to fall and is therefore likely to be politically unpopular. In the spirit of the Paris Agreement (UNFCCC 2015), which expresses the ambition of reducing agricultural emissions while protecting food production, we assess a carbon policy that applies both a carbon tax and a subsidy to producers to manage the trade-off between food production and mitigation. The policy maintains ruminant production and consumption levels in all regions, but for a much lower global emission reduction of 185 $MtCO_2$-eq year^{-1}. This research provides policymakers with a quantitative basis for designing policies that attempt to trade off mitigation effectiveness with producer and consumer welfare.

Keywords: Mitigation; Greenhouse gases; Ruminants; Carbon policy

3.1 Introduction

Global measures to tackle climate change are urgently needed to avoid extreme and irreversible impacts on the world's ecosystems and economy (IPCC 2014). Early action will also help to limit large future costs associated with stabilizing atmospheric concentrations of greenhouse gas (GHG) emissions (Stern 2007). Amid strong public support for action on climate change in most jurisdictions, policies for global action are being reformulated as expiry of the Kyoto Protocol in 2020 looms large. The Paris Agreement (UNFCCC 2015) at the 21st session of the Conference of the Parties (COP 21) to the United Nations Framework Conventions on Climate Change (UNFCCC) has led to several sources of renewed optimism. Chief among these is greater involvement from low- and middle-income countries, particularly China. Financial support by high-income countries of US$100 billion per year by 2020 was further fortified with an extension until 2025, and a revised higher goal is to be set after this period (European Commission 2016). Perhaps most significant is the pursuit of a more ambitious target of a 1.5°C increase above pre-industrial levels—well below the previously agreed 2°C target (UNFCCC 2015; Mitchell et al. 2016). The need to reduce agricultural emissions while protecting food production also receives explicit mention in the Paris Agreement, an ambition which is explored in this study.

Ever since the livestock sector's substantial contribution to climate change was well publicized in the *Livestock's Long Shadow* report by the Food and Agricultural Organization of the United Nations (Steinfeld et al. 2006), a number of research efforts have been mobilized to assess the potential for mitigating livestock GHG emissions (Popp et al. 2010; Havlík et al. 2014; Gerber et al. 2013; Smith et al. 2007, 2014). Herrero et al. (2016) recently reviewed the main contributions to this body of work, summarizing the global GHG mitigation potentials and policy options for the livestock sector and identifying important knowledge gaps. The authors found that while the technical potential for the sector to mitigate emissions through supply side practices such as improving animal diets, animal productivity, and carbon sequestration is relatively large (around 2.3 metric gigatons of carbon dioxide (CO_2) equivalent emissions per year ($GtCO_2$-eq year^{-1})), the quantity of emissions that is economically viable to mitigate through these measures is much smaller (around 0.4 $GtCO_2$-eq year^{-1} at US$20 per metric ton of CO_2 emissions ($20 tCO_2-eq^{-1})), owing to high abatement costs and barriers to adoption. The authors find far larger mitigation potentials of 4.3–6.4 $GtCO_2$-eq year^{-1} are possible from substantial reductions in the share of animal products human diets, particularly red meat. However, the economic viability and policy feasibility of such measures is highly uncertain.

In what is essentially a sequel to the *Livestock's Long Shadow report*, Gerber et al. (2013) conduct a comprehensive life cycle assessment of global livestock emissions and estimate the potential for mitigating these emissions. The authors estimate that 1.1 $GtCO_2$-eq year^{-1} of all supply chain emission could be abated if all livestock producers raised their production efficiency to same level as the top 25% of producers in each production system and region. Gerber et al. (2013) explain that economic barriers such as costs of mitigation practice adoption, technology transfer, and perceived risks of practice change all raise the minimum rate of return that producers would be willing to accept to adopt these practices. This provides justification for the use of mitigation incentives such as carbon taxes or abatement subsidies, as long as they are set at levels that do not exceed the marginal damage costs associated with climate change. However, to gain traction among policymakers, mitigation policies need to be commensurate with development and food security goals, particularly in low-income countries.

Global support for carbon pricing as the mitigation instrument of choice has been mounting in recent years. Following a groundswell of support from 74 countries and more than 1000 companies at the 2014 United Nations (UN) Climate Summit, the Carbon Pricing Leadership
Coalition was officially launched at COP 21. This unprecedented alliance of government, civil society, and business leaders has emerged to promote the widespread adoption of carbon pricing (Carbon Pricing Leadership 2016). Initiatives specific to the livestock sector have also begun organizing global mitigation efforts around UN Sustainable Development Goals (SDGs), including those based on taking urgent action to combat climate change (SDG 13) and to reverse land degradation (SDG 15), which is an important option for sequestering soil carbon. For example, the

Global Dairy Agenda for Action (2016) has expressed its commitment to reducing its GHGs and climate-related impacts through measures including feed and pasture management. The Livestock Global Alliance (2016) and the Global Agenda for Sustainable Livestock (2016) are other important multi-stakeholder coalitions that have expressed their commitment to these SDGs.

With growing enthusiasm for action on climate change as new agreements for the post-Kyoto period continue to be negotiated, now is the opportune time to revisit the potential contribution that globally coordinated mitigation policies in agriculture could make. Accordingly, in this study we assess the ex-ante potential of global carbon price policies, focussing on the ruminant livestock sector [inclusive of the major ruminant species—cattle (*Bos Taurus* and *Bos indicus*), sheep (*Ovis aries*), and goats (*Capra hircus*)]. The agriculture sector as a whole contributed 5.2–5.8 $GtCO_2$-eq year^{-1} in 2010, representing 10–12% of total annual anthropogenic emissions (Smith et al. 2014). Ruminants comprise the dominant share of these emissions: ruminant digestion (enteric fermentation) and manure deposited on pasture by ruminants account for 32–40 and 15% of agricultural GHG emissions, respectively, based on Intergovernmental Panel on Climate Change (IPCC) accounting methods (Smith et al. 2014).

This study contributes to a small but growing body of economic modeling work that has assessed the mitigation potential of carbon price policies in the global livestock sector. It builds on work by Golub et al. (2013) by developing a new disaggregation scheme for the livestock sector, which allows us to explore in more detail the potential impacts of carbon policies on the structure of global ruminant sector. In the "Discussion" section, we compare findings from other global economic mitigation assessments including Golub et al. (2013), Avetisyan et al. (2011), and Wollenberg et al. (2016). These studies all rely on marginal abatement cost (MAC) data from the US Environmental Protection Agency (US EPA 2006; US EPA 2013), which exclude soil carbon and uses an average cost accounting approach for calculating abatement costs. Our study advances on this literature by taking advantage of recently published MAC curves developed by Henderson et al. (2017), which include soil carbon and accounts for heterogeneity in producer costs within regions and production systems to provide more robust MAC estimates. More details about this MAC study and its integration with the present analysis are provided in "Methods and data."

The main objectives of this research are to assess the GHG mitigation potential of carbon policies targeting ruminant sector producers, with particular emphasis on the additional mitigation potential, as well as the adjustment challenges posed by market-based policy instruments. We test alternative policy designs, which differ with respect to their emphasis on either maximizing mitigation potential or minimizing negative impacts on ruminant producers and consumers. Finally, we draw on a key model revision, namely the specification of dairy as a multiproduct (meat and milk) industry, to provide additional insights about the structural impact that carbon policies would have on the ruminant sector.

3.2 Methods and data

3.2.1 Modeling framework

The analysis in this study is based on a version of the general equilibrium model known as the Global Trade Analysis Project–Agro-Ecological Zone–Greenhouse Gas (GTAP-AEZ-GHG) model (Golub et al. 2013; Hertel et al. 2009). The GTAP-AEZ-GHG model is based on GTAP-E model (Burniaux and Truong 2002; McDougall and Golub 2007), which was initially designed for analyzing energy–economy and environment–trade linkages. The GTAP-E model is in turn based on the standard GTAP model (Hertel 1997). In GTAP-AEZ-GHG, as well as in the standard GTAP model, the regional household collects all factor earnings and taxes. The regional household spends its income according to a Cobb-Douglas expenditure function and derives its utility from three sources: private expenditure, government expenditure, and saving. Private household expenditures on goods and services are determined by a constant difference of elasticity expenditure function. Intermediate inputs (demanded by producers) and final consumption goods (demanded by private households and government in each region) are traded across regions. The Armington approach to trade is employed so that domestic and imported goods and imports coming from different countries/regions are imperfect substitutes. The model assumes perfect competition, constant returns to scale, and profit and utility maximizing behavior of firms and regional households, respectively. Production sectors are modeled using nested constant elasticity of substitution functions. The model also assumes that all markets are in equilibrium. Factor market clearing requires that supply equals demand for skilled and unskilled labor and capital, natural resources and land, and adjustments in each of these markets in response to the climate policy determine the resulting factor price impacts.

The GTAP-AEZ-GHG model extends the GTAP-E and standard GTAP models by incorporating land use and GHG emissions modules. Within each region of the model, the land endowment is split into agro-ecological zones (AEZs) (Lee et al. 2009) to capture heterogeneous environmental and economic characteristics of land use activities. The model incorporates detailed non-CO2 GHG and CO2 emissions mapped directly to regions and economic sectors. For the analysis presented here, the GTAP-AEZ-GHG model database was extensively modified to permit a more accurate representation of production, consumption, emissions, and abatement in the global livestock sectors. The GTAP-AEZ-GHG model described by Golub et al. (2013) was based on GTAP version 6 database, representing global economy in 2001. Using GTAP version 7 database (Narayanan and Walmsley 2008), Irfanoglu (2013) updated the model to a base year of 2004. The latter serves as a starting point in the analysis presented in the current paper. Next, the standard GTAP ruminant sector was split into large ruminant and small ruminant meat sectors. The large ruminant sector is almost exclusively comprised of cattle, whereas the small ruminant sector comprises sheep and goats. Following this, we took steps to create a multiproduct dairy sector, producing both meat and milk, based on all animals in the herd that are required to support the production of milk, including milk cows, breeding animals, and animals fattened for meat production as a by-product of the dairy herds. This involved separating the cattle meat associated with our broadly defined dairy sector from the large ruminant sector and then linking this dairy meat commodity to the GTAP dairy sector. In this new dairy sector, meat and milk are produced as joint products. The production and consumption structures of GTAP-AEZ-GHG model were also modified to introduce substitution between ruminant meat produced by the multiproduct dairy sector and meat produced by the specialized beef sector, to reflect that these two meat products are close substitutes.

The standard GTAP database follows the format of one produced commodity per sector. The introduction of a multiproduct dairy sector in our analysis was motivated by the need to account for the vastly different emission intensities of meat produced by the dairy and specialized beef cattle herds. Gerber et al. (2013) estimate that meat from the latter is nearly four times as emission intensive as meat from the dairy herd (Gerber et al. 2013). This large difference in emission intensities relates to the size of the breeding herd overhead and the volume of outputs produced by each production system. As explained by Gerber et al. (2013), the breeding herd overhead refers to the animals in the herd that are dedicated to reproduction rather than production. The breeding herd is the main source of emissions in cattle systems due to their relatively large size and the low quality of feed they receive compared to either milk cows or cattle being fattened. Globally, reproductive animals comprise 69% of the specialized beef herd and only 52% of the dairy herd (Gerber et al. 2013). Moreover, because the dairy herd produces both milk and meat, its GHG emissions are spread over a greater volume of products, both in terms of protein content and economic value, than for specialized beef. Given these differences in emission intensities, we expect that carbon policies will lead to a contraction of meat supplied from the specialized beef sector relative to the dairy sector. To modify the database and create a multiproduct dairy sector, we relied on data from Global Livestock Environmental Assessment Model (GLEAM) (Gerber et al. 2013), which specifies the proportion of cattle meat from dairy herds and beef herds. GLEAM is a spatial model of livestock production, which models the biophysical relationships between livestock populations, production, and feed inputs for each livestock production system and country in the world (Gerber et al. 2013; Opio et al. 2013). The model has been cross-validated across a range of ruminant production systems, and regions, and publications based on GLEAM have been through rigorous peer review (Gerber et al. 2013; Opio et al. 2013). In addition, the GHG emissions corresponding to the newly created ruminant sectors in the GTAP database were also updated using GLEAM. The abatement responses for each ruminant sector and region were then calibrated to the recently published MAC curves by Henderson et al. (2017). This was done by linking animal GHG emissions [methane (CH_4) and nitrous oxide (N_20)] to the products of each ruminant sector and then, while constraining output quantities and input prices to match the assumptions of the MAC curves, we adjusted an elasticity parameter governing the trade-off between production resources and emissions to match the mitigation response of Henderson et al. (2017) MAC curves at the selected carbon price of \$20 $tCO_2\text{-}eq^{-1}$.

3.2.2 Emissions and marginal abatement costs

For the purposes of brevity and ease of exposition, the data and results are aggregated into nine global regions, namely South Asia (S Asia), Latin America (L America), Sub Saharan Africa (SSA), East and South East Asia (E and SE Asia), Middle East and North Africa (MENA), Russia and Central Asia (Russia and CA), Europe, Oceania and North America (N America), and two ruminant sectors (multiproduct dairy sector and a combined beef and small ruminant (BSR) sector). This ruminant sector aggregation was also motivated by the management similarities between beef and small ruminants, compared to the relatively more intensively managed dairy sector. Total global ruminant GHG emissions from enteric fermentation and manure sources amount to about 3.36 GtCO2-eq year−1, with 45% from the dairy sector and 55% from the BSR sector (Figure 3.1). Key regions for emissions are L America, S Asia, SSA, E and SE Asia, followed by N America, Europe, and MENA. This order of emission contributions closely corresponds to size of the ruminant populations in each region.

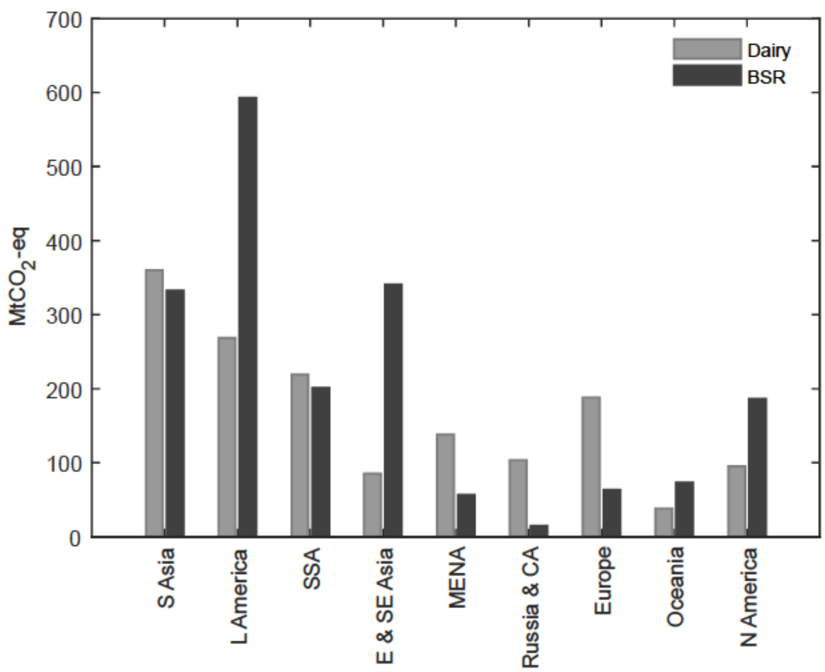

Figure 3.1 Ruminant GHG emissions (CH_4 and N_2O from enteric fermentation and manure) by region and sector

As articulated by Avetisyan et al. (2011) and Hertel et al. (2009), the cost and therefore the mitigation incentive of a carbon price-based policy depends on the economic emission intensity of a sector's output. That is, the amount of GHG emissions from a sector divided by the economic value of its output. For any carbon price, this will determine the relative cost of the carbon tax to producers. Since ruminant products are one of the most emission-intensive products in the agricultural sector (Golub et al. 2009), we expect carbon prices to generate relatively large mitigation incentives in these sectors. An additional factor influencing the cost of the policy is the flexibility with which producers can reduce emissions without compromising production. This depends on the availability of affordable options for lowering their emission intensity. As shown by Beach et al. (2008), Moran et al. (2011), and Henderson et al. (2017), there are a number of low-cost mitigation options that can raise productivity and lower the emission intensity of ruminant outputs at the same time (e.g., improved feed quality). In these studies, the MAC curves were estimated under assumptions that typify MAC assessments, such as constant output quantities as well as constant input and output prices. These curves describe incremental increases in the costs of reducing GHG emissions using a range of practices. These marginal costs increase as the cheapest abatement options are exhausted initially, followed by increasingly more expensive options. Given the importance of the MAC curves from Henderson et al. (2017) in influencing the mitigation outcomes of this study, we provide a brief summary of the options and approach used in that study, but refer readers to the paper for further details.

Henderson et al. (2017) advanced on previous assessments by incorporating spatial heterogeneity in the costs and benefits of abatement practices to calculate marginal costs rather than more commonly reported average costs of abatement. Five of the most promising available abatement options were selected by Henderson et al. (2017), based on agreement in the literature about their effectiveness and suitability under a wide range of ruminant production systems. These options included improved grazing management and the sowing of legumes to sequester soil carbon in grazing lands, as well as the feeding of dietary oils and the urea treatment of crop straws to target enteric CH_4. Henderson et al. (2017) estimate that 249 metric megatons of CO_2 equivalent emissions ($MtCO_2$-eq) could be abated by all ruminant sectors collectively each year at a carbon price of \$20 $tCO_2\text{-eq}^{-1}$. Nearly three quarters of this mitigation potential was from grazing land measures that sequester soil carbon (improved grazing management and legume sowing), with the remaining contribution from the dietary measures that targeted reductions in enteric (CH_4) emissions.

We use these results from Henderson et al. (2017) as a benchmark in this study to represent the quantity of emission reductions possible at \$20 $tCO_2\text{-eq}^{-1}$ under the usual MAC curve assumptions of constant output and prices. As with other MAC studies, this benchmark does not consider market interactions, which can alter input and output prices and lead to a substitution towards less emission-intensive products by producers and consumers, and change the costs of mitigation, especially when applied at a large scale. We test two scenarios to account for these effects which have the potential to significantly alter mitigation outcomes, as outlined below.

3.2.3 Policy scenarios

As policy arrangements for the post-2020 period, following expiry of the Kyoto Protocol, are still taking shape, we kept our policy scenarios as general as possible. Two global policy scenarios inclusive of both abatement practices and market interactions were tested and compared to the MAC benchmark which is a purely practice-based mitigation scenario:

MAC benchmark: Practice-based mitigation of ruminant GHG emissions at \$20 $tCO_2\text{-eq}^{-1}$.

Scenario 1: Market and practice-based mitigation with a \$20 $tCO_2\text{-eq}^{-1}$ tax levied on ruminant producers' GHG emissions.

Scenario 2: Market and practice-based mitigation with a \$20 $tCO_2\text{-eq}^{-1}$ tax levied on ruminant producers' GHG emissions, combined with an output subsidy to offset the cost of the tax.

The MAC benchmark represents the quantity of mitigation that would be possible from implementing abatement practices in the absence of market interactions. It serves as a useful benchmark to compare the subsequent scenarios against, to demonstrate the important role that these interactions play. Scenario 1 is purely motivated by the objective of enhancing economic efficiency, since taxing producers' entire volume of emissions is the most efficient approach to deal with externalities such as GHGs. This approach is economically efficient because, according to economic theory on managing externalities, it creates the correct incentives for producers with high emission intensities to adjust production practices or exit the industry and prevents new emission intensive entrants (Baumol and Oates 1988). This approach however ignores the obvious political resistance that such a policy will generate and the important competing objectives of economic development and food security. Scenario 2 takes these concerns into account and returns the carbon tax revenue collected to producers in the form of an output price subsidy. In doing so this policy seeks to maintain marginal incentives to abate emissions, while compensating producers for the cost of the policy associated with GHG emissions that are too expensive to reduce at the given carbon price. With both policy instruments (Scenario 1 and Scenario 2), the tax on emissions provides an incentive for producers to expend resources to offset or abate emissions. The increase in resource use incurs additional costs and therefore only occurs to the point where the cost of an additional unit of resources (i.e., the marginal cost) is equal to the carbon price of \$20 $tCO_2\text{-}eq^{-1}$. This results in an increase in the price of supplying ruminant products because the additional resources expended to reduce emissions and, in Scenario 1, the unabated taxed emissions increase production costs. We expect the latter costs to dominate in Scenario 1 and result in a significant increase in the price of ruminant products, and cause a corresponding reduction in demand and output. Since the tax costs imposed on unabated emissions are negated by a subsidy in Scenario 2, producers should be able to sell their products at a more competitive price than in Scenario 1, and they should therefore be able to maintain their output at close to baseline levels.

3.2.4 Sensitivity analysis

To address possible model and data uncertainty, we conducted a sensitivity analysis on a selection of key model parameters and emissions data. We implemented the Gaussian Quadrature approach to systematic sensitivity analysis developed by DeVuyst and Preckel (1997). For economy-wide equilibrium models such as the one used in this study, this approach is preferred to Monte Carlo methods because it requires much fewer number of solutions. The procedure follows Pearson and Arndt (1998) and generates a mean and standard deviation for each endogenous variable based on the uncertainty underpinning key economic parameters in the model. As mentioned, the GTAP-AEZ-GHG model employs an Armington assumption for the trade of goods, whereby domestic and imported goods are imperfect substitutes, and the same holds true for imports coming from different regions. How easily a region can change the composition of its imports and split between domestic and imported varieties in response to a policy is determined through the value of the Armington trade elasticity. If the trade elasticity is small, then the scope for sourcing from countries with low emission intensities of production and/or from countries with many cheap abatement options is limited. On the other hand, with very high trade elasticities, the global distribution of production will be much more sensitive to any cost differentials that emerge due to the carbon policy, and we will see much larger output and emission reductions in emission-intensive ruminant sectors. Due to the critical role that Armington parameters play in determining these trade patterns, we consider sensitivity of the results with respect to the trade elasticities, both among imports and between composite of imports and domestic goods and services. We also included two other important parameters in the sensitivity analysis, namely the calibrated MAC elasticities that determine responsiveness of mitigation to the carbon price policies in each ruminant sector and region, and the region and sector-specific emission intensities of ruminant production. For each of these parameters, we specified symmetric triangular distributions, assumed the parameters range from 0.5 to 1.5 times the central value, and varied all of the parameters together. That is, if one parameter is over-estimated, then all of them are. The latter assumption will give us the maximum standard deviation of the results and hence the most conservative confidence interval.

3.3 Results

3.3.1 Scenario 1

The results in this study reflect average annual changes over the medium term (i.e., an approximate 20-year period). The global mitigation results presented in Figure 3.2 clearly reveal the power of market incentives. By harnessing important market interactions such as product substitution and trade in Scenario 1, it was possible to generate a massive additional increase in the overall quantity of emission reductions from 249 to 626 $MtCO_2$-eq $year^{-1}$. This is because the taxed ruminant products in emission-intensive regions and sectors become more expensive and are substituted by other meat products and ruminant products from less emission-intensive regions and sectors.

Three quarters of the total emission reductions under the global carbon tax are from the BSR sector, with the remaining quarter provided by the dairy sector (Table 3.2). Notably, most of the reduction in ruminant emissions stems from reductions in output (71%), as the fall in consumer demand due to higher prices from the carbon tax dominate the reductions achieved by lowering emission intensities. This is most clearly the case in the BSR sector, where the combination of relatively high emission intensities and low capacity for abatement results in larger contraction in global output (5% for BSR compared to 1% for dairy). The Scenario 1 tax causes a value weighted average reduction in global ruminant production of only 2%; however, the low-income regions experience a disproportionate fall in production, especially for the BSR sector (Figure 3.3), because they tend to be more emission intensive.

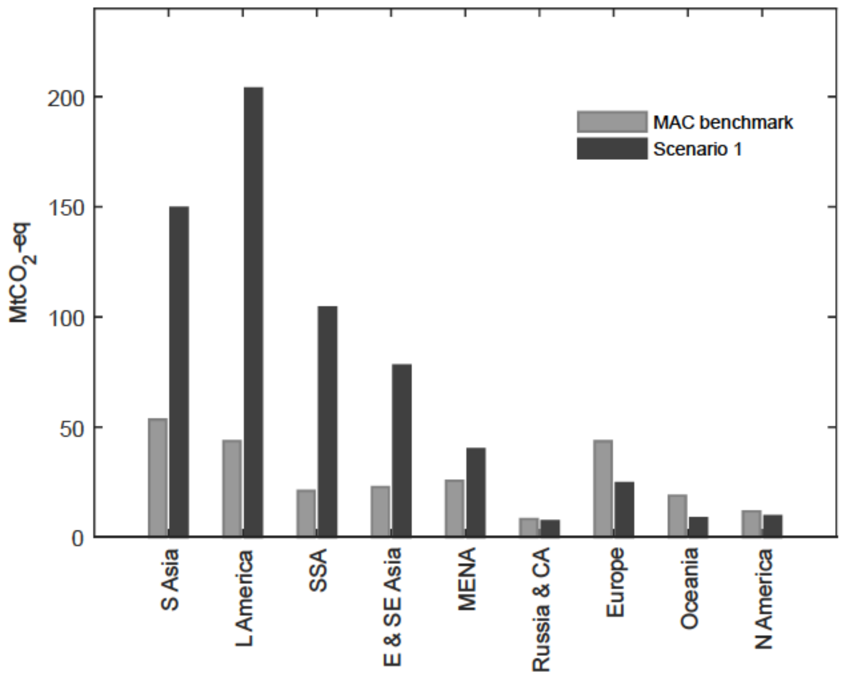

Figure 3.2 Annual GHG mitigation without market interactions (MAC benchmark) and with market interactions under global carbon tax of $20 tCO_2-eq (Scenario 1), by region, for all ruminant sectors combined

In contrast, output changes are either negligible or positive in N America, Europe, and Oceania (Figure 3.3) because products from these regions become relatively cheaper, leading to trade-based substitution of these products into markets previously supplied with more emission-intensive products. Consequently, market interactions lower the abatement potential of the sector in these regions (Figure 3.2).

The regional distributions of the emission reductions from the emission tax for each sector are shown in Figures 3.4 and 3.5, where mitigation is decomposed into emission reductions from changes in output and changes in emission intensities. While most of the emission reductions from the dairy sector arise in S Asia, SSA, L America, and MENA, Europe is not far behind, and in terms of the volume of mitigation achieved by lowering the emission intensity of production, it is second only to S Asia. Naturally, in regions where dairy products are more emission intensive (e.g., S Asia, SSA, MENA, and L America), output reductions drive a much larger share of their mitigation potential.

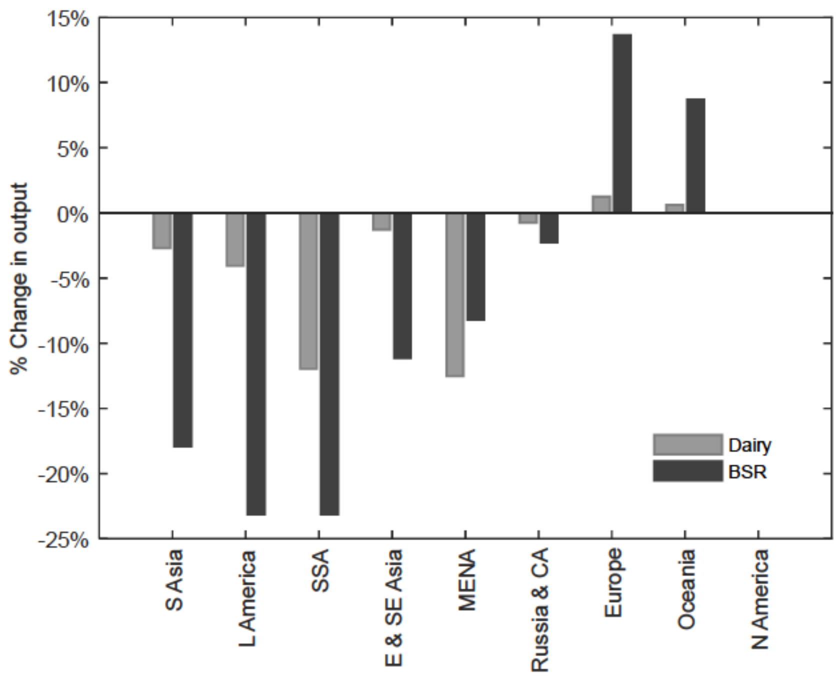

Figure 3.3 Annual percentage changes in ruminant output under the global \$20 tCO_2-eq carbon tax (Scenario 1), by sector and region

A similar regional pattern of mitigation emerges for the BSR sector, with S Asia, SSA, and L America again among the top 3 regional sources of emission reductions, although this time E and SE Asia displaces MENA in fourth position given the relatively large share of world's BSR production in E and SE Asia, particularly in China. In both sectors, the same three regions (Europe, Oceania, and N America) display either flat or slightly increasing output as higher export demand for products with relatively low emission intensities from these regions offset the additional costs imposed by the emissions tax.

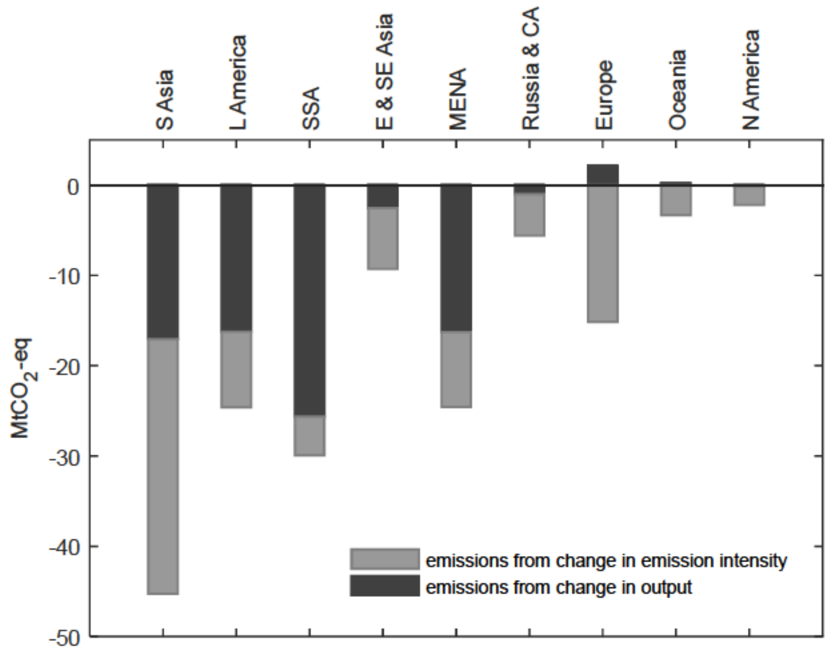

Figure 3.4 Annual mitigation of dairy sector emissions in Scenario 1, decomposed into emission reductions from falling output and from lower emission intensities, by region

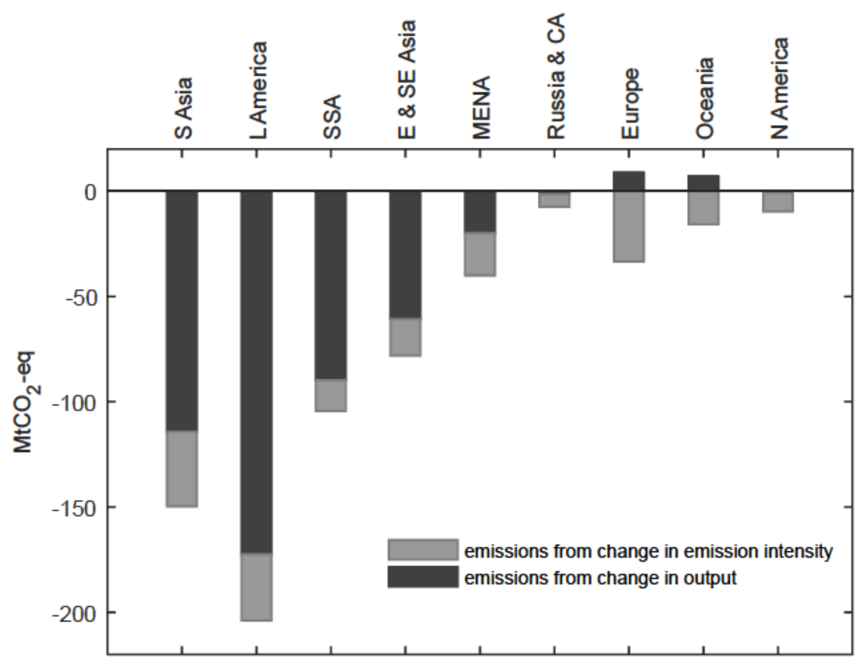

Figure 3.5 Annual mitigation of BSR sector emissions in Scenario 1, decomposed into emission reductions from falling output and from lower emission intensities, by region

We now turn our attention to the impact that a global ruminant carbon tax could have on reallocating the shares of meat supplied from the beef and dairy sectors. As mentioned, the dairy sector in this study includes the entire dairy herd, which operates as a multiproduct system supplying both milk and meat products. Since meat produced by the dairy sector is much less emission intensive than meat from the beef sector, the global carbon tax led to an increase in the share of cattle meat supplied by the dairy sector and an equivalent contraction in the share of meat supplied by the beef sector (Figure 3.6 and Table 3.1).

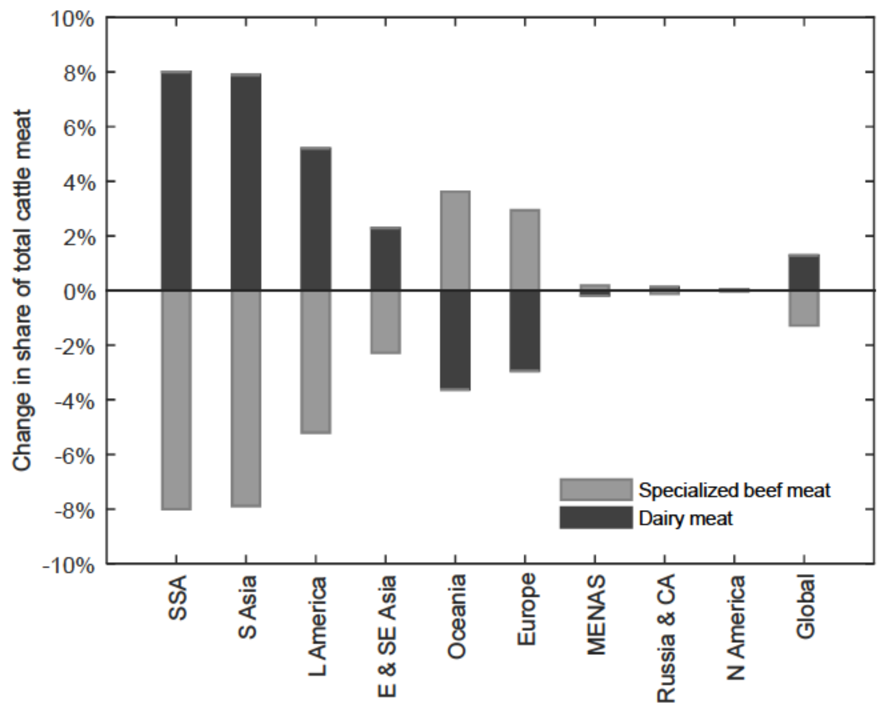

Figure 3.6 Annual percentage changes in cattle meat supplied from dairy and beef sectors the global \$20 tCO_2-eq carbon tax (Scenario 1), by region

For S Asia and SSA, the shift towards meat supplied from the dairy sector is relatively large by 8%. In contrast, there is an offsetting influence in Oceania and Europe where beef production and exports increase to make up for some of the fall in cattle meat production in low-income regions. The combined effect is a 1.3% increase in meat from dairy at the global level. While this shift towards a sector that is less emission intensive represents an improvement in resource use efficiency, the negative impacts on production in low-income regions calls into question the suitability and political feasibility of such a blunt policy option. In addition, from a purely practical perspective, it would be very difficult to collect tax payments from lo-income producers given that they are unlikely to be able to afford the additional expense. Thus, for carbon policies to be feasible in these contexts, some form of compensation for affected producers will be necessary.

Table 3.1 The percentage shares (%) of cattle meat from dairy and beef sectors by region, in the baseline and in Scenario 1

	S Asia	L America	SSA	E & SE Asia	MENA	Russia & CA	Europe	Oceania	N America
Baseline									
Dairy meat	60	33	69	34	97	99	75	39	27
Beef meat	40	67	31	66	3	1	25	61	73
Scenario 1									
Dairy meat	68	38	77	36	97	100	73	36	27
Beef meat	32	62	23	64	3	0	27	64	73

3.3.2 Scenario 2

With these concerns in mind, we now explore the impacts of the policy instrument in Scenario 2, which returns the emissions tax revenue to producers as an output subsidy. The results in Figure 3.7, Figure 3.8, Table 3.2, and Table 3.3 reveal the striking effectiveness with which this policy instrument can maintain output and consumption levels, while delivering reasonable mitigation outcomes. The total global reduction in emissions from this policy is 185 $MtCO_2$-eq year^{-1}, of which 99% is achieved by reducing emission intensities. While the carbon tax policy delivers much larger emission reductions, the amount of mitigation achieved by lowering emission intensities is virtually identical to that achieved in Scenario 2.

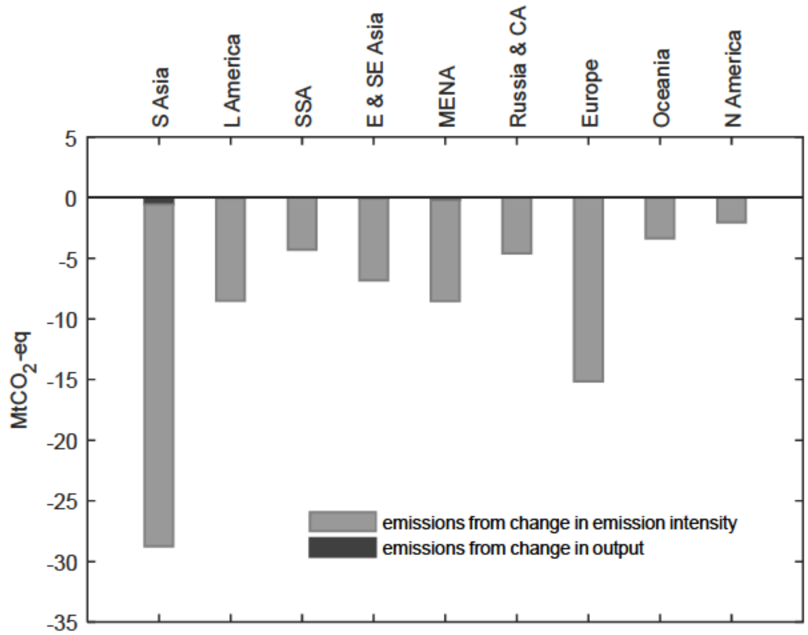

Figure 3.7 Annual mitigation of dairy sector emissions in Scenario 2, decomposed into emission reductions from falling output and from lower emission intensities, by region

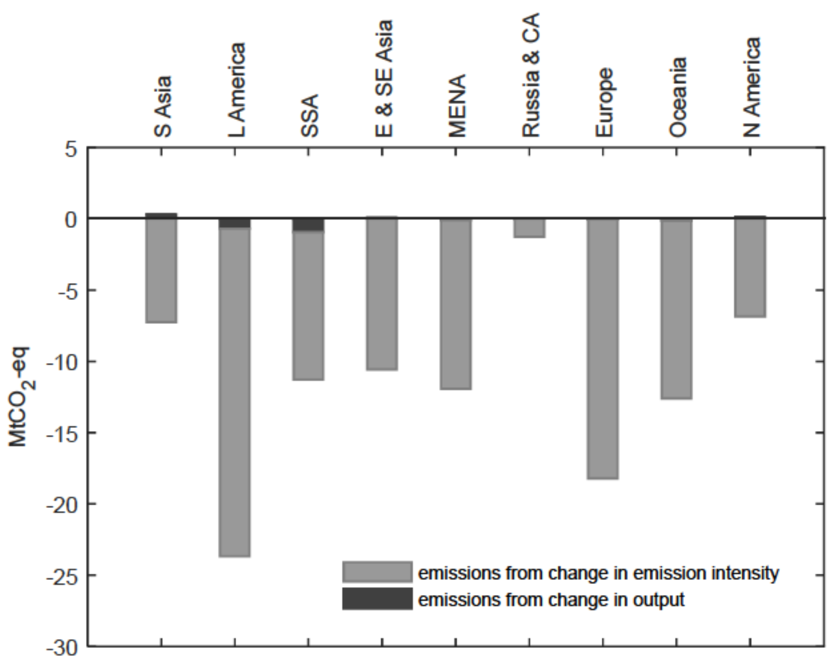

Figure 3.8 Annual Mitigation of BSR sector emissions in Scenario 2, decomposed into emission reductions from falling output and from lower emission intensities, by region

The largest differences in total mitigation between the two scenarios are for the BSR sector, where the overwhelming share of mitigation under the carbon tax came from a fall in production (Table 3.2). As with Scenario 1, S Asia, L America, and MENA are in the top 4 mitigating regions for the dairy sector (Figure3.7). However, this time, Europe is in second spot and SSA makes a relatively minor contribution. This is mainly due to the greater mitigation opportunities in Europe (Henderson et al. 2017). For the BSR sector, there are larger differences in the regional pattern of abatement for Scenario 2 (Figure 3.8) compared with Scenario 1 (Figure 3.5). While L America is still the dominant contributor, this time, Europe, Oceania, and MENA occupy the remaining top 4 places, instead of S Asia, SSA, and E and SE Asia. This again relates to the greater effectiveness and feasibility of mitigation options in these regions (Henderson et al. 2017).

Table 3.2 Summary of the global GHG mitigation outcomes for the ruminant sectors under Scenario 1 and Scenario 2, decomposed into emission reductions from falling output and from lower emission intensities

Sector	Source	Scenario 1 mitigation ($MtCO_2$-eq)	Scenario 2 mitigation ($MtCO_2$-eq)
Dairy	**Dairy total**	**158**	**82**
	Share of total reduction	(25%)	(44%)
	Emission intensity reduction	81	81
	Share of Dairy reduction	(51%)	(99%)
	Output reduction	77	1
	Share of Dairy reduction	(49%)	(1%)
Beef & Small ruminants	**BSR total**	**468**	**103**
	Share of total reduction	(75%)	(56%)
	Emission intensity reduction	101	102
	Share of BSR reduction	(22%)	(99%)
	Output reduction	367	1
	Share of BSR reduction	(78%)	(1%)
Total	**Total**	**626**	**185**
	Emission intensity reduction	182	183
	Share of total reduction	(29%)	(99%)
	Output reduction	444	2
	Share of total reduction	(71%)	(1%)

From a food security perspective, the Scenario 2 policy instrument does far better than the pure carbon tax in Scenario 1. The near maintenance of both dairy and BSR production (Figures 3.7 and Figure 3.8) is also reflected in the changes in household consumption of unprocessed and processed ruminant products shown in Table 3.3. Here, the relatively large falls in consumption under

Scenario 1, particularly in low-income regions, are virtually eliminated in Scenario 2, as the output subsidy allows producers maintain their product prices at a near baseline levels.

Table 3.3 Percentage changes (%) in household consumption of unprocessed and processed (proc.) ruminant products in each policy scenario

	S Asia	L America	SSA	E & SE Asia	MENA	Russia & CA	Europe	Oceania	N America
Scenario 1									
Milk	-2.9	-5.4	-13.6	0.7	-7.7	-0.9	0.9	-0.4	-0.8
Meat	-5.7	-12.0	-11.9	-11.0	-10.1	-2.0	-4.4	-6.2	-5.6
Proc. dairy	-1.3	-2.6	-11.5	-1.5	-12.2	-0.1	0.2	-0.3	-0.3
Proc. meat	-2.9	-8.1	-12.6	-1.2	-4.8	-1.2	0.7	-2.3	-2.4
Scenario 2									
Milk	-0.1	0.0	-0.1	0.0	-0.1	0.0	0.0	-0.1	0.0
Meat	0.0	-0.2	-0.1	-0.1	-0.2	-0.1	-0.1	-0.2	-0.1
Proc. dairy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Proc. meat	0.0	-0.1	-0.1	0.0	-0.1	0.0	-0.1	-0.1	0.0

Note – meat is a composite of meat from all ruminant sectors (dairy, beef and small ruminants)

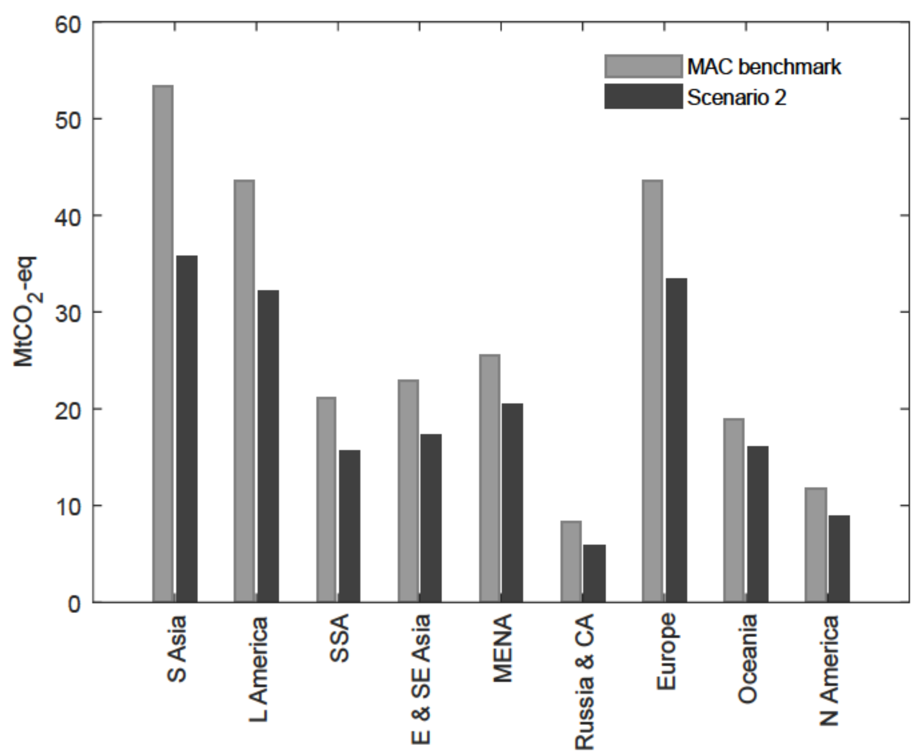

Figure 3.9 Annual GHG mitigation without market interactions (MAC benchmark) and with market interactions under the global carbon tax/subsidy instrument (Scenario 2), by region, for all ruminant sectors combined

In contrast to Scenario 1, the market interactions associated with policy Scenario 2 lower the quantity of emissions reduced when compared to the MAC benchmark (Figure 3.9). The 185 $MtCO_2$-eq year^{-1} mitigation potential from Scenario 2 is around three quarters of that achieved under MAC benchmark, in the absence of market interactions. This occurs because the global scale of the mitigation effort has the effect of increasing the price of the resources associated with mitigating emissions. If instead the Scenario 2 policy was implemented in one sector and country at a time, the mitigation outcome would be nearly identical with the MAC benchmark. Further discussion about the role of market interactions under different policy settings is given in Section 3.4.

3.3.3 Sensitivity analysis

The sensitivity of the GHG mitigation results to the parameter variations for Scenario 1 is displayed by region and sector in Table 3.4. For ease of interpretation, we focus on the coefficient of variation (CV), which is the ratio of the standard deviation to the absolute value of the mean. A low CV corresponds to an outcome in which we can place greater confidence in the results. We consider a CV value of 0.5 (i.e., where the mean is twice the standard deviation) as a threshold to indicate whether the model results are robust or not. Under the assumption of normality, a CV of less than 0.5 indicates that 95% confidence interval does not include zero. On this basis, the results are robust with respect to the parameter variations, with coefficients of variation below 0.5 for all regions and sectors except for the BSR sector in Oceania. This is a reassuring outcome that provides a reasonable degree of confidence in the overall performance of the model.

Table 3.4 Sensitivity of the GHG mitigation results ($MtCO_2$-eq yr^{-1}) by region and sector with respect to trade elasticities, MAC elasticities and emission intensities

	Dairy sector			BSR Sector		
Region	**Mean**	**St. deviation**	**CV**	**Mean**	**St. deviation**	**CV**
S Asia	-45.78	12.96	0.28	-105.96	32.78	0.31
L America	-24.99	7.86	0.31	-180.34	53.05	0.29
SSA	-30.73	11.08	0.36	-74.96	21.34	0.28
E & SE Asia	-9.39	2.74	0.29	-70.14	25.26	0.36
MENA	-25.13	8.37	0.33	-15.60	4.12	0.26
Russia & CA	-5.64	1.64	0.29	-1.75	0.49	0.28
Europe	-13.21	3.72	0.28	-11.59	3.31	0.29
Oceania	-3.13	0.90	0.29	-5.56	3.21	0.58
N America	-2.21	0.61	0.28	-7.51	2.41	0.32

3.4 Discussion

3.4.1 Summary of findings and insights

The findings from this study reveal that the market impacts from carbon price policies substantially affect mitigation outcomes, especially when implemented at a global scale. These effects can work to enhance mitigation outcomes by encouraging the substitution of emission intensive products for cleaner products or diminish mitigation outcomes by raising the use and prices of resources needed for mitigation. The strength of these counteracting effects depends on the nature of the policy instrument being implemented. Under the Scenario 1 emissions tax, the substitution incentives from significantly higher costs of ruminant production dominate the outcome, resulting in a dramatic 151% increase the total mitigation potential at \$20 tCO_2-eq^{-1} from 249 $MtCO_2$-eq year^{-1}, estimated in the MAC benchmark, to 626 MtCO2-eq year^{-1}. This represents a 17% reduction of global ruminant emissions. On the other hand, the 185 $MtCO_2$-eq year^{-1}of mitigation potential from policy Scenario 2 is well short of the potential achieved in the MAC benchmark. In this case, the subsidy component in Scenario 2 nullified the market substitution effects, leaving higher prices of mitigation resources as the dominant market impact.

Apart from their differing global mitigation potentials, the two policy options have very different impacts on production and consumption. There are also contrasting motivations for their inclusion in this study. Taxes that are applied to every unit of pollution are more economically efficient than policies with compensating subsidies because they create more appropriate entry and exit conditions for the sector. While policymakers are unlikely to employ such an approach (e.g., Scenario 1), it is nonetheless instructive from a normative viewpoint to understand what an economically efficient reconfiguration of production might look like. We can see from Scenario 1 that this reconfiguration includes an increase in dairy cattle production at the expense of specialized beef production, with a corresponding increase in the proportion of cattle meat supplied by the dairy sector at the global level. This restructuring stems from the more efficient and less emission-intensive nature of the dairy production, and it is felt most strongly in low-income countries.

The strong economic efficiency credentials of the pure emissions tax are diametrically opposed to its negative impacts on food security, producer, and consumer welfare in low-income countries. By contrast, the more politically acceptable tax/subsidy instrument (Scenario 2) was remarkably effective in maintaining the supply and consumption of ruminant products, thus providing a more realistic assessment of what could be achieved with a globally coordinated mitigation policy for the ruminant sector.

3.4.2 Comparisons with other studies

A key strength of this study is its use of recent and improved MAC curves for the ruminant sector (Henderson et al. 2017), which incorporate soil carbon sequestration (Henderson et al. 2015) and heterogeneity in mitigation costs among producers within regions and production systems. To date, comparable global analyses that explore market interactions such as Golub et al. 2013 and Avetisyan et al. (2011) and Wollenberg et al. (2016) have relied on MAC curves from the US Environmental Protection Agency (US EPA 2006; US EPA 2013), which excluded soil carbon and used an average cost accounting approach. With regard to mitigating animal emissions (i.e., CH4 and N2O from enteric and manure sources), the marginal costs which we use are higher than those from US EPA (2006 and 2013). For example, at \$20 tCO_2-eq, the global mitigation potential according Henderson et al. (2017) is 78 compared to 136 $MtCO_2$-eq $yr.^{-1}$ by US EPA (2013). The main reason for this discrepancy is that the former study applies stricter conditions for the inclusion and application of mitigation practices. A smaller portion of this discrepancy is due to the inclusion of some additional mitigation sources by US EPA (2013), namely manure CH_4 emissions from milk cows and pigs. The variability associated with these instruments can create industry resistance. The present study, which is based on interdisciplinary data synthesis and modeling, makes an important contribution to understanding the likely mean impacts of mitigation policies at a global scale. A valuable next step in this small but growing body of work is to assess the efficiency of different policy designs in the presence of risk aversion and uncertainty. As outlined by Herrero et al. (2016), this research needs to be conducted with due consideration to the broader goals of development, food and nutritional security, and adaptation to climate change. In particular, we need to develop the right policy settings and instruments to better manage these multiple and often competing goals.

3.5 Conclusions

With growing enthusiasm for action on climate change following the Paris Agreement and the establishment of the Carbon Pricing Leadership Coalition at COP 21, now is an opportune time to revisit the potential contribution that globally coordinated mitigation policies in agriculture could make. While ruminant production systems generate a substantial share of the world's GHG emissions, they can also play an important role in tackling climate change. This research provides policymakers with a quantitative basis for comparing policies that vary according the emphasis they place on mitigation effectiveness and economic efficiency versus producer and consumer welfare. The priority given to these objectives will naturally vary from country and result in a less uniform global application of policy designs and mitigation responses than assessed here. Nevertheless, there are several findings from this study that are relevant for a range of global policy configurations.

Firstly, we show that market-based mitigation policies can greatly amplify the mitigation potential identified in marginal abatement cost studies by harnessing powerful market forces such as product substitution and trade. A \$20 tCO_2-eq^{-1} carbon tax applied to ruminant emissions was shown to mitigate up to 626 $MtCO_2$-eq $year^{-1}$. However, the mitigation potential from the global carbon tax is some respects an upper bound because it causes global ruminant-based food production to fall and is therefore likely to encounter political resistance. This research also shows that carbon pricing could cause a restructuring of the cattle sector, by increasing dairy cattle production at the expense of specialized beef production, as cattle meat supplied by the dairy sector is less emission intensive. This insight can help policymakers and planners anticipate some of the structural changes that a more carbon-constrained future may bring, when mitigation policies are embraced more enthusiastically in the future.

To address the fall in ruminant production caused by the carbon tax, we introduced a producer subsidy to compensate producers for their tax expenses. This policy mechanism succeeded in preventing a decline in ruminant production in all global regions, but at the cost of a substantially reduced global mitigation potential of 185 $MtCO_2$-eq $year^{-1}$ (5% of global ruminant GHG emissions). Given its obvious importance for food security and human welfare, the case for compromising on mitigation effectiveness to maintain production is arguably stronger for agriculture than for other sectors of the economy. Accordingly, our main global mitigation strategy recommendation is for policymakers and mitigation advocates to promote the uptake of hybrid tax-subsidy instruments, such as presented in Scenario 2 of this study. While the subsidy component of this instrument does water down the mitigation potential of the emissions tax, it does offer policymakers with a blueprint for meeting the Paris Agreement ambition to reduce agricultural emissions while protecting food production. Moreover, since this instrument can maintain ruminant production levels, it has the potential to accommodate a more ambitious carbon price that is closer to the marginal rate of damage for GHG emissions, such as the \$85 tCO2-eq^{-1} estimated by Stern (2007), without compromising its political expediency. However, as the carbon price increases, trade-offs between mitigation and the welfare of producers and consumers will emerge, as the price of abatement and production resources rise.

Finally, whichever carbon policy approach is eventually pursued, it is clear from this and related research that carbon policies which target livestock producers are unlikely to reduce a very substantial share of global emissions. As shown by Herrero et al. (2016), dramatically higher emission reductions could be possible by reducing the share of red meat in human diets. For this reason, we also recommend that more research be done on designing feasible and equitable policy approaches to reduce demand for ruminant products, particularly in high income countries where there are negative health impacts associated with the overconsumption of red meat (Tilman and Clark 2014).

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STATEMENT OF AUTHORS' CONTRIBUTION

We, the PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

	Author's Name (please print clearly)	**% of contribution**
Candidate	Benjamin Henderson	80
Other Authors	Alla Golub	5
	Daniel Pambudi	5
	Thomas Hertel	2
	Cecile Godde	2
	Mario Herrero	2
	Oscar Cacho	2
	Pierre Gerber	2

Name of Candidate: **Benjamin Henderson**

Name/title of Principal Supervisor: **Prof. Oscar Cacho**

[redacted]

06 / 04 / 2018

Candidate

Date

[redacted]

09/04/2018

Principal Supervisor

Date

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We, the PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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Name of Candidate: **Benjamin Henderson**

Name/title of Principal Supervisor: **Prof. Oscar Cacho**

[redacted]

06 / 04 / 2018

Candidate　　　　Date

[redacted]

09/04/2018

Principal Supervisor　　　　Date

Chapter 4: Closing system-wide yield gaps to increase food production and mitigate GHGs among mixed crop–livestock smallholders in Sub-Saharan Africa

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Chapter 4: Closing system-wide yield gaps to increase food production and mitigate GHGs among mixed crop–livestock smallholders in Sub-Saharan Africa

Abstract

In this study we estimate yield gaps for mixed crop-livestock smallholder farmers in seven Sub-Saharan African sites covering six countries (Kenya, Tanzania, Uganda, Ethiopia, Senegal and Burkina Faso). We also assess their potential to increase food production and reduce the GHG emission intensity of their products, as a result of closing these yield gaps. We use stochastic frontier analysis to construct separate production frontiers for each site, based on 2012 survey data prepared by the International Livestock Research Institute for the Climate Change, Agriculture and Food Security program. Instead of relying on theoretically optimal yields—a common approach in yield gap assessments—our yield gaps are based on observed differences in technical efficiency among farms within each site. Sizeable yield gaps were estimated to be present in all of the sites. Expressed as potential percentage increases in outputs, the average site-based yield gaps ranged from 28 to 167% for livestock products and from 16 to 209% for crop products. The emission intensities of both livestock and crop products registered substantial falls as a consequence of closing yield gaps. The relationships between farm attributes and technical efficiency were also assessed to help inform policy makers about where best to target capacity building efforts. We found a strong and statistically significant relationship between market participation and performance across most sites. We also identified an efficiency dividend associated with the closer integration of crop and livestock enterprises. Overall, this study reveals that there are large yield gaps and that substantial benefits for food production and environmental performance are possible through closing these gaps, without the need for new technology.

Keywords: productivity; yield gap; emission intensity

4.1 Introduction

Smallholder farming systems in Sub-Saharan Africa are known to have sizeable yield gaps (Tittonel and Giller 2013; Dzanku et al. 2015; Nin-Pratt et al. 2011) and to therefore have large potential for increasing food production. The yield gap concept is commonly used in agronomic assessments, which compare observed yields with maximum potential yields under certain agro-ecological conditions for a particular region. As noted by Neumann et al. (2010), Nin-Pratt et al. (2011), and Dzanku et al. (2014) these potential yields are often overestimated because they are based on optimal conditions (e.g. where pests and diseases are effectively controlled) and often ignore practical regional and farm-level constraints (Rockström and Falkenmark 2000). A number of recent studies that focus on Africa and the globe, use statistical and mathematical programming approaches based on variations in observed yields, which can provide more realistic yield gap estimates (Neumann et al. 2010; Dzanku et al. 2014; Tittonel and Giller 2013; Baldos and Hertel 2012; Foley et al. 2011; Licker et al. 2010). These and other yield gap studies for Africa (Mutegi and Zingore 2014) and the globe (Rockström and Falkenmark 2010) are, however, limited as they do not include livestock. This is a significant omission given that most food production in Sub-Saharan Africa comes from mixed crop-livestock systems (Herrero et al. 2010).

Variations in farm productivity arise because of differences in production environments, production technologies, and the efficiency of production processes (Lovell et al. 1994). The scope for closing yield gaps depends on the degree to which each of these factors is responsible for the gap. For instance, it may not be possible to close the portion of the yield gap that is caused by an unfavourable production environment, because environmental variables such as precipitation are, for the most part, not under the discretion of farm managers. Conversely, part of the yield gap can be closed through management decisions including more precise matching of agronomic inputs and crop requirements (technical efficiency improvement), and through the adoption of more productive technologies such as improved animal breeds (Nin-Pratt et al. 2011).

This study is concerned with improving yield gaps through improvements in the efficiency of production, and it is based on the construction of separate production frontiers for mixed crop-livestock smallholder farmers in seven Sub-Saharan African sites covering six countries (Kenya, Tanzania, Uganda, Ethiopia, Senegal and Burkina Faso). In response to the growing interest from the research community in exploring nexus between productivity and environmental performance (Burney et al. 2010; FAO 2010; Gerber et al. 2013), we also assess the impacts of closing yield gaps on GHG emission intensities for livestock and crop products.

The frontier-based approach used in this study is also used by Neumann et al. (2010) and Baldos and Hertel (2012) to estimate global yield gaps for crops, however we consider both crops and livestock. The production frontiers estimated in this study are based on the most technically efficient farms within each site, and they represent the maximum amount of output that can be produced from the existing production inputs used by each farm. To accommodate the multiple-output nature of these production systems, we estimate distance functions using a stochastic frontier analysis (SFA) estimation procedure. This is a robust methodology with sound theoretical underpinnings in production economics, which also permits the statistical significance testing of model specifications (Coelli et al. 2005; Bogetoft and Otto 2011).

4.2 Data

Given the importance of livestock production among smallholders in Sub-Saharan Africa, this study addresses a crucial gap in the literature by estimating system-wide yield gaps for in these production systems. We use the term “system-wide” to convey that all farm production inputs and outputs (inclusive of both crops and livestock) are included in our yield gap estimates. Previous studies have only assessed yield gaps within crop enterprises. It also makes a unique contribution by exploring the effects of yield improvements for multiple outputs on the emission intensity of production.

The data for farm production and farm attribute variables used in this study come from the IMPACTlite database prepared by International Livestock Research Institute for the Climate Change, Agriculture and Food Security programme (Rufino et al. 2013), and is based on farm household surveys conducted over the 2012 calendar year. This study focuses on seven of the nine Sub Saharan African sites in this database covering six countries. Five of the sites are in East Africa (Nyando and Wote (Kenya); Hoima (Uganda); Lushoto (Tanzania); and Borana (Ethiopia)) and two are in West Africa (Yatenga (Burkina Faso); and Kaffrine (Senegal)). The two sites in West Africa are situated at less than 350 m altitude and have annual rainfalls ranging from 400 to 800 mm, with substantial year to year variability (Table 4.1). The sites in Eastern Africa show strong spatial heterogeneity of climate and topography, with low annual rainfall in Wote and in Borana and much higher rainfall in Hoima and Lushoto. Furthermore, rainfall predictability in Eastern Africa is relatively high and helps to reduce risks of crop failure. The remoteness, measured by proximity to nearest city, varies among the sites, with Borana being relatively more remote than that other sites. The key challenges that both West and Eastern Africa are facing are an increasing population, water stress, a widespread land erosion, a declining soil fertility and a high climate variability (Förch et al. 2013).

Table 4.1 Topographic, climatic and location characteristics of the sites

Study site	Elevation (m above sea level)	Rainfall (mm/yr)	Distance to main city[a] (km)	Main city's name - number of inhabitants
Nyando	1100-2500	900-1200	46	Kisumu – 259,258
Wote	900-1000	520	85	Machakos – 150,041
Hoima	620-1600	1400	36	Masindi – 94,622
Lushoto	900- 2250	1200– 1300	153	Tanga – 187,455
Borana	1000-2000	500-600	244	Arba Minch – 95,373
Yatenga	300-350	400-700	22.5	Ouahigouya – 73,153
Kaffrine	15-50	500-800	1	Kaffrine – 32, 942

Source: Förch et al. (2013) and SIPPEY (Système d'Information Populaire pour les Collectivités Locales au Sénégal) (2007).
[a] Distances to main city were calculated using Google Maps.

A selection of some the main production inputs and outputs from the surveys is also provided in Table 4.2. There is a diversity of production systems both across the sites, ranging from the agro-pastoral system in Borana, characterised by large ruminant herds relative to farm land area, to the more crop-based systems in Hoima and Kaffrine. Grain production is important in all sites, with vegetable production also significant in Hoima, Yatenga and Lushoto. Local ruminant breeds predominate across the study areas, with cross bred cattle more common in parts of Lushoto, Nyando (Rufino et al. 2013). The average farm sizes are similarly small in most sites with the exception of Hoima and particularly Kaffrine, where the farm sizes are appreciably larger.

From the survey data we constructed two aggregate output variables, one for livestock and one for crops, and five input variables including land, labour, animals, materials, and farm assets. All of the variables, except for land (ha) and labour (hours), are composites for which indices were required to aggregate their various components. For animals, tropical livestock unit (TLU) index was used to aggregate different animal types. This index takes into account the feed requirements of different animals and is therefore reflective of their varying resource requirements (ILRI 2011; FAO 2003). The standard measure for one TLU is one cattle with a body weight of 250 kg. By contrast a 30 kg sheep or goat with is equal to 0.2 TLUs, and is therefore assumed to consume 20 percent as much feed as 250 kg cow. For farm assets we relied on ILRI (2011) and BMFG (2010) to aggregate different asset classes. These included all productive farm assets including items such as ploughs, water pumps and wheelbarrows. The values assigned to each type of asset reflect their relative economic values. For example, a powered water pump has a value twelve times greater than a shovel and three times greater than a plough (ILRI 2011; BMFG 2010). For livestock products, crop products and materials (which includes fertilizers, seeds, pesticides, herbicides, feeds, vaccinations) we constructed Fisher quantity indexes (Diewert 1992). This required the use of quantity and price data from the IMPACTlite household survey database and, compared to most economic index numbers, the Fisher index has a number of desirable statistical properties including dimensional invariance (i.e. it is independent of the units of measurement used) and proportionality (i.e. if all quantities increase by the same proportion, then the index will increase by the same proportion) (Coelli et al. 2005). The Fisher indexes are dimensionless quantities that are relative to a "base farm" in each sample and, as such, they have no interpretative value and do not warrant inclusion in the Table 4.2. For the purposes of exposition we have included Fertilizer, one of main components of the Material input. Similarly the main livestock and crop products are also displayed in Table 4.2. The Fertilizer input summarised in Table 4.2 is a composite of all synthetic fertilizers used in each site. We have included the exact selection of input and output variables, including the Fisher quantity indexes that were used in each stochastic frontier model, in Appendix A (Table A4.1).

After cleaning the data and removing incomplete records we were left with an average of 146 farms per site: 181 in Nyando (3 observations removed); 150 in Wote (21 observations removed); 147 in Hoima (2 observations removed); 145 in Lushoto (30 observations removed); 168 in Borana (22 observations removed); 127 in Yatenga (25 observations removed); and 101 in Kaffrine (25 observations removed). Incomplete records were those identified as those missing key production inputs (e.g. land, labour, farm assets) as well as those with input data, but and no reported outputs.

Table 4.2 Production characteristics of the study sites: a selection of the main farm inputs and outputs

	Livestock (TLU index)	Labour (hrs)	Land (ha)	Farm assets (Index)	Fertilizer (kg)	Milk (lt)	Eggs (kg)	Grains (kg)	Legume-pulse (kg)	Vege-tables (kg)	Fruit (kg)
Nyando											
mean	6.8	981	4.3	12.9	2.5	988	209	1,150	132	229	62
st. dev	5.0	934	4.6	8.0	15.1	1,750	443	1,261	337	664	337
Wote											
mean	8.3	1,421	4.5	11.5		182	108	403	288	15	1,707
st. dev	6.1	1,048	3.3	7.4		276	113	430	267	143	3,928
Hoima											
mean	3.8	2,513	10.4	11.3	15.8	191	175	1,112	395	1,355	168
st. dev	5.9	1,890	15.3	5.6	117.5	845	203	1,592	670	1,582	625
Lushoto											
mean	2.2	2,858	2.1	7.7	33.4	664	88	477	179	796	286
st. dev	2.2	2,454	1.4	5.2	73.9	2,276	158	491	209	2,029	1,696
Borana											
mean	17.4	1,633	3.7	11.1		1,061	36	578	278		
st. dev	12.0	1,595	2.6	6.6		1,386	92	717	329		
Yatenga											
mean	9.1	2,332	4.6	14.5	65.0	77	28	1,534	400	853	38
st. dev	12.0	4,034	3.2	13.0	176.3	651	196	1,374	543	1,813	183
Kaffrine											
mean	10.0	4,474	26.3	12.8	333.1	133		2,354	3,015	246	1,066
st. dev	9.8	3,029	22.2	6.3	559.7	340		4,286	10,080	647	2,854

Seven farm and farmer attribute variables were also assembled and used in the analysis to test if they could explain some of the variations in farm performance in each site. These variables are displayed in Table 4.3 and they include: age of farm household head (years); gender of farm household head (dummy variable: value of 1 for female and 0 for male); off farm income (proportion of total household income from outside the farm); market participation (proportion of farm products that are sold, based on their value in local currency units); domestic assets (aggregated using index in ILRI (2011)) as a measure of overall household wealth; livestock specialization (proportion of total farm products that come from livestock, based on their value in local currency units); and household size (number of persons living in the farm household).

Table 4.3 The socio-economic attributes of farms and farmers in each study site

	Age of household head (yrs)	Off farm income (%)	Household size (hd)	Market participation (%)	Domestic Assets	Gender[a] (% female head household)	Livestock specialisation (%)
Nyando							
mean	50.3	15.9	5.8	35.5	21.7	20.4	34.9
st. dev	14.0	14.1	2.2	26.8	31.5		23.3
Wote							
mean	49.9	21.4	5.4	35.0	24.5	10.7	50.0
st. dev	13.1	41.9	2.0	21.3	41.2		23.6
Hoima							
mean	46.1	43.5	7.0	54.7	33.9	11.6	20.4
st. dev	13.6	126.3	2.7	23.7	35.6		22.5
Lushoto							
mean	51.3	20.5	4.8	39.3	9.2	27.6	19.5
st. dev	45.4	45.4	1.7	25.5	10.6		25.0
Borana							
mean	46.4	10.0	6.4	17.0	3.5	14.3	59.2
st. dev	15.2	26.7	2.4	21.9	3.0		24.6
Yatenga							
mean	50.3	78.6	10.6	31.4	64.3	4.7	33.3
st. dev	14.1	268.4	4.7	78.0	49.0		27.0
Kaffrine							
mean	53.0	27.4	12.4	38.4	29.5	1.0	24.8
st. dev	13.4	39.7	3.7	24.7	20.1		26.4

a The gender variable is modelled as a dummy variable, but for expository purposes it is displayed here as the percentage of female headed households in each site.

There are clear differences between the sites with regard to all of the attributes apart from the average ages of the farm household heads (Table 4.3). There are particularly large disparities in the reliance of off farm income, livestock specialisation and market participation. The geographically remote site of Borana has the lowest share of income from off farm sources, the lowest proportion of farm products sold into markets, and the highest specialisation in livestock production. This reflects the fact that ruminant production is possible on poor quality land, unsuitable for crop production, and often located in remote areas that are less accessible to markets. This relationship is supported by Frelat et al. (2015) who, using similar data sources, show that farm households that have poor market access are particularly dependent on livestock to meet their food energy requirements. At the other end of the spectrum is Hoima, with the highest degree of market participation and lowest reliance on livestock production.

4.3 Methods

4.3.1 Stochastic frontier analysis

Frontier efficiency methods for estimating technical efficiency have been around since mid-last century (following the work of Malmquist (1953), Shephard (1953) and Farrell (1957), who introduced the concepts of distance functions and efficiency measurement), but rose to prominence in the field of production economics much later (Coelli et al. 2005). The two main approaches for measuring technical efficiency are stochastic frontier analysis (SFA) and data envelopment analysis (DEA). These approaches are conceptually very similar however SFA uses econometric methods (Aigner et al. 1977; Meeusen and van den Broeck 1977), while DEA relies on mathematical programming (Charnes et al. 1987). The strengths and weaknesses of each approach have been extensively discussed in the literature (Coelli et al. 2005; Bogetoft and Otto 2011). The main difference is that DEA, being non-parametric, does not impose a functional form on the data and is therefore the more flexible of the two approaches. SFA, on the other hand, requires the selection of a functional form for the production frontier. While this reduces the flexibility of the approach, SFA can deal with statistical noise arising from measurement errors, data anomalies and uncertainties, and the incomplete specification of functions. This capacity to deal with statistical noise explains the term "stochastic" in SFA, and it is property which is particularly useful for the studies in developing countries where measurement and reporting errors are hard to avoid. With DEA, statistical noise from these factors will affect the position of the frontier and, consequently, technical efficiency scores. For this reason we selected the SFA approach to estimate separation production frontiers for each of the seven study sites.

The SFA frontier describes the maximum possible level of production given the amount of all production inputs used in the sample population, taking into account both statistical noise and technical inefficiency; the latter causing farms to lie below the frontier. As we are dealing with mixed farm systems that have multiple outputs, we use a multi-output distance function approach. We choose a transcendental logarithmic (translog) functional form due to its flexibility and other desirable properties such as the ability to impose homogeneity, and the concavity of the transformation function to the origin (Coelli and Perelman 2000).

The translog distance function with M (*m = 1, 2, … , M*) outputs and K (*k = 1, 2, … , K*) inputs, and for I (*i = 1, 2, … , I*) firms, is given by:

$$\ln D_{Oi} = \alpha_0 + \sum_m \alpha_m \ln y_{mi} + \frac{1}{2}\sum_m \sum_n \alpha_{mn} \ln y_m \ln y_{ni} + \sum_k \beta_k \ln x_{ki} + \frac{1}{2}\sum_k \sum_l \beta_{kl} \ln x_k \ln x_{li} + \sum_k \sum_m \gamma_{km} \ln x_{ki} \ln y_{mi} \quad (1)$$

Where "O" indicates an output-orientated distance function.

The restrictions required for homogeneity of degree one in outputs are $\sum_m \alpha_m = 1$, $\sum_n \alpha_{mn} = 0$, $\sum_m \gamma_{mn} = 0$, while symmetry restrictions require $a_{mn} = a_{nm}$ and $\beta_{kl} = \beta_{lk}$. A convenient method of imposing the homogeneity constraint upon Equation 1 is to follow Lovell et al. (1994) and arbitrarily choose one of the outputs, such as the *M*th output, to normalise the function:

$$\ln(\frac{D_{Oi}}{y_{1i}}) = \alpha_0 + \sum_m \alpha_m \ln(\frac{y_{mi}}{y_{1i}}) + \frac{1}{2}\sum_m \sum_n \alpha_{mn} \ln(\frac{y_{mi}}{y_{1i}}) \ln(\frac{y_{ni}}{y_{1i}}) + \sum_k \beta_k \ln x_{ki} + \frac{1}{2}\sum_k \sum_l \beta_{kl} \ln x_k \ln x_{li} + \sum_k \sum_m \gamma_{km} \ln x_{ki} \ln\left(\frac{y_{mi}}{y_{1i}}\right) \quad (2)$$

Including both a symmetric random error term (for statistical noise) and an asymmetric error term (for inefficiency) into the model, requires the rewriting of the technical inefficiency measure lnD_{Oi} as $-u_i$. The random error term v_i can then be added to the translog function, which is now redefined in terms of $\ln y_{1i}$ as:

$$\ln y_{1i} = \alpha_0 + \sum_m \alpha_m \ln\left(\frac{y_{mi}}{y_{1i}}\right) + \frac{1}{2}\sum_m \sum_n \alpha_{mn} \ln\left(\frac{y_{mi}}{y_{1i}}\right) \ln\left(\frac{y_{ni}}{y_{1i}}\right) + \sum_k \beta_k \ln x_{ki} + \frac{1}{2}\sum_k \sum_l \beta_{kl} \ln x_k \ln x_{li} + \sum_k \sum_m \gamma_{km} \ln x_{ki} \ln\left(\frac{y_{mi}}{y_{1i}}\right) + v_i + u_i \quad (3)$$

Following Morrison et al. (2000) we transform the left side of the equation to be $\ln y_{1i}$ rather than $-\ln y_{1i}$. This causes the signs of the coefficient estimates corresponding to the distance function to be reversed, so that they conform to the expected signs of standard production function models, easing the interpretation of the results. We explore the impacts of farm attribute variables, such as farmer age and market participation, on inefficiency by including them as components of the z_i vector, where:

$$u_i = \delta_0 \sum_j \delta_j z_{ji} \quad (4)$$

Where the δ_js are unknown parameters to be estimated and z_{ji} (j=*1, 2, ... , J*) is a column vector of technical inefficiency explanatory variables. We used maximum-likelihood methods to estimate the stochastic translog distance function with the usual distributional assumptions for the v_i and u_i terms: the v_i are random variables assumed to be i.i.d. (independently and identically distributed) $N(0, \sigma_u^2)$; and the u_i are nonnegative random variables independently distributed as truncations at zero of the $N(m_i, \sigma_u^2)$ distribution where $m_i = \delta_j z_{ji}$. Estimation was carried out using the FRONTIER econometric package developed by Coelli and Henningsen (2014) for implementation in R software. By using output distance functions, the technical efficiency scores estimated in this study quantify the maximum extent to which output can be produced from existing production inputs, and from existing practices and technologies.

4.3.2 Calculation of GHG emission intensities

Baseline GHG emissions from livestock (CH_4 and N_2O from animals and manure management) and crops (N_2O emissions from fertilizers, manures and plant residues) were calculated using Tier 1 methods outlined in Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC 2006). Emission intensities were then calculated by dividing the emissions from livestock and crop production by their corresponding products, expressed in terms of protein and energy equivalents, respectively. The various livestock outputs were converted into protein equivalents based on protein conversion factors from Opio et al. (2013) and MacLeod et al. (2013), and then aggregated into ruminant and poultry products. Similarly the crop products were converted into energy equivalents based on the USDA Food Composition Database (USDA 2015), and then aggregated into separate grains and beans/pulses products. Emission intensities were estimated for both the observed or baseline situation and a fully efficient scenario in which the yield gaps in each sample population are assumed to be closed. To estimate the emission intensities in the fully efficient scenario we first had to estimate the new output quantities associated with closing the yield gaps. Given that the technical efficiency scores provide a proportional measure (between 0 and 1) of actual output relative the maximum achievable output for each farm, this was achieved by simply dividing the observed output levels of each farm by its respective technical efficiency score. This is a valid approach because the technical efficiency values in this study are based on the simultaneous expansion of all outputs, while holding inputs fixed and maintaining the same proportional mix of outputs observed in the baseline. Since the closing of yield gaps is based on expanding outputs without changing baseline input levels, GHG emissions were treated the same as the production inputs, and left unchanged as a result of closing the yield gaps. Consequently, we assume that yield gaps are closed as a result of improved management of existing resources (e.g. better animal husbandry to increase the productive lifespan of animals and more precise matching of agronomic inputs to meet crop growth requirements) rather than through changes in practices and technologies (e.g. a switch to more energy rich feeds, heavier animal breeds, and higher agronomic input systems).

4.4 Results

4.4.1 Yield gaps and technical efficiency

The average technical efficiency score for smallholders at each site ranges between 0.43 and 0.72 (Table 4.4). The efficiency scores are also expressed as potential yield gaps by converting them to percentage increases in output for each site. This conversion was simply performed by calculating the percentage increase required to increase each aggregate efficiency score from their estimated value to a value of 1. This is a coarse measure of the yield gap, because it gives equal weight to each farm within each site and does not differentiate between products. More disaggregate yield gap estimates addressing each of these limitations are provided later in Table 4.5. The yield gaps range from a 39% increase in Kaffrine to more than doubling of output in Lushoto and Borana. These are encouraging findings, as they show there is scope to generate reasonably large increases in output with existing practices and existing levels of input use. The variance in yield gaps tends to be greater in sites with lower mean technical efficiency scores (e.g. Nyando and Borana), as shown by the coefficients of variation (CV) in Table 4.4. This is expected, because sites with a larger spread in performance should generally have larger yield gaps.

Table 4.4 The Average technical efficiency scores and yield gap estimates for each site

	Nyando	Wote	Hoima	Lushoto	Borana	Yatenga	Kaffrine
Mean TE	0.56	0.70	0.63	0.46	0.43	0.57	0.72
Yield gap (%)	79	43	58	115	133	76	39
CV (%)	49	30	28	57	49	43	25

The distributions of the farm level technical efficiency scores, assembled in increasing order within each site, are presented in Figure 4.1. As with the mean scores, these distributions vary quite widely between sites. A relatively large proportion of smallholders in Wote and Kaffrine, in particular, clustered around high efficiency scores in excess of 0.6. Whereas farmers in Borana, Lushoto and Nyando are spread much more uniformly across all efficiency levels, reflecting the findings of relatively large average yield gaps in these sites (Table 4.4). Market participation appears to have some attenuating influence on the size of yield gaps for some sites, as indicated by the high efficiency scores in the more market orientated Kaffrine and Hoima sites, and the relatively low scores in Borana. The statistical significance of the relationship between the farm attribute variables and efficiency within each site are reported later in this section. The complete list of parameter estimates of the stochastic frontier models for each site is also included in Appendix A.

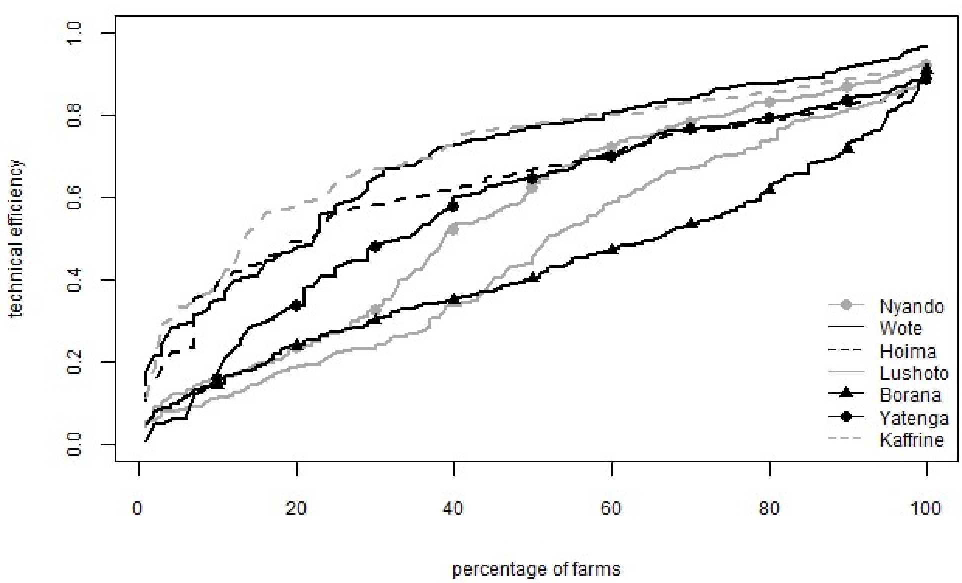

Figure 4.1 The distribution of farms by technical efficiency in each study site

To further explore the potential gains from closing yield gaps, we report output targets which could be achieved by closing yield gaps for a selection of the main livestock and crop products in each site (Table 4.5). As previously explained, the yield gap targets in Table 4.5 are calculated by dividing the observed farm outputs for each farm by its respective technical efficiency score. While the magnitude of these changes broadly corresponds to the mean yield gaps in Table 4.4, some differences emerge due to variations in product mixes and efficiency levels among farms. For instance, in Lushoto the potential for product expansion is generally higher than its average yield gap. This is because relatively more inefficient farms, with larger yield gaps, assume a greater output share of the main products in this site.

Table 4.5 The potential percentage increases in the production of the main livestock and crop products as a consequence of closing yield gaps

	Milk	Eggs	Chicken	Grains	Beans/pulses	Tubers/roots
Nyando	55%	96%	98%	77%	49%	58%
Wote	40%	37%	33%	39%	36%	28%
Hoima	28%	56%	47%	46%	65%	70%
Lushoto	45%	154%		155%	136%	209%
Borana	167%	102%		97%	108%	
Yatenga	100%	38%	127%	68%	75%	48%
Kaffrine	38%		67%	33%	33%	16%

The results outlined above indicate that there is a wide range of farm performance within each site. Below we report on the inefficiency effects component of the estimated models, to see if the variations in performance can be explained by the farm attributes listed in Table 4.6. This table contains the coefficient values estimated for each farm attribute variable along with an indication of its level of significance. As the inefficiency effects in the models are a linear function of these observed variables (Battese 1995), a negative sign on the coefficients in Table 4.6 indicates a negative relationship with inefficiency, or a positive relationship with technical efficiency.

The Market participation coefficient is negative in all sites and statistically significant in five of these. Thus the more market-orientated farmers that are able to sell a greater proportion of their outputs are more efficient. Similarly, domestic asset wealth has quite a consistent negative correlation with inefficiency, however this relationship is only significant in Yatenga. In contrast, farms that obtain a higher share of their income from off farm sources were consistently more inefficient, with this relationship being statistically significant in four sites. The link between livestock specialisation and inefficiency is more mixed, although it tends to be positively related to inefficiency in the sites where the coefficient is statistically significant. Interestingly, there appears to be an efficiency dividend associated with the closer integration of crop and livestock enterprises. The four sites where livestock specialisation is positively related to inefficiency are the most livestock dependent. Whereas this variable is negatively related to inefficiency in the sites that depend more on crops, with the only statistically significant and negative coefficient in Lushoto, the most crop-dependent site assessed.

A reasonably consistent picture emerges with regard to the age and gender. Age is positively related to inefficiency in most sites (although only statistically significant in Nyando and Hoima), suggesting that older farmers tend to be less efficient. Whereas Gender was positively related to inefficiency in the three sites for which this relationship was significant, suggesting that female headed farms face greater challenges regarding farm management than their male counterparts. The policy implications of these relationships between farm performance and farm characteristics are explored in the Discussion and conclusions section.

Table 4.6 The relationship between technical inefficiency and socio-economic farm attributes, including coefficient values and levels of significance for each variable

	Nyando	Wote	Hoima	Lushoto	Borana	Yatenga	Kaffrine
Age	0.025^{a}	0.004	0.023^{b}		0.0001	-0.063	-0.001
Off farm income	0.003^{c}	0.008^{a}	0.0005	0.006	0.009^{a}	0.002^{c}	
Household size	0.040	0.067			0.029	0.315^{d}	
Market participat.	-0.035^{a}	-0.029^{b}	-0.029^{d}	-0.019^{c}	-0.007^{c}	-0.058	-0.060
Domestic assets	-0.005	-0.027	0.007	-0.022	-0.027	-0.029^{d}	
Gender	0.38^{c}	-0.054	-0.18	1.16^{a}	0.378^{c}	-4.61	-3.67
Livestock special.	0.000	0.010^{c}	-0.017	-0.037^{d}	0.014^{b}	0.023^{d}	-0.071

a,b,c,d indicate level of statistical significance: a (0.001); b (0.01); c (0.05); d (0.1)

The ability to use statistical hypothesis tests in SFA is an important advantage for this method over non-parametric approaches such as DEA. In Table 4.7 we provide results from the null hypothesis that inefficiency effects are absent from the model, i.e. that all deviations from the frontier are the result of random noise instead of inefficiency. This hypothesis is rejected at the 5% level of significance or less in five of the seven sites, and at the 10% level of significance for two sites (Table 4.7).

We also report results of the null hypothesis that the inefficiency effects are not a function of the farm attribute variables in Table 4.8. This hypothesis is strongly rejected across all sites at between 0.1% and 1% levels of significance. Thus even though many of these attribute variables are individually insignificant, the joint effects of these variables are significant in each site.

Table 4.7 Hypothesis test; null hypothesis specifies that inefficiency effects are absent from the model

	Test statistic (z-value)
Nyando	2.45[c]
Wote	2.67[c]
Hoima	2.07[c]
Lushoto	1.67[d]
Borana	1.65[d]
Yatenga	2.98[b]
Kaffrine	2.15 [c]

a,b,c,d indicate level of statistical significance: a (0.001); b (0.01); c (0.05); d (0.1) .

Table 4.8 Hypothesis test; null hypothesis specifies that inefficiency effects are not a function of the farm attribute variables

	Log (Likelihood)	Test statistic (Chi-sq)
Nyando	-144.2	101.3[a]
Wote	-80.1	60.0[a]
Hoima	-148.2	23.9[a]
Lushoto	-156.4	31.6[a]
Borana	-127.6	32.4[a]
Yatenga	-133.1	22.7[b]
Kaffrine	-58.5	13.37[b]

a,b,c,d indicate level of statistical significance: a (0.001); b (0.01); c (0.05); d (0.1) .

4.4.2 Environmental impacts (GHG emission intensities)

As discussed, improvements in technical efficiency can also deliver environmental benefits in terms of reducing the GHG emission intensity of farm products as well as improving natural resource use more generally. To illustrate this potential we calculate the emission intensities for livestock products (Table 4.9) and crop products (Table 4.10), before and after closing yield gaps. As expected, the emission intensities of poultry products are considerably lower than for ruminant products in every site. The baseline emission intensities within each livestock product class are of a similar order of magnitude, with the exception of poultry products in Kaffrine, which are higher owing to the focus on broiler rather than egg production; with the former being much less efficient (FAO 2013). Significant reductions in the emission intensities of livestock products are possible across all sites, with falls of between 20 and 63% possible for ruminant products and between 27 and 61% for poultry products.

Table 4.9 Changes in the emission intensity (EI) of livestock products (kg CO_2eq / kg protein) from closing yield gaps

	Baseline EI of poultry products	Efficient EI of poultry products	% reduct.	Baseline EI of ruminant products	Efficient EI of ruminant products	% reduct.
Nyando	0.3	0.1	49%	250	161	36%
Wote	0.8	0.3	27%	868	615	29%
Hoima	0.6	0.4	36%	475	371	22%
Lushoto	0.6	0.2	61%	209	141	33%
Borana	0.7	0.4	50%	615	230	63%
Yatenga	2.0	1.3	34%	563	298	47%
Kaffrine	4.5	2.7	40%	271	216	20%

Table 4.10 Changes in the emission intensity (EI) of selected crop products (kg CO_2eq / MJ) from closing yield gaps

	Baseline EI of grains	Efficient EI of grains	% reduct.	Baseline EI of beans/pulses	Efficient EI of beans/pulses	% reduct.
Nyando	0.003	0.002	43%	0.007	0.005	33%
Wote	0.011	0.008	28%	0.029	0.021	27%
Hoima	0.006	0.004	32%	0.005	0.003	39%
Lushoto	0.012	0.005	61%	0.007	0.003	58%
Borana	0.003	0.002	58%	0.006	0.002	62%
Yatenga	0.009	0.005	40%	0.006	0.003	43%
Kaffrine	0.019	0.014	25%	0.006	0.005	25%

4.5 Discussion and conclusions

Despite the importance of livestock production in Sub-Saharan Africa, the issue of yield gaps among either livestock or mixed crop-livestock smallholders in this region is severely under-researched, as previous yield studies have focused on crops. This study addresses an important gap in the literature by estimating yield gaps for both crops and livestock in these production systems. Moreover, by considering the expansion of outputs for given levels of production inputs for each farm, the production improvements identified in this study can be assured of increasing total factor productivity without the risk of inadvertently making farmers economically worse off. By contrast, the improvement of partial productivity indicators (e.g. output per animal or per hectare) can result in greater use of inputs that are not considered in these indicators and thereby cause total factor productivity and farm profits to fall.

There are substantial yield gaps in the mixed smallholder farm communities assessed in this study, and closing gaps would provide marked benefits for smallholder incomes, food supply and environmental performance. We estimate that there is the potential to raise the production of the main livestock products from between 28 and 167%, and the main crop products by between 16 and 209%. There do not appear to be any clear regional patterns, as sites from both East and West Africa have a blend of small and large yield gaps. These potential improvements crop production are also comparable with those from other yield gap studies. For example, in a global assessment Neumann et al (2010) estimate that crop yields are between 50 and 64% of their maximum potential, which translates to potential yield improvements of between 56 and 100%. Neumann et al (2010) used similar frontier-based methods as this study, however, their assessment as based on gridded spatial data which is likely to mask some of variability that would be present at the farm-level. In an assessment of yield gaps in African smallholder maize production across several countries, Tittonell and Giller (2013) estimated that observed yields on moderately fertile soils were between 36 and 61% of what could be attained under local conditions. Which suggests that yields could be increased by between 64 and 178%. Although Tittonell and Giller (2013) used a different approach, based on comparing average yields to maximum yields from field trials and top performing farmers, the findings are very similar to ours.

As mentioned, the nexus between productivity and environmental performance has recently attracted growing attention from the research community, with several studies including Burney et al. (2010), FAO (2010)and Gerber et al. (2013) demonstrating the strong positive role that productivity improvements can play in lowering the emission intensity of agricultural production. This study adds further support to these findings, with sizeable reductions in emission intensities estimated for crop and livestock production. Emission intensities were estimated to fall by 20 to 63% for the main livestock products and by 25 to 62% for the main crop products, as a consequence of closing yield gaps. Closing yield gaps by improving technical efficiency will also generally improve the efficiency with which other natural resources, including land and water, are used. By changing from an output-oriented to an input-oriented frontier it would be possible to estimate absolute reductions in GHG emissions, and other in the use of resources such as land, for a given level of output. This presents a possible future extension of this study.

We should caution, however, that while we have controlled for variations in environmental factors on production that are beyond the control of farmers (e.g. precipitation and growing degree days) by confining each frontier model to geographically small sites, and by using a parametric approach that can account for statistical noise resulting from reporting errors, the estimated yield gaps may still incorporate some environmental factors beyond the control of farmers. Additionally, the standard assumption of TE scores from SFA and DEA frontier methods reflecting variations in farm performance under existing technologies and practices is not guaranteed. However, where the frontier sample populations are not in the process of rapid technological change this assumption can be upheld more easily. Since our study sites are characterised by low levels of technology adoption and innovation (owing to capital and scale constraints) and we focus on a single production year, we are confident that our results reflect the potential for improvement with existing practices. That said, it is impossible to rule out small differences in technologies across the sample just as it is impossible to exclude all factors beyond the control of farmers when estimating TE. For these reasons, our estimated potentials for improvements in yields and emission intensities must be viewed as upper bound estimates of what can be achieved without the introduction of new technologies and practices.

While the estimation of yield gaps provide useful benchmarks for policy makers about potential improvements, it is equally important to understand the drivers behind these gaps. To this end, our assessment of the link between farm attributes and yield gaps provides some possible site-specific leverage points, to help inform policy makers and extension agents in the design and targeting of capacity building programmes. We found a very strong and statistically significant link between market participation and farm performance in most sites, which suggests that efforts to promote market participation could be an important part of sustaining the closure yield gaps, particularly when farmers are able to produce in excess of their household needs. Further, three of the four most statistically significant relationships between market participation and efficiency were found in the most livestock orientated sites. While this reveals that smallholders tend to rely more on livestock production in areas with poor market access, it also indicates that measures to promote the participation in market could be more beneficial in these areas.

The discernment of an efficiency dividend from the closer integration of crop and livestock enterprises was particularly instructive. There are a number of potentially beneficial synergies between livestock and crops which, while not explicitly analysed, can play an important role in raising the overall technical efficiency of the farm. The benefits of integration are derived from both the direct use of outputs from one enterprise into another and the use of by-products from one enterprise in another that would usually be left unexploited. For example, livestock can benefit crop production by providing organic fertilizer (manure) and traction. On the other hand, crops can benefit livestock production by providing feed in the form of residues. In this study, the benefits to integration were found to be larger for sites that were more specialized in either livestock or crop production. This finding is supported by the seminal work of McIntire, Bourzat, and Pingalii (1992), who showed that in more livestock dependent areas of Africa with low land productivity, crop production is not in competition with livestock and can provide residues for animal feed during times when pasture is less abundant.

There were also strong relationships between the age and gender of the farm household head and efficiency in some of the sites. In the few sites were these variables were significant they were associated with larger yield gaps. The link between farmer age and inefficiency is a relatively common finding (Tipi et al. 2009; Battese and Coelli 1995; Mathijs and Vranken 2000; Bozoğlu and Ceyhan 2007) and reflects the tendency for older farmers to be less innovative and receptive to extension initiatives than their younger counterparts. Similarly, female headed households tend to face larger yield gaps, with this relationship also being significantly in only a few sites. This may result from greater barriers to accessing input and output markets, and various farm services including extension together with higher risk aversion (Babu and Sanyal 2014). As discussed, these findings could be used to help direct capacity building programs to smallholders most in need of support, as well is indicate production structures that are most likely to perform efficiently. However, this assessment does not clearly discern which types of farms are likely to be the most receptive to technical support. While this study is an important first step, closer examination of and comparison of farms, including through field visits, would be needed to identify constraints and opportunities on site-by-site basis.

Finally, it is important to note that there are a number of ways to estimate yield gaps. This study relies on the *ex post* measurement of performance gaps between farms assuming no change in existing practices and technologies. Another important approach is to estimate, *ex ante*, the potential for increasing productivity by adopting new technologies, including improved varieties and breeds of crops and livestock. These approaches involve different, but complementary ways to achieve similar goals.

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We, the PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

	Author's Name (please print clearly)	**% of contribution**
Candidate	Benjamin Henderson	80
Other Authors	Cecile Godde	3
	Daniela Medina-Hidalgo	3
	Mark van Wijk	3
	Silvia Silvestri	2
	Sabine Douxchamps	2
	Eloise Stephenson	2
	Brendan Power	1
	Cyrille Rigolot	1
	Oscar Cacho	1
	Mario Herrero	2

Name of Candidate: **Benjamin Henderson**

Name/title of Principal Supervisor: **Prof. Oscar Cacho**

[redacted]

Candidate

06 / 04 / 2018

Date

[redacted]

Principal Supervisor

09/04/2018

Date

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Name of Candidate: **Benjamin Henderson**

Name/title of Principal Supervisor: **Prof. Oscar Cacho**

[redacted]

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Candidate   Date

[redacted]

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Principal Supervisor   Date

Chapter 5: Assessing the sustainable development and intensification potential of beef cattle production in Sumbawa, Indonesia, using a system dynamics approach[1]

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Chapter 5: Assessing the sustainable development and intensification potential of beef cattle production in Sumbawa, Indonesia, using a system dynamics approach

Abstract

The intensification of beef cattle production in dryland areas of East Indonesia has the potential to substantially raise the incomes of smallholder farmers that dominate the sector. In this study we assess the potential for intensifying beef production on Sumbawa Island, by introducing a household feedlot production system (2-20 animals) based on the *Leucaena leucocephala* (leucanea) tree legume as an improved source of feed. We used a system dynamics approach to model the entire value chain, accounting for herd dynamics, demand dynamics and seasonality. Our findings complement the growing body of biophysical evidence about the potential success of this intervention, by simulating improvements in the annual profitability for beef farmers in the project area of up to 415% by 2023. Increases in farm profit were shown to depend near equally on the higher productivity of the leucaena feeding system and an associated price premium, demonstrating the importance of supporting improved agricultural production with better marketing practices. The intervention was also shown to generate positive or neutral benefits for the main post-farm value chain actors. Importantly, it also reduced the GHG emission intensity of outputs from the beef herd by 16% by 2020. We explored number of scale-out pathways, including a relatively moderate pace of autonomous adoption for our main analysis, resulting in the accumulation of 3,444 hectares of leucaena 20-years after the initial project phase, which could sustain the fattening of 37,124 male cattle per year. More ambitious rates of scale-out were found to be possible without exceeding the animal and land resources of the island.

5.1 Introduction

The intensification of beef cattle production in dryland areas of East Indonesia has the potential to substantially raise the incomes of smallholder farmers that dominate the sector. With a growing body of research providing solid evidence about benefits of tree legume-based feeding systems for beef cattle production in this region (Dahlanuddin et al. 2015), now is an opportune time to explore the potential for applying this intervention at a large scale. In this study we assess the potential for intensifying beef production on Sumbawa Island, Indonesia, using the *Leucaena leucocephala* (leucanea) tree legume as an improved source of feed (Shelton and Dalzell 2007) for the sector. Sumbawa Island is located in the province of Nusa Tengarra Barat (NTB). The beef cattle population of the island was 590,295 in 2015 and official statistics show it has been growing steadily over the past five years (Dinas Peternakan dan Kesehatan Hewan NTB 2016). With high beef prices and growing demand for beef increasing sale and slaughter rates, official reports of an increasing cattle population are a subject of discussion and debate.

Cattle production in Sumbawa tends to be more extensive than other parts of Indonesia, typified by low input use and a reliance on poor quality roughages, including native grass and crop residues. This deficiency along with poor animal management results in low productivity and marginal economic returns. There are presently no commercial feedlots on the island, although a household fattening sector is beginning to emerge (Waldron et al. 2016).

Most cattle, particularly fattened males, are exported live to Lombok and other markets outside NTB. In 2013 there were 24,526 slaughter cattle exported from Sumbawa Island to Lombok and 19,952 to markets outside NTB (Waldron et al. 2016). The cattle marketing system comprises numerous actors, including traders, brokers and butchers. Markets are reasonably competitive, although market power is quite concentrated in the final stages of the live export chain. However, a lack of formal price reporting and the use *ad hoc* judgements, rather than scales to measure animal weight, is a source of marketing inefficiency. While there is no clear evidence that intermediaries are exploiting this lack of transparency to extract excessive margins (Waldron et al. 2016), the marketing system is limited in its capacity to reward farmers with higher prices for heavier and younger meat animals. As such, farmers are less likely to receive the financial returns and incentives they require to invest in intensifying production.

Existing research on beef production systems in Sumbawa, the neighbouring island of Lombok, and East Java provide a well-founded template for the intensification and development of the Sumbawa beef sector. Experimental results show that the weaned male Bali cattle fed leucaena hay have a daily live weight gain (LWG) of 0.47 kg/day (Dahlanuddin et al. 2015), which is far superior to the 0.03 kg/day rate for animals fattened on native grass reported in that study. Other studies report similar improvements in performance, with male Bali cattle fed native grass found to have a LWG of around 0.1 kg/day (Marsetyo et al. 2012) compared to rates of 0.22-0.42 kg/day (Quigley et al. 2009) for cattle fed tree legumes. There is also solid evidence that these productivity improvements can translate into economic benefits, with improvements in cattle fattening profits of 172% possible through supplementing low quality animal diets with leucaena in East Java (Priyanti et al. 2010). Further, beef fattening in Jati Sari (Sumbawa) with a leucaena based diet was found to generate net returns of 131,067 Indonesian Rupiah (Rp) per day per head in the wet season, compared to Rp 19,250 with a low-quality baseline diet (Waldron et al. 2016).

However, on Lombok Island the potential for improved productivity at scale was limited by available land for growing forages (Dahlanuddin et al. 2016). Individual animal productivity and turn off rates could be dramatically increased but the overall cattle population did not increase in response to widespread adoption of improved nutritional and forage interventions because of land constraints. Human population is much lower on Sumbawa Island and land area per farmer is far greater, with much larger tracts of cleared extensive grazing land suited to leucaena production, which is not currently used for food crops.

The purpose of this research is to assess the potential for intensifying beef production on Sumbawa Island, by introducing a household feedlot production system (2-20 animals) based on feed from leucaena grown on-farm. The project site is part of the Applied Research and Innovation Systems in Agriculture (ARISA) project, which aims to increase smallholder incomes through the adoption of improved farming and value chain performance by brokering relationships between research institutes and the private sector (http://aip-rural.or.id/arisa/index.php/about).

We use a system dynamics (SD) approach to model the entire value chain, taking into account herd dynamics, demand dynamics and seasonality. We use this framework to assess the costs and benefits of livestock intensification, improved marketing efficiency and the opportunities and constraints for scaling up the intervention from an initial project site to the entire beef sector of the Sumbawa Island. Given the current starting point of low productivity and investment in the Sumbawa beef sector, such large scale change will be a substantial challenge and would depend on sustained extension support and sufficient market incentives to reward adoption (Dahlanuddin et al. 2016). Specific research questions include:

- What is the impact of the leucaena-based feedlot intervention on the net incomes of smallholders?
- How are these benefits shared among different value chain actors?
- How much additional gain can be obtained from demand-side measures that raise the price of cattle?
- What is the potential for scaling up the intervention, and to what extent are animal and land resources constraints likely to constrain this process?
- How large are environmental co-benefits of the intervention package in terms of lower greenhouse gas (GHG) emission intensities of beef products?

5.2 Methods

5.2.1 Data

The relevant data for this study were assembled at two different scales. Firstly, at the ARISA project site scale and secondly for the island of Sumbawa. The project area includes more than 70 farmer groups from the districts of Sumbawa and Sumbawa Barat, including 1,005 farms and a beef cattle population of 5,013. The cattle used in the project site and throughout Sumbawa Island are almost exclusively comprised of the Bali beef breed. Each farmer group contains 10 to 20 farmers that work together and sometimes share resources such as cattle pens and feed. The formation of these groups is encouraged by government to facilitate more efficient delivery of technical support. The baseline output of these cattle systems is low and annual sales of fattened male animals are only 351 head (hd) per year. Physical data, economic data and performance parameters for the breeding and fattening components of the project area beef herd are presented in Table 5.1. In the project feedlots, young male feeder stock are purchased at 140kg and after 154 days of feeding are sold at an average weight of 210 kg. This compares to 427 days for animals on a baseline diet and results in a shortening of the age at sale of from 3.3 to 2.5 years old. Cattle in the project feedlots are assumed to be fed a diet of 100% leucaena, equivalent on average to 5kg of dry matter (DM) per day, resulting in 770 kg of leucaena being required per animal over the 154 fattening period. Local research demonstrates the feasibility of fattening bulls on 100% leucaena diets without adverse effects on animal health (Dahlanuddin et al. 2015). It also makes economic sense because once the trees are established it more affordable than concentrate feed and there is a lack of good energy supplements available on farm. Given the average annual leaucaena yield of 8.3 tDM ha^{-1}, each hectare of leucaena can support a feedlot throughput of 10.8 slaughter animals per year. By contrast, baseline animal diets are mainly comprised of native grasses occasionally supplemented with low quality crop residues such as maize leaves and rice straw.

Table 5.1 Baseline and project data for cattle breeding and fattening

	Baseline	With project
Breeding herd data & parameters		
Fertility rate (%)	70	77[a]
Calving interval (weeks)	60	58[a]
Age at first calving (years)	4	4
Natural abortion rate (%)	5	5
Calf mortality rate (%)	10	10
Heifer replacement rate (%)	20	20
Fattening herd data & parameters		
Fattening duration with Leucaena (days)	427	154
Average purchase weight (kg)	140	140
Average sale weight (kg)	210	210
Average daily weight gain (kg day^{-1})	0.16	0.45
Dressing percentage (%)	46-48	50-52
Live weight cattle purchase price (Rp kg^{-1})	37,000	37,000
Live weight cattle sale price (Rp kg^{-1})	37,000	42,550[b]
Leucaena yield (t DM ha^{-1})	n/a	8.3
Cattle purchase price (Rp hd^{-1})	5,180,000	5,180,000
Cattle sale price (Rp hd^{-1})	7,500,000	7,770,000 [b]
Leucaena establishment costs (Rp ha^{-1})	n/a	1,689,030
Feed collection costs (Rp hd^{-1})	1,121,227	810,448
Other animal costs (Rp hd^{-1})	198,773	204,883

a. These parameters are endogenously determined in the model simulation under Scenario 2 (described in the "Scenario description and scope" section). The values included in this table represent the estimated improvements 10 years from the commencement of the intervention.
b. These prices reflect the 15% price premium for Scenario 2, described in the "Scenario description and scope" section.
Source: The live weight cattle price is taken from Waldron et al. (2016) and all other costs were obtained through interviewing project staff and farmers (In compliance with PLOS ONE requirements for research involving human participants, we confirm that this project was approved by the CSIRO Social Science Human Research Ethics Committee).

The leucaena establishment costs include equipment for fencing, nursery needs (shading and poly bags), seeds and labour. The feed collection costs include both labour and motorbike fuel, and the other animal costs include veterinary costs, marketing costs, water and costs associated with the maintenance and construction of feedlots. In the simulations presented later, the costs and returns are based on year 2015 prices relevant to the study area. As shown in Table 5.2, the total cattle population for the island of Sumbawa is 590,295. This is the total population that will be considered for assessing different scenarios about scaling out the leucaena feeding intervention across the island of Sumbawa, as described in the "Scenario description and scope" section and the "Results" section.

Table 5.2 Cattle population data for Sumbawa Island in 2010-2015, by district

	2010	2011	2012	2013	2014	2015
Sumbawa Barat	41,536	47,781	54,393	59,507	61,128	61,813
Sumbawa	156,797	162,924	197,141	215,675	216,167	228,826
Dompu	74,889	85,612	96,205	105,250	106,992	112,503
Bima	91,725	117,842	148,089	162,012	166,094	170,118
Kota Bima	16,781	12,034	13,592	14,870	15,180	17,035
Total	381,728	426,193	509,420	557,314	565,561	590,295

Source: Dinas Peternakan dan Kesehatan Hewan Provinsi NTB. Annual Report (2016).

5.2.2 System dynamics model

We developed a dynamic simulation model, using an SD approach, to simulate the ex-ante impacts of our intensification, marketing and scale-out scenarios. We used iThink (http://www.iseesystems.com/) program to construct our model and the model structure and codes are available from the authors upon request. The full set of model equations and data are also provided in the supporting information for this paper (Appendix B). This modelling approach is grounded in control theory and the modern theory of nonlinear dynamics (Sterman 2000). The SD approach incorporates dynamic interactions, feedback effects, and delays among different components of the system (Sterman 2000). It is well suited to complex systems such as livestock value chains, in which time lags associated feed supply, breeding and fattening cycles, and the presence of market and resource scarcity feedbacks can generate complex and unintuitive system behaviour (Hamza and Rich 2015). In recent years, several SD models have been used to simulate and assess the behaviour of livestock value chains over time. An SD model was also developed to assess the potential for the manufacturing and marketing of goat cheese in Mexico (McRoberts et al. 2013). More recent studies used a SD approach to evaluate the commercialization goat value chains in Mozambique (Hamza et al. 2014) and to evaluate the impacts of improved access to export markets in Namibia (Naziri et al. 2015).

Each value chain sector and production process in our model is captured by a series of stocks and flows and their relationships and behaviour are modelled using differential and integral calculus. Examples of the main stocks in the model include the cattle population or herd and the area of land planted with leucaena. The cattle population is comprised of interlinked stocks animal cohorts, grouped on the basis of age, purpose and gender. These include breeding females, calves, weaners, males for fattening and for reproduction, and heifers for replacing breeding females and for sale as breeding stock on other islands.

These stocks of animals accumulate and decline over time according to the inflows and outflows to and from these stocks. Fertility, growth, mortality and cattle sales rates determine the size of these flows, and therefore the size of the stocks of cattle and land use over time. When in equilibrium, the inflows (births) and outflows (deaths and sales) balance out to maintain a steady population or stock of cattle. The baseline trajectory for the cattle population in our project area was gradually increasing, implying that inflows have been exceeding outflows over time in recent years.

The post-farm sectors of the value chain include inter Island traders who purchase and sell both heifers and fattened males, and local butchers who purchase and process cull animals for local consumption. Our model also introduces periodic demand shocks for three important Muslim festivals, namely, Eid Al Adha, Ramadan, and Prophet Muhammad’s Birthday (Mawlid). These events cause temporary, but relatively large spikes in consumption and cattle prices. We assume a 15% increase in the volume of male cattle consumed over the month of Ramadan, a 10% increase over one month for Mawlid, and a doubling in weekly rate of male cattle sold for slaughter over a two-week period in the lead up to Eid Al Adha. These spikes in demand are accompanied by a 10% price increase for Ramadan and Mawlid, and a 25% increase in the lead up to Eid Al Adha. We also capture the seasonality of breeding cycles in the farm system with conception mostly occurring at the beginning of the wet seasons and calving in occurring in the dry season.

The male animal fattening component of our model is separated into traditional fattening and feedlot fattening subcomponents. Our feedlot intervention causes a shift of male feeder stock in the project area from traditional to feedlot fattening and a corresponding shift in the diets of male feeder stock from native grasses and other low quality forages to wild and planted leucaena. Feedlot enterprises also have access to male feeder stock from outside the project area, which is important for utilising feed from leucanea planted during both the project and scale-out phases of the intervention. Farm income is derived from the sale of males fattened for export, heifers exported for breeding, and from cows and bulls that are culled at the end of their service lives. In Figure 5.1, we provide a simplified causal loop diagram to summarise the model structure and highlight the major feedback loops in the beef sector in Sumbawa.

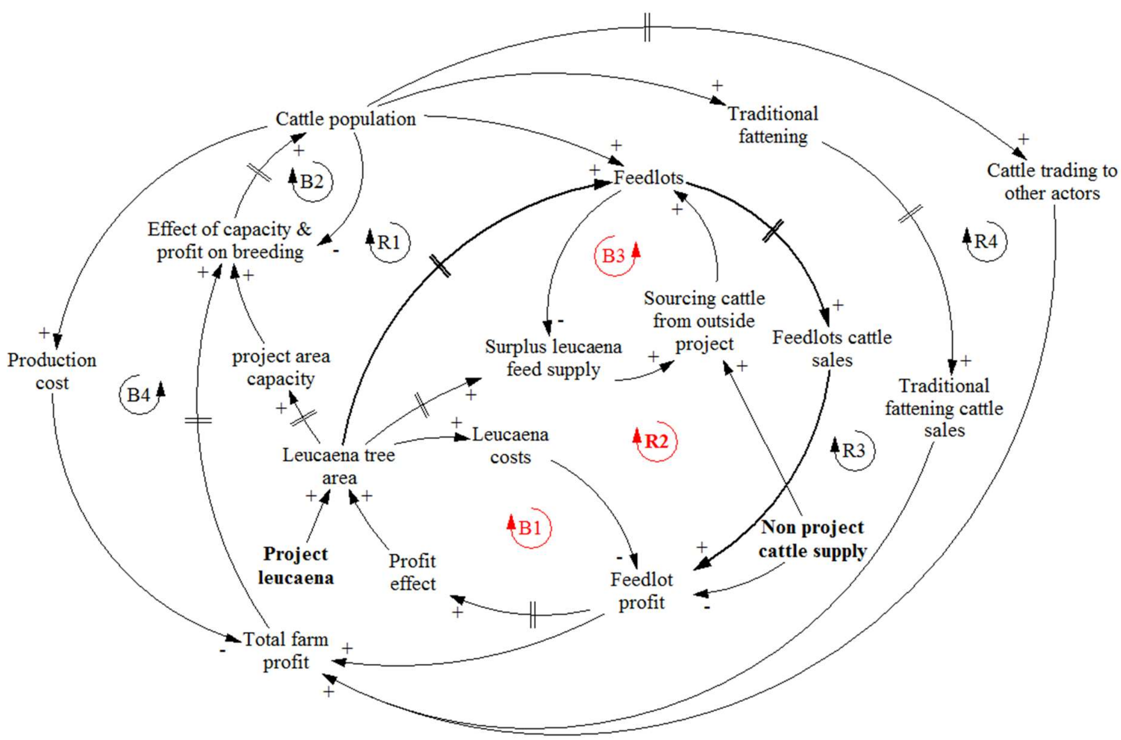

Figure 5.1 Portrait of model structure highlighting the main feedback loops in the model

The arrows in Figure 5.1 represent the main causal relationships among the model components. The polarities (+ and – signs) on the arrowheads indicate the direction of these causal relationships. A positive (+) sign indicates that a change in a source variable will change the variable of destination in the same direction (e.g., an increase in variable 'Feedlots cattle sales' leads to an increase in 'Feedlot profit'). In contrast, a minus (-) sign indicates the two correlated variables move in opposite directions (e.g., an increase in 'Leucaena costs' leads to a decrease in 'Feedlot profit', and vice versa).

There are a number of positive or reinforcing (R) and negative or balancing (B) feedback loops which regulate the overall dynamics of our value chain model. The symbol (//) denotes delays in the system (e.g., there is a time lag between change in 'Feedlot profit' and the decision to invest in leucaena (i.e. 'Profit effect'), or the time it takes 'Feedlots' and 'Traditional fattening' operations to fatten cattle for sale. The primary positive feedback is the profitability of the cattle production system. Profit improvements, either through the feedlot or marketing interventions, encourage additional investments into leucaena planting and feedlot activity, and better animal husbandry which raises animal fertility (see R1 and R2 in Figure 5.1). On the other hand, the oversupply of leucaena tree areas increases leucanea costs which lowers feedlot profit and provides a negative feedback signal causing investment into leucaena planting to taper off (see B1). In a similar vein, an increase of surplus leucaena feed supply leads to an increase in the sourcing of cattle from outside the project area, which increases the cattle population in the feedlots and, hence, reduces surplus leucaena feed supply (See B3). The Sumbawa cattle supply chain system is governed by several additional feedback loops (as indicated in Figure 5.1), however, it is R2, B1, and B3 that are dominant feedback loops governing the model outcome during the scaling-out of the intervention. To explain the key relationship between leucaena plantings and feedlot profits in more detail, we display the following two model equations that govern this relationship:

$$Desired\ Leucaena\ Area_{t_{n+1}} = Profit\ Effect_{t_n} \times Leucaena\ Tree\ Area_{t_n} \qquad (1)$$

$$Profit\ Effect_{t_n} = (Feedlot\ Profit\ _{t_n} / Feedlot\ Profit\ _{t_0})^{\ AE} \qquad (2)$$

Where the desired future planting area ($Desired\ Leucaena\ Area_{t_{n+1}}$) is determined by the product of the existing area of mature trees ($Leucaena\ Tree\ Area_{t_n}$) and a variable that represents the impact of profit improvements on the desired planting area ($Profit\ Effect_{t_n}$), at time period t_n. This variable is in turn determined by the profitability of feedlot production at any point in time

($Feedlot\ Profit_{t_n}$) relative to the profitability of feedlot production in the initial time period, t_0, raised to the power of a parameter that can be described as the acreage elasticity (AE) with respect to profit. This parameter determines the responsiveness with which the land area planted with leucaena expands in response to an increase in profit. We assume a value of 0.15 in our analysis, which means that a 1% increase in profit will provide the incentive for a 0.15% expansion in the crop area. While acreage elasticity of supply with respect to prices have been estimated for many crops, very few studies have estimated acreage elasticities with respect to profit, and neither of these two parameters have been estimated for leucaena. We therefore based our selected AE value on a range of estimates for other crops. AE values varying between 0.16 and 0.33, depending on the time periods used, were estimated for aggregate cropland in Brazil (Barr et al. 2010). The authors also translated these estimates to the more commonly reported acreage elasticities of supply with respect to price values of 0.38 and 0.90 (Barr et al. 2010). Other relevant studies have estimated values for this parameter, with respect to price, of 0.77 for rubber plantations in Malaysia (Mustafa et al. 2016), and of 0 to 1.55 for a range of crops in the US (Lee and Sumner 2016). Based on this sample of estimates in the literature, our assumed AE value of 0.15 can be considered to be relatively conservative. However, given the uncertainty about the value of this key parameter, we explore the sensitivity of the model results to a range of AE values from 0 to 0.3.

We also keep track of enteric methane emissions from the cattle herd over time. To do this we use the Tier 1 emission factor relevant for cattle from Asia, which is equal to 47 (kg CH_4 head^{-1} yr^{-1}), as well as Tier 2 emission factors which are more precise because they take into account the weights of different cattle cohorts within the herd (e.g. cows, heifers, bulls, replacement animals), their growth rates, and diet quality (IPCC 2006). For the Tier 2 approach, we assume that the dry matter digestibility of fattening animals increases from 62%, in the baseline, to 67% (Bassala et al. 1991) when fed with fresh leucaeana leaves in the project scenarios. To assess the GHG emission performance of the system we calculate emission intensities by dividing the methane emissions produced by each animal in the herd by the carcass weight (CW) of sales generated by the herd. The CW is calculated by multiplying the live weights of animals of animals exiting the beef herd by their dressing percentage. As shown in Table 5.1, the average dressing percentage of all animals sold in the baseline is assumed to be 47%, while the dressing percentage male animals fattened with leucaena is assumed to increase to 51%. We express emissions in carbon dioxide equivalent (CO_2-

eq) by multiplying methane emissions by its global warming potential of 25 for a 100-year time horizon (IPCC 2007).

5.2.3 Scenario description and scope

There are two scenarios tested in addition to the baseline, which are summarised below:

Scenario 1: Conversion to a leucanea-based feedlot system

Scenario 2: Conversion to a leucanea-based feedlot system and marketing-based price improvement

For both scenarios, we assess the short-run impacts and long-run impacts. In the former we focus on a ten-year period, which is the time frame of most relevance to estimating the ARISA project impacts. To meet the ARISA project goal of increasing net farmer incomes by 30% by 2018, it is necessary to focus on measures that can deliver solid gains in the short-run. For the long run, we extend the time frame to between 25 and 40 years to assess the potential for scaling up the intervention from the project site to the entire island of Sumbawa.

The main impact from adopting the Scenario 1 intervention is an increase in the fattening rate of young male beef cattle. This requires the sourcing of animals from the beef herd within the project area and then from outside the project area, as the increase in the throughput of cattle in the project feedlots exhausts the stocks of locally sourced male cattle. As the intervention raises the profit of the system as a whole, we assume that farmers will also put additional effort into improving the performance of cattle breeding herds, to exploit the potential for higher returns and to increase the supply of feeder stock. As discussed in the "Results" section, this causes in an increase in the fertility rate and a reduction in the calving interval over time. In the initial project years, the potential and uptake of the feedlot enterprise is driven by scheduled plantings of leucaena. Following this, plantings are assumed to occur endogenously through diffusion and uptake in response to the success of the intervention, as higher profits encourage new plantings. In the first couple of years of the project, feedlot activity is low and reliant on the harvest of wild leucaena growing on common land until the new leucaena plantings mature.

Coupled with this, we assess the potential gains from marketing-based price improvements for slaughter animals implemented as a 15% price premium above the baseline market price. This is assumed to be achieved through two steps. Firstly, by working with trading companies to increase access to high valued markets, such as those in the hotel sector of Jakarta, Mataram and other important urban centres. The greater reliability of the quantity of slaughter animals supplied and higher standardisation of quality in terms of attributes such as weight and age and higher dressing percentage, that are possible with the project intervention, should help facilitate the access to the higher value markets. In addition, we assume that more transparent marketing arrangements in determining prices, including more widespread use of scales by farm groups to measure animal weights and the provision of more current information on market price movements, will also underpin the price premium. While we have set the value of the premium to 15% somewhat arbitrarily, it is line with expectations based on anecdotal evidence about the price increases received by farmer groups that have improved their feeding systems, and adopted more transparent marketing arrangement.

5.3 Results

The model results are presented at two different scales: firstly, short-run results are presented at the ARISA project site scale; and secondly long-run scale-out results are presented for the island of Sumbawa. Results from both Scenario 1 and Scenario 2 are presented in the short-run, however, for the purpose of brevity only Scenario 2 is presented in the section on the long-run results. Recall that the two scenarios are identical apart from the introduction of the price premium for feedlot fattened beef in Scenario 2. The implications of the leucaena-based feeding intervention on the GHG emission intensities of beef production are then presented in the final subsection.

5.3.1 Short-run project scale

In the initial project years, the potential and uptake of the feedlot enterprise is driven by scheduled plantings of leucaena (exogenous variable named *project leucaena* in Figure 5.1), which occur over the duration of the project (44, 50, 57, 67 ha yearly from 2015 to 2018). However, due to the time delay between planting and harvesting, the full benefits of these scheduled plantings are only realised in 2020 (Figure 5.2). At this point, there is some surplus in leucaena available for feed because of time lags between planting, trees maturing, and decisions about building feedlots and sourcing male feeder stock (see B3 feedback loop in Figure 5.1). As a consequence, there is a 17 month pause before the economic success of the intervention and the feed shortages combine to autonomously spur new plantings of leucaena (see R2 feedback loop in Figure 5.1). Feed from these additional trees becomes available after the maturation period of a further 18 months (delay mark // on the arrow between 'leucaena tree area' and 'surplus leucaena feed supply').

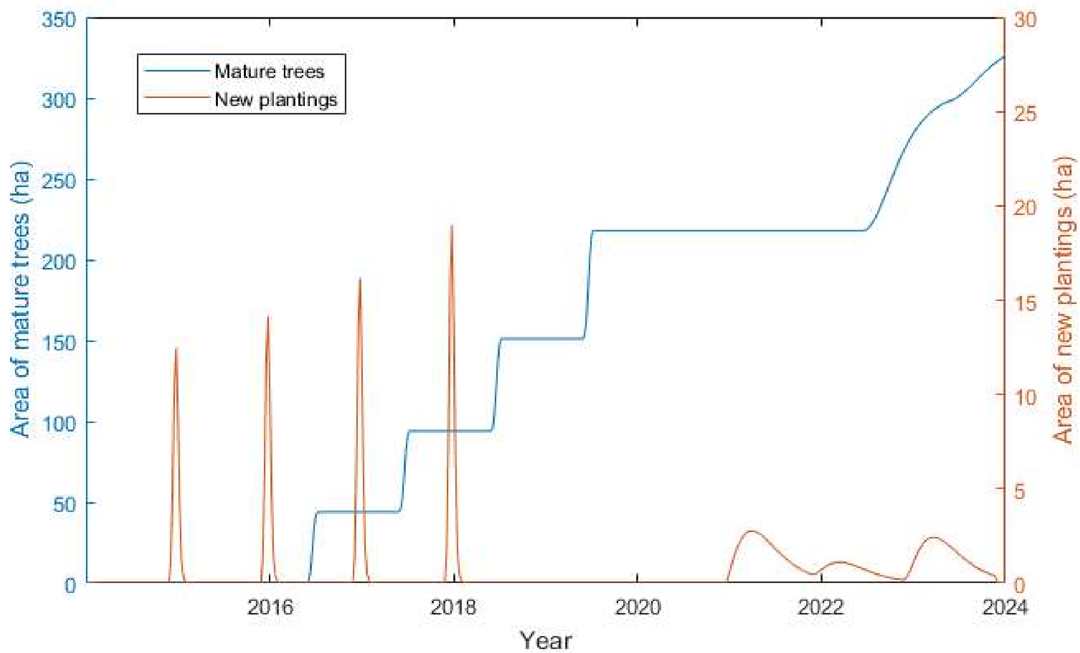

Figure 5.2 Scheduled and autonomous plantings of leucaena, and stocks of mature leucaena trees for Scenario 2

The short-run economic success of the lecuaena feedlot intervention on cattle fattening profits is captured in Figure 5.3, where weekly farm profits from the intervention without (Scenario 1) and with (Scenario 2) the price premium are compared with the baseline situation. Note that the seasonal fluctuations in demand (due to celebrations around Idul Fitri, Eid al Adha and Mawlid) are clearly visible as spikes in profit. These are caused by a pulse in both the price of cattle and the volume of sales around these events (see "Methods" section). In the initial years of the project (2015 to 2018), the economic benefits from on farm plantings are are relatively low as the revenue from beef sales barely offset the costs of leucaena establishment. This is because of the relatively small area of planting and the time delay between planting and maturation of the trees. However, the use of wild leucaena in this initial period ensures that the new enterprise profits under Scenario 1 are

110% higher than in the baseline. By 2023, when both the project plantings have matured and the utilization of leaucaena by cattle is close to complete, the increase in weekly profits in Scenario 1 surges to a level that is on average 220% higher than the baseline over the course of the year. With the addition of the Scenario 2 price premium, profits increase further, reach 415% of baseline levels in 2023. These results suggest that the returns of the price premium from improved marketing efficiency are of near equal importance to the gains that come from the adoption of the leucaena-based feedlot system. However, the former is not possible without the latter.

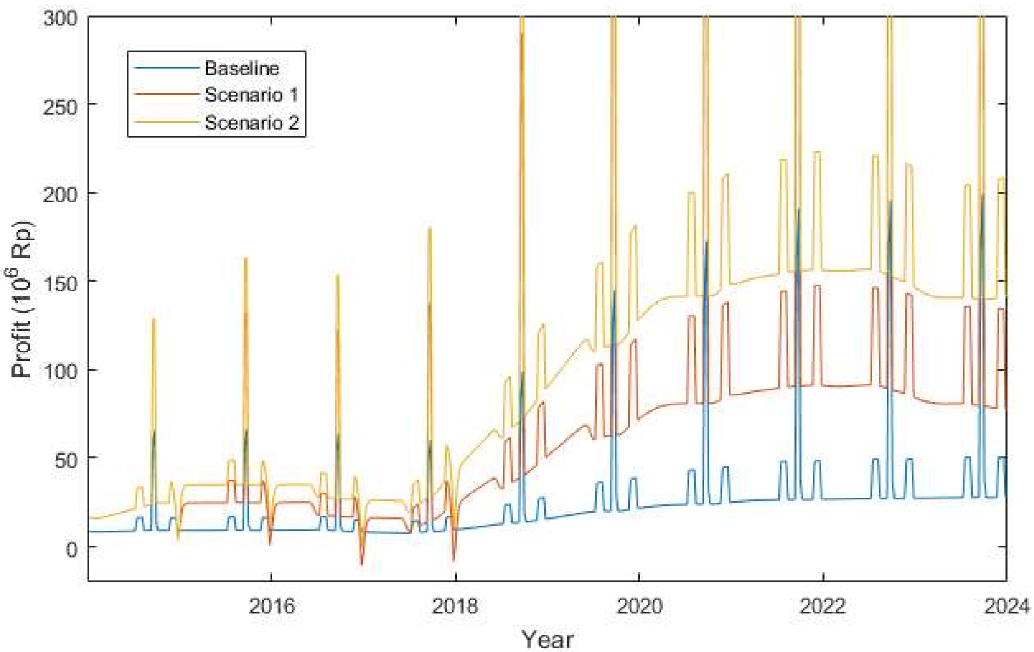

Figure 5.3 Weekly feedlot farm profits for the Baseline, Scenario 1 and Scenario 2 (Rp. Per week)

The economic benefits of the intervention package extend beyond the farm gate, with varying impacts for different actors in the value chain (Figure 5.4). Unsurprisingly, the additional profits for traders track the pathway of profit flows for the feedlots, because the higher volume of throughput from these enterprises results in a higher volume of trades. Nevertheless, these benefits for the traders that source cattle from farmers adopting the package maybe offset, to a large extent, by losses to other traders that would have sourced fattened males that are now directed through the feedlots. In contrast to the farm sector, the project has no short-run impact on the throughput or profits of the local butcher sector. This is because this sector relies on cull animals from the breeding herd (which include older cows and bulls that reach the end of their service life), and the intervention does not increase the supply of these animals in the short-run.

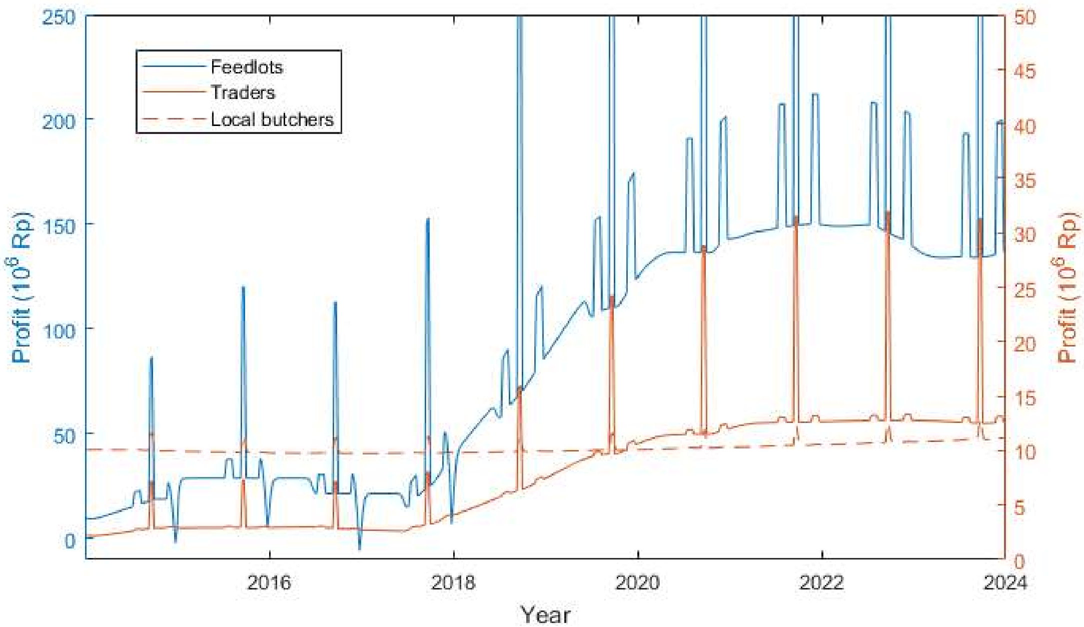

Figure 5.4 Weekly profits for the three main value chain actors for Scenario 2 (Rp. Per week)

5.3.2 Long-run scale-out

In this section we present long-run simulation results to demonstrate the potential for scaling-out the leucaena-based feedlot intervention under the Scenario 2 package, which includes the 15% price premium from improved marketing. The key determinants for the long-run scale-out include the availability of male feeder stock, land for planting leucaena, and the responsiveness of new plantings to improvements in profit. According to local expert knowledge a ratio of weaned males available for fattening relative to the cattle population within the project area around 8-12% is likely depending on the performance of the breeding herd over time. Assuming a ratio 10%, this would result in 10% x 590,295 = 59,030 male cattle available for fattening within the island of Sumbawa in addition to the 351 available in the project area. Another factor that may constrain the scaling out of the intervention is the amount of land available for the planting of leucaena. However, given the high per hectare yield of leucaena and the relatively short fattening duration with this feed source, only 5,476 hectares would be required to supply the 59,030 annual throughput of male feeder stock (inclusive of project and non-project cattle) for 2015. To put this into context, there are 87,000 hectares of arable drylands in the Sumbawa district alone, much of which would be suited to leucaena production. Moreover, in the ARISA project area leucaena is being planted in hilly fallow areas not suited to other crops and is therefore unlikely to be attracting opportunity costs related to the displacement of other crops.

Under these constraints and model assumptions, the project scale-out proceeds at a pace of 19% per year from the time that project plantings reach full maturity and new endogenous plantings commence at the beginning of 2021 until the end of 2028. This amounts to an average of 83 additional hectares of trees each year, which is close to double the average rate of 42 hectares per year in the planting rate during the project phase from 2015 to 2019. After this the pace of scale out accelerates, with an average annual increase of 364 ha in leucaena planted between 2031 and 2038. The total stock of mature leucaena plantings reaches 3,444 ha by mid-2039 (Figure 5.5). By this time the corresponding throughput of fattened males reaches 37,124 head per year, which represents 63% of the total annual availability of 59,030 male feeder stock on the island of Sumbawa.

A notable feature of long-run scale-out is the cyclical nature of the autonomous leucaena plantings over time (governed mainly by R2, B1, and B3 feedback loops in Figure 5.1), with sowing events occurring over four separate oscillations ranging from 2 to 3 years in duration (Figure 5.5). These planting events increase in amplitude over time, but the area planted in each event comprises a similar share of the stock of mature trees in each corresponding time period. Such oscillations are typical in all economic industries and occur as a consequence of time delays in information feedbacks within production and value chain systems (Sterman 2000). In our case, the decision to plant leucaena is motivated by shortages in the supply of leucaena relative to the amount of cattle available to fatten and profitability of feedlot enterprise. However, the decision to begin and cease planting is imperfect because of time delays in receiving and acting upon information about shortages and excesses in supply and forming an expectation of future profit of cattle production. The resulting periods of oversupply and undersupply causes the oscillating behaviour of leucaena planting.

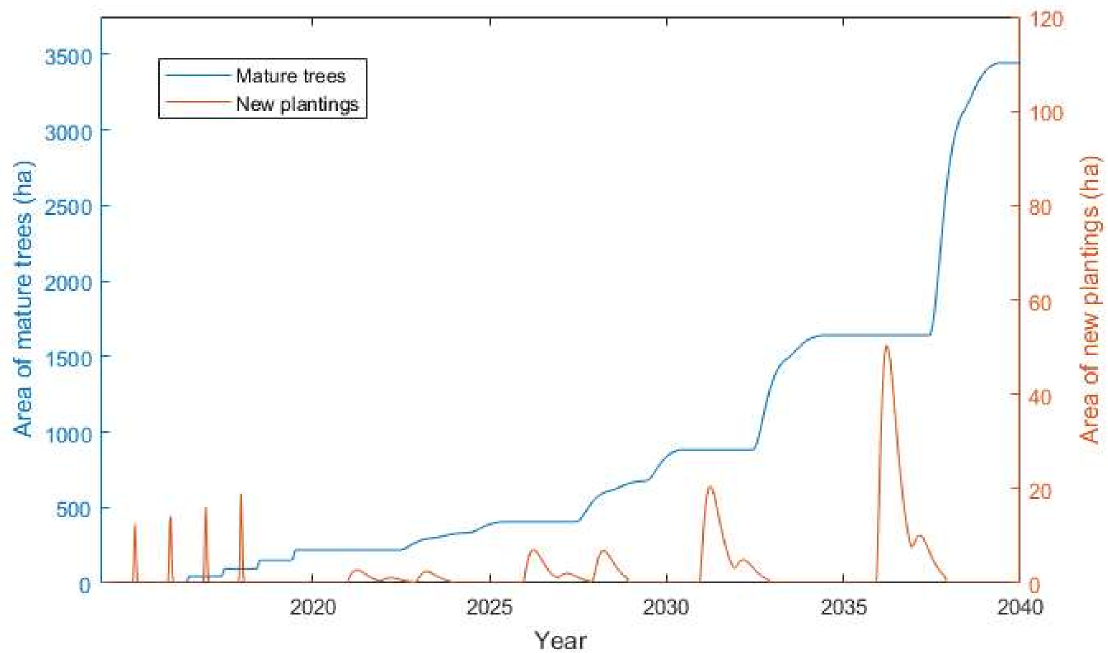

Figure 5.5 New plantings and corresponding stock of mature leucaena trees in the long-run for Scenario 2

From the perspective of land and animal resource availability on the island, the scale-out pathway displayed in Figure 5.5 proceeds at a relatively moderate pace. Since the throughput of fattened male animals corresponding to the maximum area of planted leucaena accounts for less than two thirds of the volume of male feeder stock available each year on the island, it is possible that both the pace and total size of scale-out could be increased. Moreover, the area sown to leucaena represents a mere fraction of the potential area that could support this forage crop (see "Data" section). Since animal and land resources are not binding, we next turn our attention to adjusting the responsiveness of the intervention scale-out to profit improvement. As discussed, this responsiveness is driven by the (AE) acreage parameter.

The purpose of this analysis is not to construct a definitive or accurate projection. It is instead intended to identify which production resources could constrain the scaling-out of the intervention under differing but plausible rates of expansion. To explore these resource-based boundaries we assess the sensitivity of the results to a range of AE values. The yellow line (AE = 0.15) in Figure A5.1 corresponds to the value assumed in the preceding analysis and provides a useful reference point for the other scale-out pathways. At one extreme, an AE value to 0.05 results in very little autonomous plantings over the 35-year timeframe. At the other extreme an AE value of 0.3, which is not implausible, results in a rapid scale-out with the area of plantings reaching a maximum of 5,430 ha, by 2033. According to the model outputs, this area of leucaena supports annual throughput of 58,836 fattened males, which represents 99.7% of the total number of male feeder stock available each year. Hence, at this level of responsiveness, the intervention system can fully exploit all the animal resources available on the island of Sumbawa. In contrast, the land resources needed to support 5,430 ha of leucaena are again highly unlikely to constrain a scale-out of this size. There are however a number of reasons, which are articulated in the Discussion, why this level of scale-out may be difficult to achieve in practice. In addition to the sensitivity analysis that was performed as part of the scale-out assessment, we performed a number of validation tests recommended for SD models (Sterman 2000; Senge and Forrester 1980), for which the model performed well (see "Model validation tests" section of Appendix B).

5.3.3 Greenhouse gas emissions

The increase in the productivity of the cattle herd that is possible with the improved leucaena-based feedlot enterprise also has important implications for its environmental performance. We assess this by comparing the GHG emission intensities of production for the herd as a whole using both Tier 1 and Tier 2 emission accounting approaches for enteric methane in 2020 (Table 5.3). The same percentage reduction is estimated with both approaches, however the Tier 1 approach overestimates the emission intensities for both the baseline and for the project scenario. This overestimation occurs because the cattle in Sumbawa are smaller than the average cattle in Asia upon which the Tier 1 emission factor is based. The improved environmental performance in scenario 2 is mainly driven by a reduction in the lifespan of the male fattening animals, which reduces the overall stock of animals and their associated emissions required to support any given level of output. It is also improved, to a lesser extent, by the higher dressing percentage of the fattened animals (Table 5.1) and, in the case of the Tier 2 approach, from higher digestibility of feed for fattened animals.

Table 5.3 The GHG emission intensity of production (kgCO_2-eq kg CW^{-1}) with regard to enteric methane production in 2020

Method	Baseline	Scenario 2	Reduction
Tier 1[a]	60.9	51.2	16%
Tier 2[b]	45.2	38.2	16%

a. These results are based on the IPCC Tier 1 emission factor relevant for cattle from Asia, which is equal to 47 (kg CH_4 $head^{-1}$ yr^{-1}) (IPCC 2006).
b. These results are based on IPCC Tier 2 emission factors, which are calculated by taking into account the weights of different cattle cohorts within the herd (e.g. cows, heifers, bulls, replacement animals) and performance factors including growth rates and diet quality (IPCC 2006).

5.4 Discussion

In simulating the adoption of a leucaena-based feedlot fattening system in Sumbawa, we have shed light on the potential economic gains of the new system, its varying impacts on different value chain actors and its potential for improving environmental performance. In this section we summarise these findings and discuss how they can assist in improving project design in the short-run and in understanding the possibilities and constraints associated with various scale-out pathways in the long-run.

Our findings complement the growing body of biophysical evidence about the potential success of this intervention in Eastern Indonesia (Dahlanuddin et al. 2014; Marsetyo et al. 2012; Quigley et al. 2009), by estimating improvements in the annual profitability for beef farmers in the ARISA project area of up to 415% by 2023. Due to the time it takes for scheduled plantings to reach completion and mature, the benefits of the intervention package also take some time to manifest. Therefore, investors and policy makers need to be patient and work within a sufficiently long-term planning horizon. Increases in farm profit were shown to be near equally dependent on adoption of the feedlot system and the price premium components of the package. This demonstrates the importance of incorporating both components. Importantly, the intervention was shown to generate positive or neutral benefits for the main value chain actors, although it will lead to a rearrangement of farmer-trader relationships as the intervention is scaled-out, particularly if price premiums can be secured and sustained for feedlot fed slaughter animals.

There are also climate change mitigation benefits from the intervention, with reductions in the GHG emission intensity of meat produced by the entire beef herd of 16% in 2020. This is low compared to the 20-57% reductions in emission intensity associated with switching from native grasses to leucaena reported for northern Australian beef systems (Charmley et al. 2011; Taylor et al. 2016), because leucaena feeding was confined to the male fattening component of the herd in the present study. The baseline emission intensity estimated in this study (45 $kgCO_2$-eq kg CW^{-1}) is also relatively high compared to studies in other regions. For example, the FAO report Tier 2 emission intensities for beef production of around 28 $kgCO_2$-eq kg CW^{-1}, for enteric methane emissions in East and South East Asia combined (Gerber et al. 2013). Our higher estimate reflects the low level of herd productivity in Sumbawa, especially compared to production in East Asia. The contrast is even greater in some other developed regions. For instance, enteric methane emission intensities of 8 $kgCO_2$-eq kg per kg of live weight (approximately 16 $kgCO_2$-eq kg CW^{-1}) are reported in northern Australia (Charmley et al. 2011) and 7 $kgCO_2$-eq kg per kg of live weight (approximately 14 $kgCO_2$-eq kg CW^{-1}) in central France (Veysset et al. 2014). These studies also show that enteric methane is dominant, comprising between 82% (Veysset et al. 2014) and 95% (Charmley et al. 2011) of animal GHG emissions, with the rest from manure management and deposition on pasture.

In addition to these substantial gaps in emission intensities, beef productivity in Sumbawa is also relatively low. Recall that the ADGs for fattening animals in our study area in the baseline and with leucaena feeding were 0.16 and 0.45 kg day^{-1}, respectively. Even the improved rate of fattening in our project falls short of what is typically observed with heavier breeds in more developed regions. For example, ADGs of between 0.6 and 0.7 kg day^{-1} were reported for Aberdeen Angus steers finished on grass of in New Zealand, with ADGs of up to 1.66 kg day^{-1} for the same breed finished on concentrate feed in France (Cuvelier et al. 2005). In China, local cattle breeds fed a mixture of straw and concentrates in typical Chinese production system had ADGs of between 0.78 and 0.82 kg day^{-1}, while a rate of 1.5 kg day^{-1} was reported for imported Limousin cattle (Zou et al. 2001). Cross breeds have also been found to perform better than local breeds in China, reaching heavier slaughter weights at a younger age (Xie et al. 2012). The introduction of new genetics, possibly through cross breeding local and imported cattle, may provide additional gains to better feeding and animal management in Sumbawa. However, according to local experts, a previous attempt in the province of West Nusa Tenggara to introduce Brahman cross cows did not succeed, because farmers lacked the skills to manage larger breeds and did not have sufficient feed resources to make use of the animals' higher potential. The Indonesia Australia Commercial Cattle Breeding Program (IACCB) is a pilot program launched in early 2016 that aims to overcome these challenges and assist in commercialising beef production in Indonesia through a package of measures that includes introducing Braham cattle and improving resource utilisation (www.iaccbp.org). The success of this program in overcoming previous obstacles to breed improvement will only be known once it has been completed and evaluated.

We also explored number of pathways to scale-out in the long-run, based on differing assumptions about the responsiveness of leucaena planting in response to higher economic returns for farmers. This responsiveness is a matter of some conjecture for which we assume a relatively moderate and realistic pace of autonomous scale out, resulting in the accumulation of 3,444 hectares 20-years after the initial project phase, which could sustain the fattening of 37,124 male cattle per year. This level of throughput represents 63% of the entire male feeder stock on the island of Sumbawa. Whether this pace of scale-out could be sustained over this timeframe on a purely autonomous basis, without being helped along by additional government investments and programs is not entirely clear. However, from the perspective of animal and land resource availability, higher rates of scale-out are certainly possible and under more optimistic assumptions could reach a scale capable of utilising virtually all of the 59,030 available male feeder stock on Sumbawa Island each year, some 15 years from the completion of the ARISA project. This result contrasts with those of another study on neighbouring Lombok, where land constraints limited the scale out of a package of interventions to improve cattle productivity (Dahlanuddin et al. 2016).

While land resource availability is unlikely to constrain this level of production in Sumbawa there are a number of reasons why a burgeoning feedlot sector might face difficulties in securing all of the island's male feeder stock over this time frame. Some of these constraints, based on feedback from a number of project sites across Indonesia in which leucaena-based feeding interventions have been introduced, are summarised in (Hau et al. 2014). They found that some farmers prefer open grazing to cut-and-carry feeding, because of difficulties in meeting the much higher additional labour requirements of the latter system. Other reasons why farmers may resist adopting the new system include perceived higher risks of animal theft in the more built-up areas that feedlots tend to be located as well as a lack of capacity in tree establishment and access to seeds (Xie et al. 2012).

In some respects, the more moderate rate of scale-out in our main analysis (Figure 5.5) will reflect some of these additional constraints. However, this and more rapid rates of expansion are highly dependent on farmers receiving a price premium for younger, higher quality, fattened animals. Our results show that this marketing improvement nearly doubles smallholder profits from the intervention and is therefore integral to the scalability of the overall package. The widespread uptake of beef intensification practices, including the use of tree legume forage, is only likely to possible when coupled to such market-based incentives (Dahlanuddin et al. 2016). Supporting improvements in agricultural production with better marketing outcomes is key objective of the ARISA project, and understandably so given how fundamental it is to driving and sustaining the innovation process.

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We, the PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

	Author's Name (please print clearly)	**% of contribution**
Candidate	Benjamin Henderson	80
Other Authors	Dahlanuddin	7
	Kanar Dizyee	10
	Hermansyah	1
	Andrew Ash	2

Name of Candidate: **Benjamin Henderson**

Name/title of Principal Supervisor: **Prof. Oscar Cacho**

[redacted]

06 / 04 / 2018

Candidate

Date

[redacted]

09/04/2018

Principal Supervisor

Date

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We, the PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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Name of Candidate: **Benjamin Henderson**

Name/title of Principal Supervisor: **Prof. Oscar Cacho**

[redacted]

06 / 04 / 2018

Candidate Date

[redacted]

09/04/2018

Principal Supervisor Date

Chapter 6: The economic potential of residue management and fertilizer use to address climate change impacts on mixed smallholder farmers in Burkina Faso

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[redacted]

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	Author's Name (please print clearly)	**% of contribution**
Candidate	Benjamin Henderson	80
Other Authors	Oscar Cacho	7
	Philip Thornton	7
	Mark van Wijk	3
	Mario Herrero	3

Name of Candidate: **Benjamin Henderson**

Name/title of Principal Supervisor: **Prof. Oscar Cacho**

[redacted]

06 / 04 / 2018

Candidate

Date

[redacted]

09/04/2018

Principal Supervisor

Date

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Name of Candidate: **Benjamin Henderson**

Name/title of Principal Supervisor: **Prof. Oscar Cacho**

[redacted]

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[redacted]

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Principal Supervisor Date

Chapter 7: Discussion and conclusions

7.1 Overview

The quantitative research in this thesis provides knowledge, which can assist policy makers prepare the agriculture sector for the challenges of addressing climate change and managing its impacts on farmer livelihoods. With the inevitable emergence of climate change policies and growing consumer expectations for improved environmental performance, the analyses in this thesis reveal that there is reasonable potential for the ruminant sector to contribute to global GHG mitigation efforts, with the associated effectiveness and economic impacts varying widely depending on the choice of policy. A range of modelling assessments in different smallholder production contexts also demonstrate that there is good potential for sustainable development options to exploit synergies between agricultural development and climate change mitigation and adaptation objectives.

The main quantitative findings on GHG mitigation and adaption to climate change from the various assessments in the thesis are integrated and discussed in the next section, with reference to the research questions and issues raised in Chapter 1. Discussion about the differing contributions of abatement measures and policies to lower global ruminant emissions is made possible by the tight methodological link between the global assessments in Chapters 2 and 3. While the findings from the smaller scale assessments in Chapters 4-6 add complementary insights about different approaches for improving farm performance while, at the same time, delivering solutions for mitigation and adaptation to climate change. The focus of the following section is on integrating various findings of the thesis around the central topic of GHG mitigation and farm performance. The discussion in subsequent sections of this is chapter is arranged according to cross-cutting findings from the various chapters of the thesis. Finally, following the discussion of the main limitations of the research, this chapter concludes by offering suggestions for future research.

7.2 Integrated findings on GHG mitigation, farm performance and adaptation

While ruminant production systems generate a substantial share of the world's GHG emissions, they can also play an important role in tackling climate change. As stated in Chapter 1, the two complementary research methods employed in the global assessments of Chapters 2 and 3 enable the different roles that technical interventions and market interactions, induced by different policy choices, have in lowering ruminant GHG emissions to be captured. According to the marginal abatement cost study in Chapter 2, a global mitigation potential of 249 $MtCO_2$-eq yr^{-1} was estimated for the ruminant sector at a price of \$20 tCO_2-eq^{-1} in the absence of trade and market interactions. This mitigation potential was some distance from the total technical mitigation potential of 379 $MtCO_2$-eq yr^{-1} (11% of global ruminant GHG emissions) estimated to be possible from the selection of mitigation measures used in this assessment. As shown in Chapter 3, the use of a global carbon tax, set at the same carbon price, could significantly amplify this potential to 626 $MtCO_2$-eq yr^{-1} by harnessing market effects such as product substitution and trade. This additional mitigation potential, however, induces a contraction in ruminant-based food production, particularly in low income regions with more emission-intensive ruminant outputs. Given these negative trade-offs the overall merit of this policy option is questionable, and its potential should therefore be regarded as an upper bound estimate. In contrast, the introduction of a producer subsidy to compensate producers for their tax expenses was very effective at addressing these issues by maintaining ruminant production levels in all regions, albeit for a much reduced global mitigation potential of 185 $MtCO_2$-eq $year^{-1}$. In this case the market effects, captured by the CGE model in Chapter 3, attenuate GHG abatement relative to the Chapter 2 estimate, as the increased demand for abatement resources raises their costs and lowers their use relative to the baseline situation. Nonetheless, the case for compromising on mitigation effectiveness to maintain production is arguably stronger for agriculture than for other sectors of the economy, as recognised by the Paris Agreement ambition to reduce agricultural emissions while protecting food production. Moreover, since this instrument can maintain ruminant production levels, it has the potential to accommodate a more ambitious carbon price. Another key insight of this research is that a carbon tax could restructure the global cattle sector, increasing the share of cattle meat supplied by the dairy sector relative to the beef sector.

Complementing these findings, the frontier efficiency assessment in Chapter 4 reveals that large mitigation gains are possible by closing yield gaps within several parts of Sub Saharan Africa, without the introduction of new technologies. It was found that closing these gaps could lower the GHG emission intensity of production by between 20% and 63% for ruminant products and by between 25% and 61% for grain crop products. These results indicate that the mitigation potential for ruminants, expressed in terms of emission intensity reductions, may be larger in Sub Saharan Africa through the closing of yield gaps, compared to what is possible at the global level by adopting new mitigation measures. The closing of yield gaps in this region could also provide marked benefits for smallholder incomes, and food supply with associated increases of between 28% and 167% for livestock production and between 16% and 209% for crop production, estimated to be possible through this process. In Chapter 5, a system dynamics model was used to demonstrate that large gains in beef production in Sumbawa, Indonesia, are also possible through introduction of new practices. In this case, the adoption of leucaena-based feedlot systems was estimated to improve farm profits by up to 415%, however, in this case the intervention only provided modest abatement benefits, with a 16% reduction in the emission intensity of beef products. The relatively small reduction in emission intensity reflects the partial coverage of the intervention, which was only applied to the male fattening cohort of the beef herd. This demonstrates that more substantial reductions of cattle emissions will only be possible with abatement measures that also target the breeding cohort of cattle herds, given that this cohort is the main source of cattle emissions (Mottet et al. 2017).

In Chapter 6, the possible costs associated with climate change were estimated for a sample population of mixed smallholder farmers in Yatenga, Burkina Faso, which was one of the study sites also included in the Chapter 4 yield gap assessment, using the positive mathematical programming (PMP) method. This overlap in study sites between the chapters permits the option of closing yield gaps with existing practices to be compared with the introduction of new practices, in terms of their effectiveness in improving farm performance. In this case the measure of comparison is farm output rather than environmental performance, as the measurement of GHG emissions was not the focus of Chapter 6. In Chapter 4, the closing of yield gaps in Yatenga was shown to potentially increase the output of grains, legumes and milk by 68%, 75% and 100% respectively. In Chapter 6, the combined package of residue retention and N fertilisation, applied to farms for which it was profitable, was estimated to increase cereal, legume and ruminant output by, 53%, 18%, and 2%, respectively, on average over the simulation period. This indicates the production gains from the closing of yield gaps with existing practices, is likely to increase farm performance by more than the adoption of the new practices that were assessed. However, achieving the farm managerial improvements required to close yield gaps may prove more elusive than the more tangible approach of adopting new practices. In addition to estimating improvements in farm performance, the PMP assessment also estimated that annual profit losses from the "middle of the road" RCP6 trajectory of climate change, would reach 15% by 2045. While some of the assessed interventions, were shown to raise farm profits, none were able to claw back all of the losses from climate change.

7.3 Additional cross cutting themes among the thesis chapters

In addition to linkages between the various quantitative assessments in this thesis with regard to addressing climate change and farm performance, there are further cross-cutting themes around which the findings of these assessments can also be integrated. For instance, the economic advantages of targeting sectors and producers with practices that can contribute to climate change mitigation and adaptation for the least cost or highest return, were apparent at different scales of analyses. Related to this, positive synergies between producer profits and mitigation or adaptation outcomes were also found across the analyses, for a range of improved practices and policies. Benefits from the integration of crop and livestock enterprises were also apparent in different analyses, although some practices were shown to generate trade-offs between these enterprises. Further, all the studies in the thesis touched upon the challenges associated with barriers to the adoption of improved practices.

7.3.1 Potential benefits of targeting producers and sectors

According to economic theory, a market-based instrument such as a carbon tax or an abatement subsidy should be able to incentivise an economically efficient allocation of adoption decisions. While this feature of market-based instruments removes the decision making burden on policy makers about where to target practices, a priori knowledge can help to broadly focus policy efforts in regions and sectors with high abatement potential and cost effectiveness. Even though the economic efficiency of a policy should increase with its coverage of sectors and regions, so too will its transaction costs, including those associated with the development of additional measurement protocols, monitoring and enforcement. By considering the heterogeneity between production units within regions and study sites, the analyses in this thesis indicate where policies could cost-effectively deliver larger abatement potentials, which could help policy makers to manage these trade-offs. For example, the global study on the MACs for ruminant GHG emissions (Chapter 2) revealed improved grazing management was particularly cost effective in Latin America and Sub-Saharan Africa, while legume sowing appeared to work best in Western Europe and Latin America. Among the sectors, the most cost effective abatement options tend to be in the dairy sector, due to its capacity to obtain a higher payoff from investment into legume sowing and the urea treatment of straws. The heterogeneity of costs and returns of the various practices among the spatial units within each region indicate the potential importance of also considering different bundles of practices for different producers within regional populations. Similarly, important economic benefits were found to be possible from this type of targeting in the study reported in Chapter 6, in which intensification and adaptation options were assessed at the farm population scale in Burkina Faso. Significantly, by using an analysis at the farm-population scale, it was possible to demonstrate that the interventions which are the most profitable at the aggregate scale of the total population are not necessarily the options that would be most widely adopted. Moreover, it was also shown that this scale of analysis can prevent practitioners from reaching inaccurate conclusions that can seem plausible when considering average representative farms. For example, with the retention of crop residues decreasing profits at the aggregate level, it could easily be discarded as economically unviable when viewed through the lens of the average farm, even though it has the potential to be economically beneficial for a significant share of the farm population. This assessment also raised the question as to whether the benefits of using packages of measures instead of individual measures could be overemphasised in some cases, with packages delivering better overall results, but not for all farms.

The large range of potential economic impacts from various abatement options also suggests that different policy approaches could be considered to incentivise their uptake. It is possible that extension and capacity building programs may be sufficient to encourage the uptake of practices that are profitable, which could apply to around half of the abatement potential for improved grazing management and legume sowing, and around one fifth of the potential from urea treatment. Similarly, each of the options for improving the economic outcomes of farms under climate change, assessed in Chapter 6, generated a mixture of costs and profits for farmers in Burkina Faso. Despite these potential benefits associated with mitigation and adaptation options, the barriers to adoption should not be underestimated. With regard to options for abating GHG emissions, the more costly approaches would obviously only be economically viable in the presence of stronger policies that either regulate emissions or assign a carbon price sufficiently high to stimulate their uptake. As shown in the Chapter 3, the style of market-based policy used to provide carbon price incentives can also introduce strong trade-offs between abatement and food security objectives.

7.3.2 Productivity – environment – policy nexus

There is growing attention in the literature to agricultural development options that can simultaneously deliver improved outcomes for the environment, farm productivity and incomes (Burney et al. 2010; Gerber et al. 2013). The analyses in this thesis provide some evidence to support this approach, particularly the frontier efficiency analysis in Chapter 4 which showed that sizeable reductions in GHG emission intensities could be achieved in mixed smallholder production systems in many parts of Sub Saharan Africa, by closing yield gaps through gains in technical efficiency. At the same time, this could provide substantial benefits in terms of raising smallholder incomes and food supply. As shown in Chapter 5, large gains in farm incomes and food production were also found to be possible by intensifying beef production in Sumbawa, Indonesia, through the introduction of leucaena-based feedlot systems tailored to local production and marketing conditions. This development strategy was also shown to deliver mitigation benefits in terms of reduced emission intensities of beef products, although these reductions were modest compared to other studies including the yield study in this thesis, owing to the measure’s partial coverage of the production system. In addition, the global study on the MACs for ruminant GHG emissions (Chapter 2) revealed that around half of the abatement potential from improved grazing management and legume sowing, and around one fifth of the potential from urea treatment could be achieved profitably or at very low net cost. These practices have the potential to simultaneously deliver abatement benefits and increased producer profits. However, designing and implementing policies to overcome barriers to adoption at scale is not a trivial task, as already discussed.

One finding relevant to overcoming barriers to adoption, common across the analyses in Chapters 4 and 5, is the importance of considering both supply side and marketing strategies for smallholder development. In the system dynamics analysis on the intensification of beef production in Sumbawa, the price premium associated with improved product quality and marketing were shown to double smallholder profits and were found to be integral to the scalability of the project. Furthermore, a very strong and statistically significant link between market participation and farm performance was found in most of the study areas in the yield gap assessment, suggesting that efforts to promote market participation are an important part of sustaining the closure of yield gaps, particularly when farmers are able to produce in excess of their household needs.

7.3.3 Trade-offs and synergies with crop-livestock integration

This thesis also contributes to existing research on the trade-offs and synergies between crop and livestock enterprises that can emerge from the adoption of new practices and technologies. Results from the yield gaps paper in Chapter 4 suggest that there is an efficiency dividend associated with increased integration of crops and livestock, particularly among farms that are more specialised in either livestock or crop production. Given the econometric nature of that assessment, the precise mechanism for delivering this efficiency advantage was not clear. However, the PMP assessment in Chapter 6 reveals some potential mechanisms, as well as limitations of integration in the context of introducing new practices. For instance, fertilisation, where profitable, was found to benefit both crop and livestock enterprises of mixed farms by raising the production of grains and associated crop residue biomass as a source of ruminant feed. However, the retention of crop residues to improve soil fertility and crop productivity naturally resulted in trade-offs with livestock production by reducing the quantity of residues available for use as ruminant feed. Nevertheless, a significant share of mixed farms could improve overall farm profits from this practice, particularly those that are not overly reliant on either ruminants or on residues as a source of feed.

7.3.5 Importance of barriers to adoption

An important issue raised across most of the chapters is the challenges associated with barriers to the adoption of improved practices, which could explain why potentially profitable interventions are underutilised by farmers. With regard to practices and technologies for improving smallholder agriculture, options to address these typical development constraints, such as access to reliable markets for inputs and outputs, credit, and deficiencies in technical capacity, obviously to need to form part of the overall policy package to encourage their uptake. As discussed in the system dynamics study in Chapter 5, region-specific constraints need to be considered when designing prescriptions for intensification. For example, labour and land constraints have prevented the adoption of leucaena-based feedlot systems to intensify cattle production in many parts of Indonesia. Similarly, attempts to close yield gaps in beef production between Indonesia and more developed countries by the transfer of heavier and more productive breeds has had limited success, owing to lack of local farmer capacity and experience to manage heavier breeds with their additional resource requirements. Thus the viability of such technology transfer approaches depends heavily on them being appropriately matched with local resources and capacity, and being designed with realistic timeframes, expectations and measures for addressing local capacity constraints. Policies and programs could also benefit from targeting different segments of farm populations depending on their potential to derive economic returns from various practice improvements and technologies. However, the possibility of such an approach exacerbating existing inequalities must also be considered.

For policies incentivising the abatement of GHGs, there are clearly additional challenges associated with developing accurate and affordable approaches for measurement, reporting and verification (MRV) of greenhouse gas emissions. These issues need to be resolved before abatement programs can be rolled out at scale, to take advantage of the growing political appetite for including agricultural in global mitigation efforts. These challenges are mainly due to the agricultural sector being comprised of numerous heterogeneous producers with a great deal of variability in production conditions. With these concerns in mind, it is possible that subsidy-based schemes may be more practical, by restricting the challenges associated with MRV of emission reductions from farmers that enrol into such schemes, instead of measuring the emissions of all producers. This, along with a preference by the agriculture sector for policies based on the “beneficiary pays” rather than the “polluter pays” principal, could perhaps explain why the only market-based abatement instruments that have been implemented for agriculture are subsidy or offset schemes. One notable example is the Emission Reduction Fund in Australia, which relies on an auction mechanism to disperse government funds mainly to land use sectors, including agriculture. (Clean Energy Regulator 2018). There are other examples, including an offset scheme Alberta, Canada, that enables agricultural producers to create abatement credits which can be purchased by organisations in other sectors that have GHG mitigation obligations (Alberta Environment and Parks 2018).

7.4 Limitations and guidance for future research

Naturally there are a number of caveats and lessons from this thesis, which can offer guidance on future economic research priorities for addressing climate change in agriculture. Firstly, most of the analyses in this thesis are deterministic in nature and therefore do not incorporate uncertainty and or quantify errors related to the various abatement estimates. This reflects, to a large extent, the current state of most research on the economics of mitigation in agriculture. Addressing this limitation will provide information on the robustness of outcomes from various interventions and policies for addressing climate change, allowing policy makers to more thoroughly evaluate the merits of these options. In addition, the effectiveness of the improved grazing management and legume sowing interventions, which underpin the marginal abatement costs of mitigation in the global assessments in Chapters 2 and 3, are heavily dependent on the a priori identification of sectors and areas that are amenable to these practices. Clearly, more research is needed to develop indicators and heuristics, based on the biophysical and management characteristics of grazing lands, before this requirement can realistically be met. While an attempt was made to balance the competing objectives of GHG mitigation, food security and producer livelihoods, further research is needed into designing more pragmatic policy designs to address these objectives, particularly with regard striking a suitable balance between MRV accuracy, cost and economic efficiency. Moreover, none of the studies in this thesis address food security from a nutritional perspective, by measuring increases or constraining reductions in the essential nutrient content of different food sources affected by the various technical and policy interventions that were assessed. By redressing this neglect, recent research by Havlik et al. (2014), at the global scale, and Rigolot et al. (2016), at the farm scale, have been able to provide more robust insights about the nutritional impacts of mitigation policies and climate change. Future mitigation research should focus on the design of policies that can maintain nutritional outputs in developing country regions, as opposed to maintaining value-weighted volumes of food production.

Continuing with the global studies in Chapters 2 and 3, the potential for supply-side mitigation measures to abate GHG emissions from ruminants was shown to be quite limited. For this sector and the rest of agriculture to contribute its 1 $GtCO_2$-eq yr^{-1} abatement target as part of global efforts to limit global warming to 2°C, additional strategies must be considered. This includes consideration of measures that can alter human diets by shifting consumption away from ruminant-based products towards less emission-intensive foods. While a handful of studies have shown the large potential of such dietary changes (Hedenus et al. 2014; Bajželj et al. 2014; Stehfest et al. 2009), the possible policy mechanisms for achieving this, and their economic consequences, have not been adequately assessed. Future quantitative research to design and evaluate feasible and equitable policy approaches that address this issue, are recommended to fill this important research gap. Furthermore, it is worth noting that the range of supply-side mitigation measures included in global assessments of this thesis were not exhaustive. An attempt was made to restrict the set of measures used to construct the MAC curves in Chapter 2 to the most promising options, based on agreement in the literature and among experts about their effectives, while at the same time excluding options that were likely to negatively affect food security, such as the feeding of grain-based concentrates to ruminants. It is likely that the inclusion of additional mitigation measures would have increased the size of the mitigation potentials estimated in Chapters 2 and 3. Another limitation of these global assessments is that the mitigation estimates and policy coverage was restricted to the ruminant sector. Although this decision was based on evidence about this sector's overwhelming contribution to agricultural emissions, the extension of mitigation policies to other agricultural emissions would have provided additional insights. For instance, the application of a carbon tax to crop GHG emissions would have raised the feed costs in high income regions that use relatively more grain-based feeds and slightly attenuated the resulting increase in ruminant production in these regions, as a consequence of the global carbon tax. Nevertheless, this adjustment is likely to be slight, given that direct emissions from ruminants comprise a much larger share of the sectors GHGs than emissions linked to the production of feed.

Turning to the smaller scale quantitative assessments in Chapters 4-6, a number of additional caveats and topics for further research are also apparent. While each frontier model in the yield gap assessment (Chapter 4) was confined to individual sites within small geographical areas, it is possible that the estimated yield gaps may still incorporate environmental factors that influence production among the farms within each site. For this reason, the potential improvements in yields and emission intensities in this study should be viewed as upper bound estimates of what can be achieved without the introduction of new practices and technologies. Further, while restricting the estimation of each frontier to individual sites ensured the identification of relevant targets for each site, the construction of a meta-frontier comprised of the individual technologies from each site (O'Donnell et al. 2008), would have yielded additional insights by enabling the calculation of comparable technical efficiencies across the farms in each region. This is an additional area of research that warrants further exploration.

A further caveat worth mentioning in the Chapter 6 assessment of climate change impacts and options for mixed smallholder farmers in Burkina Faso, is that the biophysical impacts of climate change impacts were limited to the mean changes in yields over time. Increases in intra- and inter-annual variability of yields and growing conditions, which are expected to increase as a consequence of climate change, will also present producers with substantial challenges and impose additional costs. This shortcoming is common in the literature and occurs because the global circulation models (GCMs), upon which impact studies rely, focus on the mean impact of climate change. Pending advances in GCMs, it could be worth artificially embedding increases in the temporal variability of climatic effects to obtain insights about their potential effects. A related shortcoming which applies to the assessment of the leucaena-based feeding intervention for beef in Chapter 5, is that climate change impacts were not considered, despite the long-term dynamic setting of the assessment. It is possible that climate change impacts in this region could present further challenges to beef producers attempting to adopt this intervention. However, given the resilience of leucaena to dry conditions and its value as a dry season feed source, it is also possible that the returns from adopting this practice could increase relative to a baseline under climate change.

In future research that uses a range of scales to assess measures and policies for addressing climate change in agriculture, it may be worth attempting to make explicit links between the different scales of analysis. For example, the application of mitigation practices at the global scale can affect the availability of resources and generate economic impacts, such as increases in the prices of production resources. These could in turn affect the economic outcomes of related regional and farm population scale assessments. However, in this thesis, with the global assessments being static and two of the three smaller scale assessments being dynamic, it would have not have been straightforward nor necessarily desirable to attempt this.

Finally, the economic and policy implications of environmental co-benefits associated with the abatement of agricultural GHG emissions, which were not considered in this thesis, deserve more attention from researchers. For example, co-benefits from conservation agriculture and grazing management practices that sequester soil carbon, such as improved water holding capacity and reduced erosion and nutrient run-off, are economically valuable. If policy mechanisms can be designed to remunerate producers for providing these additional public benefits, their uptake of abatement practices would naturally become more economically attractive and increase. Lankoski et al. (2015) have quantified this issue, but more research in a broad range of production contexts would greatly assist policy makers in designing more effective abatement policies and programs.

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Appendices

Appendix A: Supplementary material for Chapter 4

The means and standard deviations of the input and output variables used in the stochastic frontier models for each site, are listed in table A4.1. For animals, tropical livestock unit (TLU) index was used to aggregate different animal types. This index takes into account the feed requirements of different animals and is therefore reflective of their varying resource requirements (ILRI 2011; FAO 2003). The standard measure for one TLU is one cattle with a body weight of 250 kg. By contrast a 30 kg sheep or goat is equal to 0.2 TLUs, and is therefore assumed to consume 20 percent as much feed as 250 kg cow. For farm assets we relied on ILRI (2011) and BMFG (2010) to aggregate different asset classes. These included all productive farm assets including items such as ploughs, water pumps and wheelbarrows. The values assigned to each type of asset reflect their relative economic values. For example, a powered water pump has a value twelve times greater than a shovel and three times greater than a plough (ILRI 2011; BMFG 2010). For livestock products, crop products and materials (which includes fertilizers, seeds, pesticides, herbicides, feeds, vaccinations) we constructed Fisher quantity indexes (Diewert 1992). This required the use of quantity and price data from IMPACTlite database (Rufino et al. 2013).

Table A4.1 Summary of the production inputs and outputs used in the stochastic frontier models

Site	**Livestock (TLU index)**	**Labour (hrs)**	**Land (ha)**	**Farm assets (Index)**	**Materials (Fisher quantity index)**	**Livestock (Fisher quantity index)**	**Crops (Fisher quantity index)**
Nyando							
mean	6.8	981	4.3	12.9	0.28	0.75	0.26
st. dev	5.0	934	4.6	8.0	1.39	1.22	0.36
Wote							
mean	8.3	1,421	4.5	11.5	0.19	0.41	0.36
st. dev	6.1	1,048	3.3	7.4	0.38	0.32	0.35
Hoima							
mean	3.8	2,513	10.4	11.3	1.65	0.06	2.25
st. dev	5.9	1,890	15.3	5.6	4.97	0.14	4.13
Lushoto							
mean	2.2	2,858	2.1	7.7	1.05	0.23	0.96
st. dev	2.2	2,454	1.4	5.2	2.64	0.71	3.25
Borana							
mean	17.4	1,633	3.7	11.1	90.88	47.50	5.29
st. dev	12.0	1,595	2.6	6.6	243.81	119.00	5.40
Yatenga							
mean	9.1	2,332	4.6	14.5	3.45	6.07	0.71
st. dev	12.0	4,034	3.2	13.0	13.20	12.38	0.99
Kaffrine							
mean	10.0	4,474	26.3	12.8	0.58	0.23	0.97
st. dev	9.8	3,029	22.2	6.3	0.63	0.34	1.04

The parameter definitions listed below in Table A4.2 correspond to the production function estimates for each site shown in Tables A4.3-9. The farm attribute variables (Off farm income, Gender, Household size, Market participation, Livestock specialisation, Domestic assets) that were included as explanatory variables for the technical inefficiency estimates are listed at the bottom of Tables A4.3-9.

Table A4.2 Parameter definitions

Parameter	**Definition**
a_0	Intercept
a_1	Land
a_2	Labour
a_3	Livestock
a_4	Materials
a_5	Farm_assets
a_6	Crops/Livestock
b_1_1	$Land^2$
b_1_2	Land x Labour
b_1_3	Land x Livestock
b_1_4	Land x Materials
b_1_5	Land x Farm_assets
b_1_6	Land x Crops/Livestock
b_2_2	$Labour^2$
b_2_3	Labour x Livestock
b_2_4	Labour x Materials
b_2_5	Labour x Farm_assets
b_2_6	Labour x Crops/Livestock
b_3_3	$Livestock^2$
b_3_4	Livestock x Materials
b_3_5	Livestock x Farm_assets
b_3_6	Livestock x Crops/Livestock
b_4_4	$Materials^2$
b_4_5	Materials x Farm_assets
b_4_6	Materials x Crops/Livestock
b_5_5	$Farm\_assets^2$
b_6_6	$Crops/Livestock^{2}$

Tables A4.3-9 below contain the complete list of parameter estimates of the stochastic frontier models for each study site. For each variable the tables include coefficient estimate values, standard errors as well as tests of statistical significance including Z scores and P-values, with the associated levels of statistical significance indicated in the final column of each table.

Table A4.3 Maximum likelihood estimates of the translog stochastic production frontier model for Nyando

Parameter	Estimate	Std. Error	z value	Pr(>|z|)	
a_0	0.173	0.245	0.71	0.479	
a_1	0.699	0.249	2.80	0.005	**
a_2	0.377	0.239	1.58	0.114	
a_3	-0.029	0.206	-0.14	0.888	
a_4	-0.133	0.085	-1.56	0.118	
a_5	-0.399	0.264	-1.51	0.131	
a_6	-0.774	0.129	-5.99	0.000	***
b_1_1	0.264	0.155	1.70	0.089	.
b_1_2	-0.062	0.106	-0.59	0.554	
b_1_3	-0.278	0.108	-2.57	0.010	*
b_1_4	0.026	0.040	0.66	0.511	
b_1_5	-0.106	0.138	-0.77	0.442	
b_1_6	-0.074	0.066	-1.13	0.258	
b_2_2	0.202	0.134	1.50	0.133	
b_2_3	0.008	0.104	0.07	0.942	
b_2_4	0.007	0.049	0.14	0.890	
b_2_5	-0.079	0.124	-0.63	0.526	
b_2_6	0.052	0.059	0.87	0.386	
b_3_3	0.031	0.088	0.35	0.730	
b_3_4	0.068	0.054	1.27	0.205	
b_3_5	-0.031	0.102	-0.30	0.762	
b_3_6	0.030	0.042	0.73	0.468	
b_4_4	-0.049	0.026	-1.93	0.054	.
b_4_5	-0.078	0.060	-1.30	0.193	
b_4_6	-0.019	0.025	-0.76	0.447	
b_5_5	0.200	0.212	0.95	0.344	
b_5_6	0.062	0.066	0.94	0.347	
b_6_6	-0.110	0.035	-3.14	0.002	**
Age	0.025	0.005	5.34	0.000	***
Off farm income	0.003	0.001	2.44	0.015	*
Gender	0.382	0.220	1.73	0.083	.
Household size	0.040	0.037	1.10	0.271	
Market participation	-0.035	0.008	-4.62	0.000	***
Livestock specialisation	0.000	0.008	0.00	0.996	
Domestic assets	-0.005	0.004	-1.27	0.205	
sigmaSq	0.446	0.121	3.70	0.000	***
lambda	1.366	0.557	2.45	0.014	*
log likelihood function	-144.198				

"***", "**", "*", "." indicate level of statistical significance: "***" (0.001); "**" (0.01); "*" (0.05); "." (0.1)

Table A4.4 Maximum likelihood estimates of the translog stochastic production frontier model for Lushoto

Parameter	Estimate	Std. Error	z value	Pr(>|z|)	
a_0	-0.071	0.247	-0.287	0.774	
a_1	0.536	0.258	2.080	0.038	*
a_2	0.531	0.248	2.138	0.033	*
a_3	-0.081	0.211	-0.383	0.702	
a_4	0.293	0.161	1.826	0.068	.
a_5	0.340	0.296	1.149	0.251	
a_6	-0.575	0.094	-6.102	0.000	***
b_1_1	0.110	0.285	0.384	0.701	
b_1_2	-0.064	0.196	-0.324	0.746	
b_1_3	0.556	0.205	2.715	0.007	**
b_1_4	0.101	0.102	0.988	0.323	
b_1_5	-0.225	0.188	-1.196	0.232	
b_1_6	0.187	0.061	3.084	0.002	**
b_2_2	-0.327	0.183	-1.780	0.075	.
b_2_3	-0.326	0.146	-2.236	0.025	*
b_2_4	0.243	0.098	2.477	0.013	*
b_2_5	-0.084	0.181	-0.464	0.642	
b_2_6	-0.115	0.057	-2.028	0.043	*
b_3_3	-0.069	0.220	-0.315	0.753	
b_3_4	0.219	0.110	1.989	0.047	*
b_3_5	0.405	0.165	2.452	0.014	*
b_3_6	0.016	0.052	0.299	0.765	
b_4_4	-0.152	0.078	-1.939	0.053	.
b_4_5	-0.161	0.132	-1.218	0.223	
b_4_6	0.029	0.035	0.833	0.405	
b_5_5	-0.723	0.262	-2.765	0.006	**
b_5_6	0.027	0.070	0.393	0.694	
b_6_6	-0.058	0.018	-3.134	0.002	**
Livestock specialisation	-0.037	0.021	-1.746	0.081	.
Market participation	-0.019	0.008	-2.509	0.012	*
Gender	1.158	0.317	3.650	0.000	***
Domestic assets	-0.023	0.024	-0.945	0.345	
Household size	0.264	0.054	4.898	0.000	***
Off farm income	0.006	0.004	1.573	0.116	
sigmaSq	1.218	0.351	3.475	0.001	***
lambda	3.081	1.827	1.686	0.092	.
log likelihood function	-156.364				

"***", "**", "*", "." indicate level of statistical significance: "***" (0.001); "**" (0.01); "*" (0.05); "." (0.1)

Table A4.5 Maximum likelihood estimates of the translog stochastic production frontier model for Wote

Parameter	**Estimate**	**Std. Error**	**z value**	**Pr(>|z|)**	
a_0	-0.431	0.175	-2.456	0.014	*
a_1	0.053	0.137	0.391	0.696	
a_2	-0.048	0.139	-0.345	0.730	
a_3	0.151	0.133	1.137	0.256	
a_4	-0.062	0.062	-1.007	0.314	
a_5	0.434	0.216	2.009	0.045	*
a_6	-0.443	0.089	-4.994	0.000	***
b_1_1	0.219	0.146	1.500	0.134	
b_1_2	0.069	0.118	0.586	0.558	
b_1_3	-0.057	0.064	-0.892	0.373	
b_1_4	0.002	0.029	0.056	0.955	
b_1_5	-0.175	0.136	-1.290	0.197	
b_1_6	0.126	0.058	2.153	0.031	*
b_2_2	-0.039	0.146	-0.269	0.788	
b_2_3	0.019	0.072	0.259	0.796	
b_2_4	-0.039	0.035	-1.110	0.267	
b_2_5	0.018	0.110	0.168	0.866	
b_2_6	-0.100	0.054	-1.857	0.063	.
b_3_3	-0.023	0.082	-0.274	0.784	
b_3_4	0.033	0.024	1.362	0.173	
b_3_5	-0.080	0.096	-0.833	0.405	
b_3_6	0.089	0.042	2.120	0.034	*
b_4_4	-0.020	0.010	-1.982	0.047	*
b_4_5	0.002	0.040	0.052	0.958	
b_4_6	-0.005	0.017	-0.319	0.750	
b_5_5	0.368	0.207	1.783	0.075	.
b_5_6	-0.111	0.060	-1.859	0.063	.
b_6_6	-0.124	0.032	-3.820	0.000	***
Age	0.004	0.006	0.608	0.543	
Gender	-0.055	0.332	-0.164	0.870	
Household size	0.067	0.051	1.317	0.188	
Market participation	-0.029	0.010	-2.782	0.005	**
Domestic assets	-0.027	0.018	-1.475	0.140	
Off farm income	0.008	0.002	3.380	0.001	***
Livestock specialisation	0.010	0.005	1.973	0.049	*
sigmaSq	0.342	0.115	2.961	0.003	**
lambda	1.604	0.601	2.671	0.008	**
log likelihood function	-80.150				

"***", "**", "*", "." indicate level of statistical significance: "***" (0.001); "**" (0.01); "*" (0.05); "." (0.1)

Table A4.6 Maximum likelihood estimates of the translog stochastic production frontier model for Hoima

Parameter	Estimate	Std. Error	z value	Pr(>|z|)	
a_0	-0.592	0.323	-1.835	0.067	.
a_1	0.196	0.222	0.882	0.378	
a_3	0.414	0.251	1.652	0.099	.
a_4	-0.081	0.099	-0.815	0.415	
a_5	1.205	0.452	2.669	0.008	**
a_6	-0.401	0.088	-4.539	0.000	***
b_1_1	-0.186	0.109	-1.708	0.088	.
b_1_3	0.181	0.112	1.618	0.106	
b_1_4	-0.012	0.045	-0.257	0.797	
b_1_5	-0.255	0.189	-1.350	0.177	
b_1_6	0.124	0.055	2.253	0.024	*
b_3_3	0.115	0.127	0.906	0.365	
b_3_4	-0.064	0.045	-1.426	0.154	
b_3_5	-0.075	0.164	-0.458	0.647	
b_3_6	-0.052	0.042	-1.259	0.208	
b_4_4	0.029	0.033	0.868	0.385	
b_4_5	-0.051	0.102	-0.502	0.616	
b_4_6	0.018	0.026	0.707	0.480	
b_5_5	1.114	0.459	2.426	0.015	*
b_5_6	-0.133	0.085	-1.565	0.118	
b_6_6	-0.107	0.022	-4.892	0.000	***
Market participation	-0.029	0.016	-1.804	0.071	.
Off farm income	0.000	0.001	0.529	0.597	
Age	0.023	0.008	3.017	0.003	**
Domestic assets	0.007	0.005	1.313	0.189	
Livestock specialisation	-0.017	0.016	-1.036	0.300	
Gender	-0.179	0.605	-0.296	0.767	
sigmaSq	0.985	0.500	1.970	0.049	*
lambda	1.630	0.787	2.071	0.038	*
log likelihood function	-148.188				

"***", "**", "*", "." indicate level of statistical significance: "***" (0.001); "**" (0.01); "*" (0.05); "." (0.1)

Table A4.7 Maximum likelihood estimates of the translog stochastic production frontier model for Borana

Parameter	Estimate	Std. Error	z value	Pr(>|z|)	
a_0	-0.606	0.456	-1.328	0.184	
a_1	0.184	0.283	0.649	0.516	
a_2	-0.064	0.455	-0.141	0.888	
a_3	0.863	0.310	2.786	0.005	**
a_4	-0.146	0.174	-0.837	0.402	
a_5	1.390	0.782	1.777	0.076	.
a_6	-0.533	0.130	-4.097	0.000	***
b_1_1	-0.173	0.130	-1.325	0.185	
b_1_2	0.169	0.125	1.353	0.176	
b_1_3	0.217	0.118	1.847	0.065	.
b_1_4	-0.027	0.051	-0.524	0.600	
b_1_5	-0.385	0.238	-1.620	0.105	
b_1_6	0.161	0.067	2.420	0.016	*
b_2_2	-0.314	0.248	-1.264	0.206	
b_2_3	0.307	0.125	2.452	0.014	*
b_2_4	-0.098	0.070	-1.407	0.159	
b_2_5	0.244	0.351	0.695	0.487	
b_2_6	0.065	0.077	0.846	0.397	
b_3_3	0.040	0.130	0.307	0.759	
b_3_4	-0.089	0.043	-2.061	0.039	*
b_3_5	-0.207	0.192	-1.078	0.281	
b_3_6	-0.120	0.046	-2.622	0.009	**
b_4_4	0.049	0.035	1.412	0.158	
b_4_5	0.009	0.102	0.090	0.928	
b_4_6	0.003	0.029	0.100	0.921	
b_5_5	1.288	0.620	2.077	0.038	*
b_5_6	-0.107	0.098	-1.096	0.273	
b_6_6	-0.037	0.023	-1.567	0.117	
Age	0.042	0.021	2.010	0.044	*
Off farm income	0.005	0.004	1.455	0.146	
Livestock specialisation	-0.545	0.311	-1.753	0.080	.
Market participation	-0.031	0.015	-2.073	0.038	*
Gender	-0.136	0.993	-0.137	0.891	
Household size	0.078	0.097	0.810	0.418	
Domestic assets	0.018	0.008	2.312	0.021	*
sigmaSq	1.316	0.591	2.227	0.026	*
lambda	1.793	0.607	2.955	0.003	**
log likelihood function	-143.811				

"***", "**", "*", "." indicate level of statistical significance: "***" (0.001); "**" (0.01); "*" (0.05); "." (0.1)

Table A4.8 Maximum likelihood estimates of the translog stochastic production frontier model for Yatenga

Parameter	Estimate	Std. Error	z value	Pr(>|z|)	
a_0	0.673	0.152	4.434	0.000	***
a_1	0.499	0.148	3.381	0.001	***
a_3	-0.087	0.130	-0.666	0.505	
a_4	-0.121	0.065	-1.874	0.061	.
a_5	0.217	0.176	1.231	0.219	
a_6	-0.656	0.068	-9.666	0.000	***
b_1_1	-0.297	0.187	-1.590	0.112	
b_1_3	0.073	0.089	0.828	0.408	
b_1_4	-0.010	0.072	-0.139	0.889	
b_1_5	-0.022	0.157	-0.142	0.887	
b_1_6	0.047	0.057	0.821	0.411	
b_3_3	0.011	0.112	0.096	0.923	
b_3_4	-0.078	0.044	-1.781	0.075	.
b_3_5	0.026	0.136	0.191	0.848	
b_3_6	-0.081	0.062	-1.312	0.189	
b_4_4	0.009	0.034	0.277	0.782	
b_4_5	-0.086	0.065	-1.328	0.184	
b_4_6	-0.040	0.031	-1.299	0.194	
b_5_5	-0.230	0.116	-1.984	0.047	*
b_5_6	0.109	0.064	1.688	0.091	.
b_6_6	0.021	0.031	0.659	0.510	
Off farm income	0.002	0.001	2.439	0.015	*
Household size	0.315	0.171	1.845	0.065	.
Market participation	-0.058	0.040	-1.453	0.146	
Domestic assets	-0.029	0.017	-1.698	0.090	.
Livestock specialisation	0.023	0.011	2.036	0.042	*
Gender	-4.609	5.730	-0.804	0.421	
Age	-0.063	0.050	-1.252	0.211	
sigmaSq	2.491	1.287	1.936	0.053	.
lambda	4.115	1.379	2.983	0.003	**
log likelihood function	-133.100				

"***", "**", "*", "." indicate level of statistical significance: "***" (0.001); "**" (0.01); "*" (0.05); "." (0.1)

Table A4.9 Maximum likelihood estimates of the translog stochastic production frontier model for Kaffrine

Parameter	**Estimate**	**Std. Error**	**z value**	**Pr(>|z|)**	
a_0	0.354	0.245	1.442	0.149	
a_1	-0.004	0.330	-0.012	0.991	
a_2	0.363	0.354	1.026	0.305	
a_3	0.474	0.180	2.635	0.008	**
a_4	0.291	0.187	1.552	0.121	
a_5	0.111	0.299	0.373	0.710	
a_6	-0.836	0.128	-6.513	0.000	***
b_1_1	-0.694	0.289	-2.406	0.016	*
b_1_2	0.511	0.177	2.884	0.004	**
b_1_3	-0.265	0.173	-1.535	0.125	
b_1_4	0.340	0.175	1.939	0.053	.
b_1_5	0.562	0.268	2.099	0.036	*
b_1_6	-0.018	0.065	-0.278	0.781	
b_2_2	-0.814	0.289	-2.817	0.005	**
b_2_3	0.154	0.147	1.051	0.293	
b_2_4	0.138	0.155	0.890	0.373	
b_2_5	-0.033	0.225	-0.146	0.884	
b_2_6	-0.090	0.055	-1.630	0.103	
b_3_3	0.103	0.107	0.964	0.335	
b_3_4	0.063	0.083	0.759	0.448	
b_3_5	-0.238	0.137	-1.736	0.082	.
b_3_6	0.027	0.042	0.642	0.521	
b_4_4	-0.273	0.101	-2.691	0.007	**
b_4_5	-0.168	0.117	-1.442	0.149	
b_4_6	-0.015	0.038	-0.401	0.689	
b_5_5	0.062	0.243	0.255	0.798	
b_5_6	-0.040	0.057	-0.694	0.488	
b_6_6	-0.042	0.031	-1.356	0.175	
Market participation	-0.060	0.072	-0.835	0.404	
Livestock specialisation	-0.071	0.095	-0.749	0.454	
Gender	-3.679	23.940	-0.154	0.878	
Age	-0.001	0.026	-0.050	0.960	
sigmaSq	1.744	1.712	1.019	0.308	
lambda	4.537	2.107	2.153	0.031	*
log likelihood function	-58.481				

"***", "**", "*", "." indicate level of statistical significance: "***" (0.001); "**" (0.01); "*" (0.05); "." (0.1)

Appendix B: Supporting information for Chapter 5

Sensitivity of long-run scale-out to different acreage elasticities

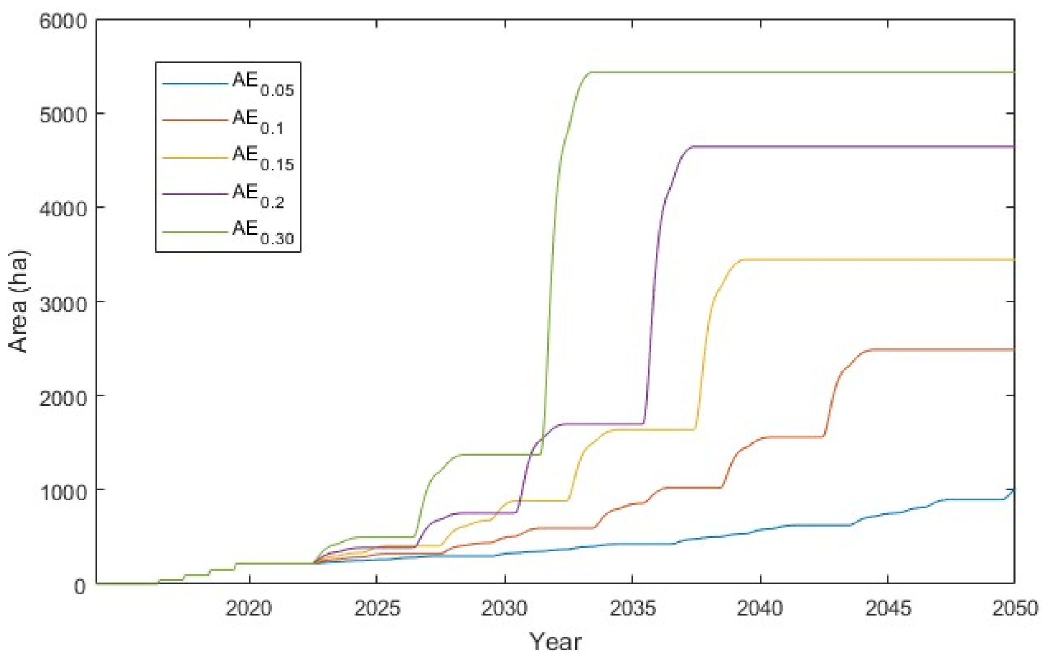


Figure A5.1 Stocks of mature planted leucaena trees in the long-run for Scenario 2 under the different acreage elasticities of supply (0.05, 0.1, 0.15, 0.2, 0.3).

Full list of model equations and data

This section contains all of the equations and data used to create and run the system dynamics model in iThink for the study: "Assessing the sustainable development and intensification of beef cattle production in Sumbawa, Indonesia, using a system dynamics approach". The equations are presented in standard iThink/Stella format.

HERD MODULE

1. Cattle in gestation

Gestation(t) = Gestation(t - 1) + (Breeding rate - Birth rate - Aborting)
INIT Gestation = 780
{cattle}

INFLOWS:
Breeding rate = ((Breeding cows*Stock 1)/8)*Actual effect of capacity breeding
{cattle/week}

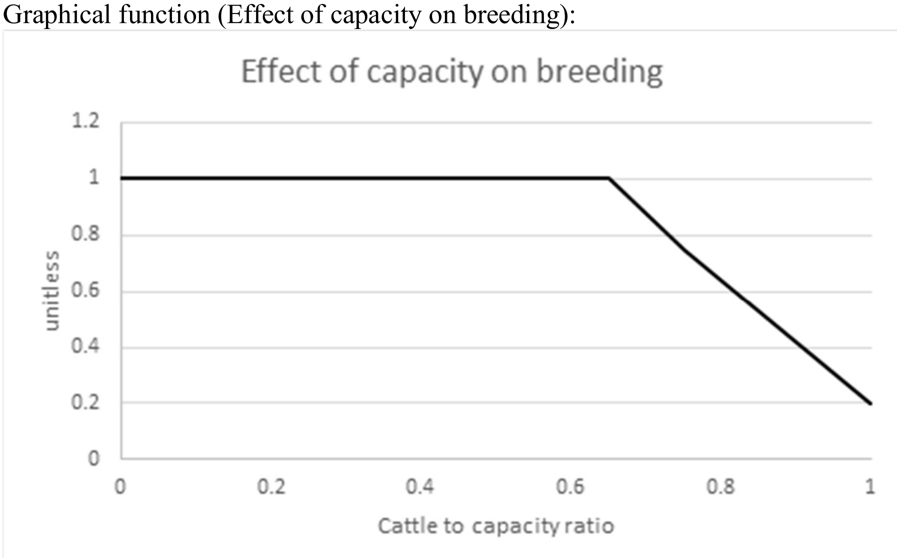
OUTFLOWS:
Birth rate = Gestation/gest time
{cattle/week}

Aborting = (Gestation*abortion rate)/52
{cattle/week}

Abortion rate = 0.05
{1/year}

Actual effect of capacity breeding = MIN((SMTH3(Effect of capacity on breeding*Actual effect of profit on production,12)),1.6666)
{unitless}

Graphical function (Effect of capacity on breeding):



Cattle to capacity ratio = (cattle population-feedlot fat-Trad fat)/Project area capacity
{unitless}

Project area capacity = 8000+Local capacity changes
{cattle}

Local capacity changes = SMTH3(Surplus feed CE, 104, 0)
{cattle}

Actual effect of profit on production = SMTH3(Effect of profit on cattle production,26)
{unitless}

Effect of profit on cattle production = (Total farm profit/init(Total farm profit))^0.1
{unitless}

2. Changes to stock of calves

Calves(t) = Calves(t - 1) + (Birth rate - weaning - Calves dying)
INIT Calves = 580
{cattle}

INFLOWS:
Birth rate = Gestation/gest time
{cattle/week}

Gest time = 39
{weeks}

OUTFLOWS:
Weaning = Cal2ves/Weaning time
{cattle/week}

Calves dying = (Calves*calf mortality rate)/52
{cattle/week}

Calf mortality rate = 0.1
{1/year}

Weaning time = 40
{week}

3. Changes to stock of weaners

Weaners(t) = Weaners(t - 1) + (weaning - Becoming young adult male - Becoming young adult female)
INIT Weaners = 184
{cattle}

INFLOWS:
Weaning = Calves/Weaning time
{cattle/week}

OUTFLOWS:
Becoming young adult male = (Weaners/time to grow)*Male to female ratio
{cattle/week}

Becoming young adult female = (Weaners/time to grow)*Male to female ratio

{cattle/week}

Male to female ratio = 0.5
{unitless}

Time to grow = 20
{week}

4. Changes to stock of pre-adult females

Pre adult female(t) = Pre adult female(t-1) + (Becoming young adult female - Becoming Heifer)
INIT Pre adult female = 238
{cattle}

INFLOWS:
Becoming Y female = Becoming young adult female*percent breeders to II traders
{cattle/week}

OUTFLOWS:
Becoming Heifer = Pre adult female/Growth time
{Cattle/week}

Percent breeders to II traders = 0.2
{unitless}

Growth time = 90
{weeks}

5. Changes to stock of heifers for selling to breeders

Heifer(t) = Heifer(t-1) + (Becoming Heifer - selling breeders to II traders)
INIT Heifer = Becoming Heifer
{cattle}

INFLOWS:
Becoming Heifer = Pre adult female/Growth time
{cattle/week}

OUTFLOWS:
Selling breeders to II traders = Heifer*1
{cattle/week}

6. Changes to stock of females to replace breeding cows
Replace female(t) = Replace female(t - 1) + (Becoming replacement female - Becoming breeding cows)
INIT Replace female = 1009
{cattle}

INFLOWS:
Becoming replacement female = Becoming young adult female*(1-percent breeders to II traders)
{cattle/week}

OUTFLOWS:
Becoming breeding cows = Replace female/Time to become breeding cows
{cattle/week}

Time to become breeding cows = 27+120
{week}

7. Changes to stock of breeding cows

Breeding cows(t) = Breeding cows(t - 1) + (Becoming breeding cows - breed cow selling to butcher)
INIT Breeding cows = 1874
{cattle}

INFLOWS:
Becoming breeding cows = Replace female/Time to become breeding cows
{cattle/week}

OUTFLOWS:
Breed cow selling to butcher = Breeding cows/Average breeding duration
{cattle/week}

Average breeding duration = 273
{week}

8. Changes to stock of males to replace breeding bulls

Replace bull(t) = Replace bull(t-1) + (Becoming replacement bull - Becoming bull)
INIT Replace bull = 140
{cattle}

INFLOWS:
Becoming replacement bull = (Becoming young adult male*percent for replacing bulls)
{cattle/week}

OUTFLOWS:
Becoming bull = Replace bull/Time to become bull
{cattle/week}

Percent for replacing bulls = 0.1912
{unitless}

Time to become bull = 47+30
{week}

9. Changes to stock of breeding bulls

Bull(t) = Bull(t - 1) + (Becoming bull - Bull selling)
INIT Bull = 165
{cattle}

INFLOWS:
Becoming bull = Replace bull/Time to become bull
{cattle/week}

OUTFLOWS:
Bull selling = Bull/Bull service time
{cattle/week}

Bull service time = 91*Ramadan & Adha Shock*Maulud demand shock
{week}

10. Changes to stock of traditionally fattened bulls
Trad fat(t) = Trad fat(t - 1) + (Males for traditional fattening - Trad fat sales)
INIT Trad fat = 881.21
{cattle}

INFLOWS:
Males for traditional fattening = (Becoming young adult male*percent remain in traditional farms M)
{cattle/week}

OUTFLOWS:
Trad fat sales = Trad fat/Grazing time M
{cattle / week}

Grazing time M = 130*Ramadan & Adha Shock
{week}

Percent remain in traditional farms M = 0.81-percent moving to feedlots
{unitless}

11. Changes to stock of young pre-feedlot males

Pre FL male(t) = pre FL male(t-1) + (backgrounding & feedlotting - back grounding)
INIT pre FL male = 63
{cattle}

INFLOWS:
Backgrounding & feedlotting = (Becoming young adult male*percent moving to feedlots)
{cattle / week}

OUTFLOWS:
Backgrounding = delay(backgrounding & feedlotting, backgrounding time)
{cattle / week}

Backgrounding time = 69
{weeks}

Percent moving to feedlots = MAX((MIN((Surplus feed CE/Becoming young adult male), 0.9)), 0)
{unitless}

12. Changes to stock of feedlot fattened cattle (including project farm (PF) and non PF, young adult males (YAM)

Feedlot fat(t) = feedlot fat(t - 1) + (back grounding + additional flows through PF feedlots - PF FL sales)
INIT feedlot fat = 100*policy switch 1: shift to FL
{cattle}

INFLOWS:
Back grounding = delay(backgrounding & feedlotting, backgrounding time)
{cattle / week}

Policy switch 1: shift to FL = [0 or 1]
{unitless}

Additional flows through PF feedlots = (Non PF YAM inputs*percent to feedlots)
{cattle / week}

OUTFLOWS:
PF FL sales = feedlot fat/fattening time
{cattle / week}

fattening time = 22*Ramadan & Adha Shock*Maulud demand shock
{weeks}

Percent to feedlots = DELAYn(1,4,3, 0)*policy switch 2: source nPF bulls
{unitless}

Policy switch 2: source nPF bulls = [0 or 1]
{unitless}

13. Functions governing the timing of breeding events

Breeding season(t) = Breeding season(t - 1) + (Start B – End B)
INIT Stock 1 = 0
{unitless}

INFLOWS:
Start B = breed week
{unitless/week}

OUTFLOWS:
End B = DELAY(Start B, 8)
{unitless/week}

Breed week = pulse(0.6,30, 52)
{unitless/week}

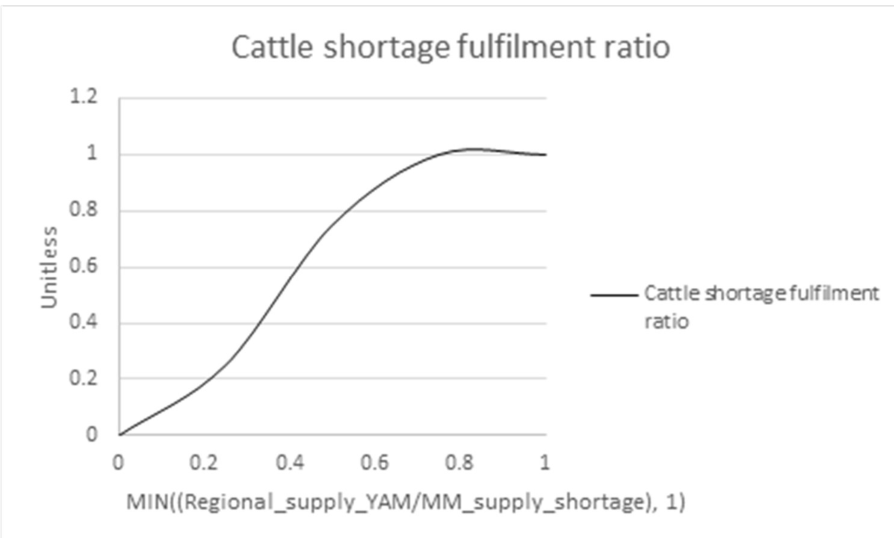
Young adult males sourced from outside the ARISA project area

YAMs from non PFs(t) = YAMs from non PFs(t - 1) + (Non PF YAM inputs - additional flows through PF feedlots - exits to Non PFs)
INIT YAMs from non PFs = 15015
{cattle}

INFLOWS:
Non PF YAM inputs = MIN((MM supply shortage*Cattle shortage fulfilment ratio), Regional supply YAM)
{cattle / week}

OUTFLOWS:
Additional flows through PF feedlots = (Non PF YAM inputs*percent to feedlots)
{cattle / week}

MM supply shortage = MAX((Surplus feed CE-backgrounding & feedlotting), 0)+PF FL sales
{cattle/week}



Exits to Non PFs = Non PF YAM inputs*(1-percent to feedlots)
{cattle/week}

Regional supply YAM = ((590295-5013)*0.1)/52
{cattle/week}

Cattle sale volumes and profits

Flow of animals to II traders = selling breeders to II traders+ Selling traditional fatteners to II traders M+ Bull selling/2+selling FL fatteners to II traders
{cattle / week}

Flow of animals to local butchers = breed cow selling to butcher+ Bull selling/2
{cattle/week}

Total FL sales = PF FL sales
{cattle/week}

YAMexits = Males for traditional fattening+backgrounding & feedlotting
{cattle / week}

Trad fattening profit = Trad fat sales*(trad fat price per hd-cost per hd)
{Rp / week}

Trad fat price per hd = 7770000*Effect of shocks on price
{Rp / cattle}

Cost per hd = 6500000
{Rp/cattle}

FL profits = Total FL sales*(price per hd-other costs per hd) - leucaena costs
{Rp / week}

Price per hd = (if Petahani trade policy=1 and time > 52 then 7770000*1.15 else 7770000)*Effect of shocks on price
{Rp/cattle}

Petahani trade policy = [0 or 1]
{unitless}

Other costs per hd = 5384883
{Rp/cattle}

leucaena costs = Planted leucaena area mature trees*168000
+Leucaena over time*1689030
{Rp/week}

Breed farm profit = (breed cow selling to butcher*cow price+ Bull selling*bull price+ selling breeders to II traders*RFexit price+YAMexits*YAM price)-breed cattle population*cost per breed animal
{Rp/week}

Cow price = 7800000
{Rp/cattle}

Bull price = 11,820,000*Effect of shocks on price
{Rp/cattle}

YAM price = 5180000
{Rp / cattle}

RFexit price = 6300000
{Rp/cattle}

Cost per breed animal = 15000
{Rp / cattle / week}

Total farm profit = breed farm profit+ trad fattening profit+ FL profits
{Rp/week}

Trader profits = Total FL sales*sale price+Trad fat sales*sale price-Trader costs
{Rp/week}

Purchase Price per hd = 7770000
{Rp/cattle}

Trader costs = Trad fat sales*(purchase Price per hd+ Marketing costs)+Total FL sales*(purchase Price per hd+ Marketing costs)
{Rp/week}

Marketing costs = 333333
{Rp/cattle}

Sale price = 8300000
{Rp / cattle}

Local butcher profits = (Bull selling/2+breed cow selling to butcher)*profit per hd
{Rp / week}

profit per hd = 1300000
{Rp / cattle}

Cattle population

Breed cattle population = cattle population-feedlot fat-Trad fat
{cattle}

Cattle population = Weaners+ Calves+ Pre adult female+ Trad fat+ Heifer+ Replace bull+ Bull+ Replace female+ feedlot fat+ Breeding cows
{cattle}

Domestic population = (cattle population-feedlot fat) + pre FL male
{cattle}

Project fatten pop = Trad fat+ feedlot fat+ pre FL male
{cattle}

Consumption shocks for Muslim festivals

Eid Shock(t) = Eid Shock(t - 1) + (A Start - A End)
INIT Eid Shock = 0
{unitless}

INFLOWS:
A Start = Eid al Adha
{unitless/week}

OUTFLOWS:
A End = DELAY(A Start, 2)
{unitless/week}

Eid al Adha = pulse(1, 36, 52)
{unitless/week}

Maulud Shock(t) = Maulud Shock(t) + (M Starts - M Ends)
INIT Maulud Shock = 0
{unitless}

INFLOWS:
M Starts = Prophet Mohamad birthday
{unitless/week}

OUTFLOWS:
M Ends = DELAY(M Starts, 4)
{unitless/week}

Prophet Mohamad birthday = pulse(0.05, 46, 52)
{unitless/week}

Maulud demand shock = (if Maulud Shock>0 then 0.9524 else 1)
{unitless}

Ramadan Shock(t) = Ramadan Shock(t-1) + (R Start - R End)
INIT Ramadan Shock = 0
{unitless}

INFLOWS:
R Start = Ramadan holy month
{unitless/week}

OUTFLOWS:
R End = DELAY(R Start, 4)
{unitless/week}

Ramadan holy month = PULSE(0.0375, 27, 52)
{unitless/week}

Ramadan & Adha Shock = (if Eid Shock>0 then 0.4 else 1)+ (if Ramadan Shock>0 then 0.964 else 1)-1
{unitless}

Effect of shocks on price = (if Maulud Shock or Ramadan Shock >0 then 0.1 else 0) + (if Eid Shock>0 then 0.25 else 0)+1
{unitless}

Leucaena production

Leucaena over time(t) = Leucaena over time(t-1) + (Input - Output)
INIT Leucaena over time = 0
{ha/week}

INFLOWS:
Input = Land allocation
{ha/week}

OUTFLOWS:
Output = Leucaena over time
{ha/week}

Planted leucaena area mature trees(t) = Planted leucaena area mature trees(t-1) + (Maturing)
INIT Planted leucaena area mature trees = 0
{ha}

INFLOWS:
Maturing = delay(Land allocation, Time to mature)
{ha/week}

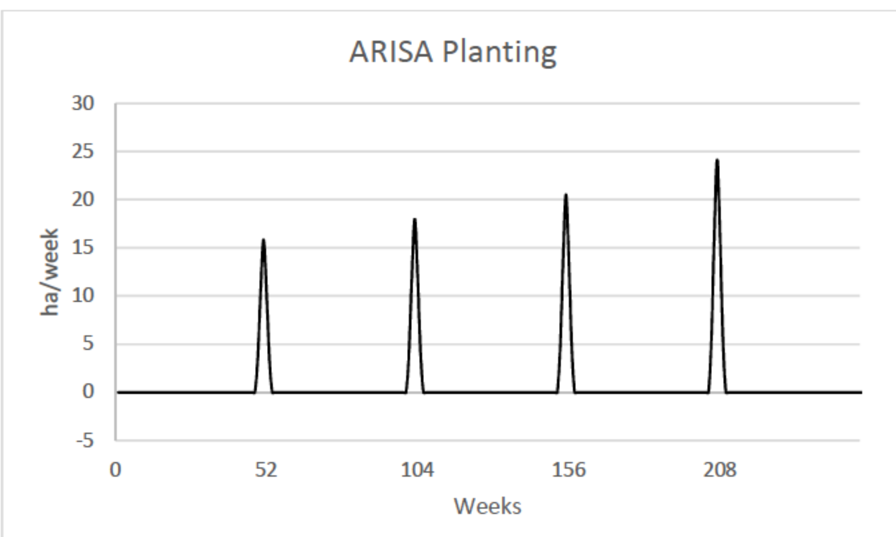
Time to mature = 78
{week}

Planted leucaena area seedlings(t) = Planted leucaena area seedlings(t-1) + (Land allocation - Maturing)
INIT Planted leucaena area seedlings = 0
{ha}

INFLOWS:
Land allocation = (ARISA plantings +max(Smoothed planting decision, 0))*policy switch 1: shift to FL
{ha/week}

OUTFLOWS:
Maturing = delay(Land allocation, Time to mature)
{ha/week}

Graphical function (ARISA Planting):



Smoothed planting decision = SMTH3(Endog planting, 26)
{ha}

Endog planting = PULSE((Desired planted area-(Planted leucaena area mature trees+Planted leucaena area seedlings)), 45, 52)

{ha}

Desired planted area = IF Surplus feed CE>2 then 0 else MIN((Effect of profit on land allocation*Planted leucaena area mature trees), Total land)
{ha}

Surplus feed CE = Feedlot feeding capacity-(feedlot fat/22)
{cattle}

Feedlot feeding capacity = Total leucanea/Feed need per hd
{cattle}

Feed need per hd = 0.77
{tonne/cattle}

Total leucanea = Planted leucaena harvest volume+ Wild leucaena harvest volume
{tonne}

Planted leucaena harvest volume = (Planted leucaena area mature trees*Leucaena yield)/52
{tonnes}

Effect of profit on land allocation = IF Expected FL profit < 0 then 1 else (if time <208 then 1 else((Expected FL profit/init(Expected FL profit))^(Profit elasticity of land allocation)))
{Unitless}

Expected FL profit = DELAY3(FL profits, 104)
{Rp/week}

Profit elasticity of land allocation = 0.15
{unitless}

Total land(t) = Total land(t - 1)
INIT Total land = 5273
{ha}

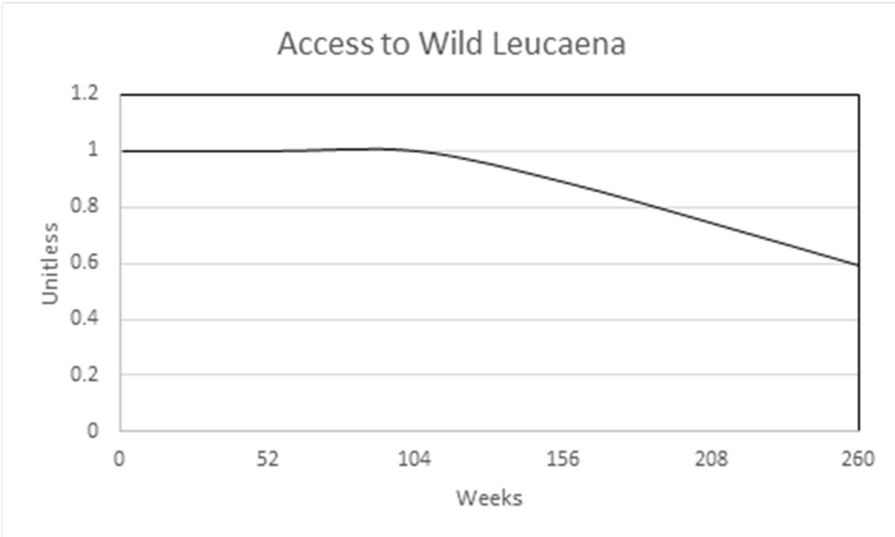
Wild leucaena

Wild leucaena area(t) = wild leucaena area(t - 1)
INIT wild leucaena area = 75
{ha}

Wild leacaena production = (Wild leucaena yield*wild leucaena area/52)*policy switch 1: shift to FL
{tonne}

Wild leucaena harvest volume = (wild leacaena yield*Access to wild leucaena)
{tonne}

Graphical function (Access to wild leucaena):



Wild leucaena yield = 4
{tonne/ha}

Leucaena yield = 8.3
{tonnes/ha}

GHG emission intensities

Emission intensity = GHG emissions/total cattle LW
{GHG/kg/yr}

GHG emissions = project fatten pop*(47*25/52)+ Bull*47*25/52+Replace bull*47*25/52+(Weaners+ Calves)*47*25/52+(Heifer+ Pre adult female)*47*25/52+Replace female*47*25/52+Breeding cows*47*25/52
{total GHG/week}

Total cattle LW = (Bull selling*394+breed cow selling to butcher*260+selling breeders to II traders*210)*0.47+ (PF FL sales+Trad fat sales)*210*0.51
{kg}

Model validation tests

In addition to the sensitivity analysis that was performed as part of the scale-out assessment, we performed a number of model validation tests recommended for SD models (Sterman, 2000; Senge and Forrester 1980). First, we performed a Structure assessment, which requires that the model structure does not include any components, variables and parameters that do not exist in real life. Based on this assessment we found that the model structure is consistent with physical real-life system that the model represents. Second, we tested the Dimension consistency of the model, and we found that the model units were consistent and did not include any parameters without no real-life interpretation and meaning. Third, we performed a Structure-behavior test, which requires that the model generates logical behavior when a feedback loop is removed from the model. For example, when the feedback loop of lecuena planting (R2) is removed (i.e. setting acreage elasticity with respect to profit 0), the scaling-out intervention was not as successful as when lecuena production feedback loop was active. This is because removing that feedback loop removes the endogenous planting mechanism of leucena after exogenous project planting events complete. Finally, we conducted an Extreme condition test for the key model parameters. For example, forcing breeding stock to be zero (by disconnecting breeding stock from the rest of the production cycle) or forcing exogenous parameter constraints to extreme value generated expected and reasonable model results.

Appendix C: Supporting information for Chapter 6

In the first part of this section, two figures are presented showing the percentage changes in prices and yields as a consequence of climate change (RCP6), with respect to the baseline without climate change, from the MAgPIE model, are presented. Following this, a table containing the estimated marginal costs and changes in these costs associated with adjustments to crop areas is presented for a single farm for expository purposes. The marginal costs and their associated coefficients and data correspond to equation (1) in the text.

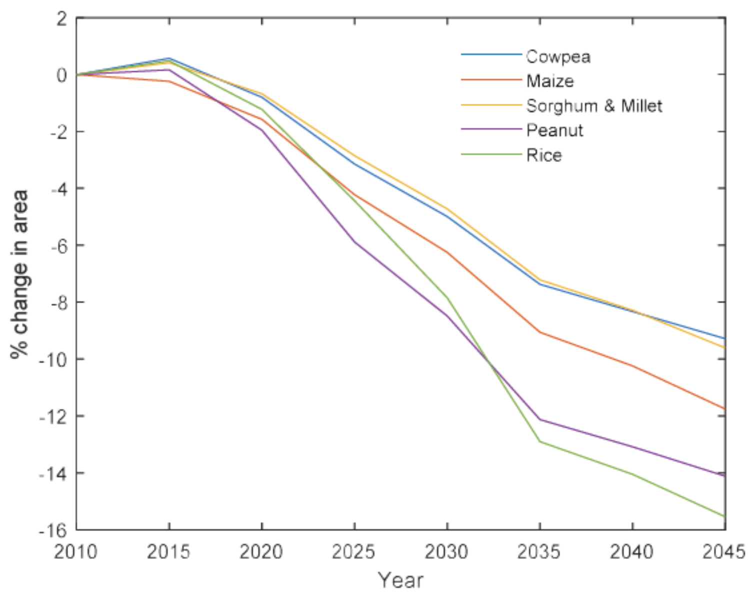


Figure A6.1 Percentage changes in crop yields with climate change (RCP6) relative to the baseline without climate change.

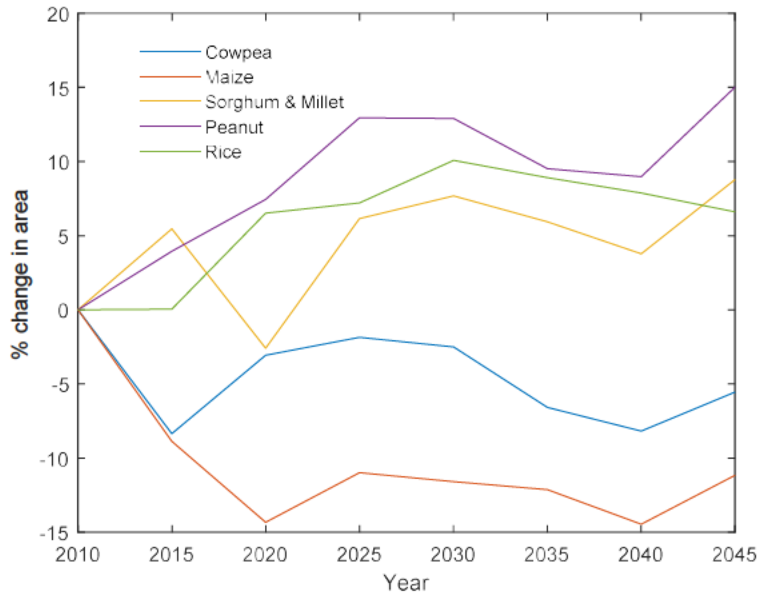


Figure A6.2 Percentage changes in crop prices with climate change (RCP6) relative to the baseline without climate change.

Table A6.1 Estimated marginal costs and changes in these costs associated with adjustments to crop areas for farm number 16 in the sample.

Item	Unit	Symbol	Cowpea	Maize	Millet	Peanut	Sorghum
Revenue	CFA/ha	$v_c' y_c$	16,500	45,000	270,000	30,000	202,499
Accounting cost	CFA/ha	c	10,993	29,980	179,879	19,987	134,909
Activity level	ha	l	0.3	0.3	1.0	0.5	0.3
Marginal costs	CFA/ha	MC	10,986	39,494	264,438	24,494	196,972
Q_f (estimated)		$Q_f = S_f B S'_f$	172,746	151,497	173,177	271,416	469,463
% change in MC for 1% change in levels			5.2%	1.3%	0.7%	5.5%	0.8%