Report on developing bottom-up Marginal abatement cost curves (MACCS) for representative farm type

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Abstract:

Developing efficient policy instruments and incentive schemes to promote the uptake of greenhouse gas mitigation measures requires some kind of prioritisation of the mitigation measures. An important consideration in this process is the estimated cost and cost-efficiency the measures. The high number of reports done in developed countries show a high variability in the country-level cost-effectiveness estimates, and suggest that approaches providing higher granularity at the spatial and farm type could suit better to the purpose of regional policy development. At the same time, there is still a gap in our understanding of economic mitigation potential of agriculture in developing and newly industrialised countries.

To address these questions this report presents three studies. The first is a literature review of the cost-effectiveness estimates of mitigation measures published in the past 15 years, discussing the variability in these estimates. The second study reports on marginal abatement cost curves for beef cattle production in Brazil. Finally, the last report presents the conceptual basis of a tool to assess the financial implications of the mitigation measures to be used in parallel with the FarmAC model, ultimately providing mitigation measure cost-effectiveness estimates specific to individual farms. Additionally, it describes the selection of mitigation measures which have been assessed at the farm level in Component 3 of the AnimalChange project.

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1. Introduction

Agriculture is expected to play a role in reducing greenhouse gas (GHG) concentrations globally. The sector has capacity to contribute to this goal via GHG emission reduction, carbon (C) sequestration and renewable energy (bioenergy production). It is estimated that a total mitigation of 1.5-15.6 Gt CO_2e/year (3-31% of the global anthropogenic GHG emissions of 50 Gt CO_2e/year (IPCC 2014)) could be achieved in agriculture and the land use and forestry sectors (Smith *et al.* 2013), with the economic potential in agriculture alone (and excluding bioenergy production) being 1.5-4.3 Gt CO_2e/year (Smith *et al.* 2008). This latter mitigation is to be achieved on farms by modifying current management practices, like improving nutrient management, restoring soils, administering feed additives to livestock and increasing the rate of genetic improvement both crops and livestock. However, agri-environmental policies are necessary to be developed to encourage the uptake of mitigation measures by farmers, either supporting the voluntary uptake or introducing compulsory regulations.

The heterogeneity of farms and farming conditions and the difficulty in estimating the mitigation on farms mean that market-based instruments (like carbon tax) can be very costly to set up in the agricultural sector. Reinforced by the complexity of international negotiations, this makes voluntary or targeted obligatory regulations favoured over market-based instruments (Beddington *et al.* 2012, Kasterine and Vanzetti 2010). Such policy instruments (often developed at national or sub-national level) require some kind of prioritisation of the mitigation measures, and an important input in this process is the cost-efficiency estimates of the measures, preferably specific to country/region, farm type, farm size and biophysical conditions (*e.g.* soil and climate).

A number of reports and scientific papers have estimated the mitigation potential and cost-efficiency of various measures, usually at a country-level and often using either economic modelling or bottom-up cost-engineering approaches to calculate the financial consequences of the implementation of the measures (see a typology and a short assessment of these approaches in (Vermont and De Cara 2010)). The measures are usually ranked according to their cost-effectiveness, and those are considered to be economically efficient of which cost-effectiveness is lower than the marginal benefits from emission reduction. This is approximated by a carbon price threshold, for example, in the UK by the social price of carbon (Price *et al.* 2007).

The bottom-up cost-engineering approach is well suited to give a detailed assessment of the mitigation measures (Kesicki and Strachan 2011), and therefore give specific advice to policy development. Still, the amount of evidence about the cost-efficiency of mitigation measures, especially when disaggregated to farm types or geographical regions, is small, as most of the studies work on the basis of country averages. Examples for the latter include numerous work on MACCs for agriculture in the European Union, New Zealand, France, Ireland and UK (Bates *et al.* 2009, MacLeod *et al.* 2010, Pape *et al.* 2008, Pellerin *et al.* 2013, Schulte *et al.* 2012), while papers presenting evidence on the difference between regions or farm types are less abundant (see examples for the US (Biggar *et al.* 2013) and France (De Cara and Jayet 2000, Dequiedt *et al.* 2014)).

A literature review in this deliverable investigates the cost-effectiveness estimates of mitigation measures published in the past 15 years, discussing the variability in these estimates and highlighting research gaps (Section 2). Furthermore, a study is presented in the deliverable aiming to advance our knowledge on mitigation measures beyond the developed countries, reporting on marginal abatement cost curves for beef cattle production in Brazil (Section 3).

The wide differences in the cost-effectiveness estimates across the studies suggest that regional, farm type level, or even individual farm level assessments might better suit to inform regional policy development and decision makers on farms about potential mitigation options. However, given the well-known trade-off between complexity and accuracy, modelling tools which can be widely used in the farming community would be less accurate in their emission and cost estimates than models requiring detailed information. One approach to this problem is a tool which can be operated by people with expertise in both modelling and in the farming practices of a region. Such a tool, namely the FarmAC model, has been developed in the AnimalChange project to assess the nutrient flows and GHG emissions of the farms. Section 4 of this deliverable presents the conceptual basis of a tool to assess the financial implications of the mitigation measures to be used in parallel with the FarmAC model, ultimately providing mitigation measure cost-effectiveness estimates specific to individual farms.

2. Literature review of the cost-effectiveness estimates of GHG mitigation measures

This section is partially based on (MacLeod and Eory 2014).

2.1 Introduction

The potential role agriculture can play in the global climate change mitigation effort is now well known. Some improvements in the emissions intensity of agricultural output have already been made as a result of increased resource use efficiency and regulations to lower nitrogen and phosphorous emissions. Still, identifying technically effective, economically efficient, and socially acceptable mitigation options remains a challenge. The cost-effectiveness of mitigation practices is often highly variable, being very dependent on location, weather, existing farm practices, etc. This section reviews the international literature on the cost-effectiveness of GHG mitigation measures, focusing on supply-side technical measures to be implemented on farm.

2.2 Methodology

A literature review was carried out to analyse the cost-effectiveness estimates of agricultural mitigation measures published within the past 15 years. The review included studies which assessed a set of mitigation measures at the same time as opposed to evaluating a single mitigation measure. Studies varied in terms of their geographical scope and sectoral scope, some being multi-sectoral, others analysing agriculture only. The list of the 37 studies reviewed is presented in Appendix 1: List of studies reviewed.

The following characteristics of the studies were recorded:

- geographical scope (*e.g.* global, EU-15, the Netherlands)
- geographical resolution (*e.g.* world regions, countries, sub-national regions, farms)
- boundaries of emission sources (on-farm versus life cycla analysis (LCA))
- interactions between measures considered or not
- MACC methodology (using the classification of Vermont and De Cara (2010), *i.e.* equilibrium models, micro-economic modelling, bottom-up cost-engineering MACCs)
- Cost-effectiveness (CE) results for individual measures are available or not

262 agricultural activities were identified as mitigation measures. This list was based on the long mitigation measure list compiled in Moran *et al.* (2008), complemented with any additional mitigation measure found in the studies reviewed. The mitigation measures were aggregated into 8 categories, and 22 sub-categories were also introduced to give a better overview of the measures. The categories were the following (the number of subcategories within each category is in brackets): cropland management (6), grazing land management (3), management of organic soils (0), restoration of degraded lands (0), livestock management (5), livestock housing and manure (3), land use change (0) and energy efficiency (5).

To avoid duplication, mitigation measures which were applicable both to cropland and grazing land were allocated to cropland management (in most cases these measures are not disaggregated in the studies). Due to the difference in the scope of the mitigation measures between studies, in some cases aggregate mitigation measures are listed alongside the more specific ones, for example both 'Dietary additives in general' and 'Ionophores' are measures. The list of the mitigation measures is presented in Appendix 2: Long list of mitigation measures.

The mitigation measures included in each of the studies were recorded to obtain a frequency table, showing in how many studies each mitigation measure was included. In some specific cases a mitigation measure analysed in a study was a composite of two or three different, though related mitigation measures. In this case it was recorded under all of the relevant mitigation measures, assuming that the CE value, if provided, applied to all mitigation measures.

To obtain the range of the CE results for mitigation measures, those studies had to be selected which reported data on the CE of individual mitigation measures. Due to the methodological differences, mitigation measure specific CE estimates were only available from bottom-up cost-engineering studies. Those mitigation measures for which three or more studies made CE estimates available were selected for further data collection, whereby the CE values were recorded. If a study provided more than one CE estimate for a mitigation measure, then the lowest and highest estimates were recorded. Otherwise the single value was recorded as both the lowest and the highest value. Finally, the CE data were converted to a common metric (EUR/tCO_2e). From this part of the analysis the rice cultivation measures were excluded, as they have very low relevance to the regions the AnimalChange project was looking at (*i.e.* Europe, Sub-Saharan Africa and South America).

2.3 Results

From the 37 studies reviewed, 10 were global, 17 targeted the European Union or European countries, three the United States, four Australia or New Zealand, two reviewed Kyoto Annex I countries and one reported on Asian countries (see Appendix 3: Overview of the studies). Regarding the geographical resolution, most of the studies (21) were reporting at a country or sub-national level, while 10 studies presented results at the global and regional scale and 6 other studies were farm-level work. The majority of the studies (30) considered on-farm emissions only. About half of the studies (19) addressed the issue of interactions between the measures (*i.e.* when the mitigation potential and/or cost of a measure changes either positively or negatively if another mitigation measure is also implemented on the farm), either accounting for the synergies and trade-offs directly (13 studies), or allocating the mitigation measures so that they are assumed not to be implemented simultaneously on the same farms (6 studies). Seven studies did not take into account interactions, and a further 11 did not specify if or how interactions had been dealt with.

Five studies used equilibrium models to calculate the mitigation potential, 8 applied supply-side micro-economic models, and the rest (24) used some form of bottom-up cost-engineering method (this category included studies relying on cost estimates produced by whole-farm bio-economic models and also studies drawing from expert opinion). CE estimates of individual mitigation measures were only available in 11 bottom-up cost-engineering studies, as the rest presented results in an aggregated way, so CE data on individual measures could not be derived from it. Those eleven studies (see their characteristics Table 1) were used to analyse the range of CE estimates for selected mitigation measures.

Table 1 Overview of the eleven studies where CE data were available for individual mitigation measures

ID	Scope	Resolution	Emission boundaries[a]	Interactions[b]	GHG gases/sinks considered
2	Global	World region	On-farm	Yes	N_2O and CH_4
10	NW Germany	Farm	On-farm	Not specified	N_2O, CH_4 and CO_2
11	EU-27	Country	On-farm	No simultaneous implementation	N_2O and CH_4
14	New Zealand	Country	On-farm	Not specified	N_2O and CH_4
15	UK	Country	On-farm	Yes	N_2O, CH_4, CO_2 and soil C

ID	Scope	Resolution	Emission boundaries[a]	Interactions[b]	GHG gases/sinks considered
18	EU-27	World region	On-farm	Not specified	N_2O and CH_4
22	Global	World region	On-farm	Yes	N_2O and CH_4
23	Kyoto Annex I countries	Country	Some LCA elements	Yes	N_2O and CH_4
28	Ireland	Country	On-farm and LCA	Yes	N_2O, CH_4, CO_2 and soil C
32	USA	Farm	On-farm	Not specified	N_2O, CH_4, CO_2 and soil C
33	France	Country	Some LCA elements	Yes	N_2O, CH_4, CO_2 and soil C

[a] *'On-farm': emissions within the farm gate are considered, On-farm + other: some off-farm emissions are considered, 'LCA': off-farm emissions (usually pre-farm or up to the retailers) are considered*
[b] *'Yes': interactions between mitigation measures are taken into account, 'Measure allocation': mitigation measures are allocated so that simultaneous implementation of measures do not happen, 'No': interactions are not taken into account, 'Not specified': the study does not specify whether interactions are considered*

The eleven selected studies reported on 9 to 26 mitigation measures each, all combined assessing 100 different mitigation measures out of the 262 identified measures. The mitigation measures' frequency table (Table 2) shows how many mitigation measures within a category or sub-category were evaluated by a particular study. It also shows how many mitigation measures a category/sub-category contained (column 'MM all') and how many of these measures were mentioned in the studies (column 'MM assessed'). The one but last column ('Total frequency') presents the number of mitigation measures assessed across the eleven studies, *i.e.* the sum of the eleven study columns. The last column ('Relative frequency') shows how well a category/sub-category is represented (Relative frequency = Total frequency / MMs all). For example, the sub-category 'Agronomy' contains 13 different mitigation measures ('MM all'); out of these 13 measures 8 appeared in at least one of the eleven studies ('MM assessed'). Five studies assessed measures belonging to 'Agronomy': Study 11, Study 15, Study 28, Study 32 and Study 33 (*e.g.* Study 11 evaluated one, Study 33 evaluated three). Altogether, the sub-category 'Agronomy' appeared 9 times in the studies ('Total frequency'), so the representation of this sub-category is 1.1.

There is a wide range in how well categories and sub-categories are represented. The most frequently appearing sub-category is 'Nutrient management' on croplands: from its 36 mitigation measures 22 are included in the eleven studies, altogether assessed 52 times. Another three well-represented sub-categories are 'Feeding practices', 'Anaerobic digestion and CH_4 capture' and 'Rice management'; the mitigation measures within these sub-categories appear 22, 19 and 18 times, respectively, across the studies. On the other end of the spectrum are categories and sub-categories which are not at all, or just marginally explored in these studies: 'Structural and management changes' (Cropland), 'Orchards', 'Fire management', 'Management of organic soils', 'Restoration of degraded lands', 'Animal health', 'Housing', 'Land use change' and 'Energy and waste'.

Particular mitigation measures were popular and appeared in multiple studies, like measures in the sub-category 'Anaerobic digestion and CH_4 capture': the four mitigation measures listed there were together assessed 19 times ('On-farm AD' was evaluated in all of the eleven studies, and 'Centralised AD' were assessed in six studies), thus the relative frequency of this sub-category was 3.8. Also popular were measures from the sub-categories 'Nutrient management', 'Grazing intensity and timing', 'Rice management' and 'Feeding practices'. However, almost two thirds of the mitigation measures (62 out of the 100) were assessed only in a single study. 18 measures were assessed in two studies and another 18 in three to six studies, while two measures appeared in 10 or 11 out of the eleven studies (these measures were 'Nitrification inhibitors' and 'On-farm AD').

Table 2 Frequency table of the mitigation measures as they appear in the eleven selected studies

Mitigation category / sub-category	MM all[a]	MM assessed[b]	Frequency of MMs within each category/sub-category by study[c] ID: 2	10	11	14	15	18	22	23	28	32	33	Total frequency[d]	Relative frequency
Cropland management total	**81**	**47**	**9**	**5**	**7**	**1**	**15**	**4**	**15**	**7**	**6**	**9**	**12**	**90**	**1.1**
Agronomy	13	8	0	0	1	0	2	0	0	0	1	2	3	9	0.7
Nutrient management	36	22	3	4	4	1	11	4	6	4	4	4	7	52	1.4
Structural and management changes	4	2	0	1	0	0	0	0	0	0	0	1	0	2	0.5
Soil and water management	11	4	0	0	1	0	2	0	1	0	1	2	2	9	0.8
Rice management	15	11	6	0	1	0	0	0	8	3	0	0	0	18	1.2
Orchards	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Grazing land management total	**21**	**11**	**1**	**1**	**0**	**2**	**1**	**3**	**0**	**0**	**2**	**2**	**5**	**17**	**0.8**
Grazing intensity and timing	7	6	1	1	0	1	0	2	0	0	1	0	3	9	1.3
Increased productivity	13	5	0	0	0	1	1	1	0	0	1	2	2	8	0.6
Fire management	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Management of organic soils total	**6**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0.2**
Restoration of degraded lands total	**9**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0.0**
Livestock management total	**76**	**24**	**11**	**3**	**1**	**5**	**7**	**4**	**2**	**1**	**2**	**0**	**4**	**40**	**0.5**
Feeding practices	21	10	6	3	1	1	3	2	0	1	0	0	3	20	1.0
Specific agents and dietary additives	25	5	1	0	0	2	1	0	2	0	0	0	1	7	0.3
Animal health	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Structural and management changes	10	3	2	0	0	1	0	1	0	0	0	0	0	4	0.4
Animal breeding, genetics, herd structure	15	6	2	0	0	1	3	1	0	0	2	0	0	9	0.6
Housing and manure total	**36**	**13**	**2**	**5**	**2**	**1**	**3**	**3**	**4**	**2**	**1**	**5**	**3**	**31**	**0.9**
Housing	10	1	0	1	0	0	0	0	0	0	0	0	0	1	0.1
Manure storage and handling	21	9	0	3	0	0	1	1	2	0	0	3	1	11	0.5
Anaerobic digestion and CH_4 capture	5	3	2	1	2	1	2	2	2	2	1	2	2	19	3.8
Land use change total	**13**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**2**	**0.2**
Energy and waste	**20**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**2**	**0.1**
Transport	2	1	0	0	0	0	0	0	0	0	0	0	1	1	0.5
Heating and electricity	7	1	0	0	0	0	0	0	0	0	0	0	1	1	0.1
Waste	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Electricity generation	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
Other energy and waste	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
TOTAL	**262**	**100**	**23**	**14**	**11**	**9**	**26**	**14**	**21**	**10**	**12**	**17**	**26**	**183**	**0.7**

[a] *Number of mitigation measures grouped into the category/sub-category; MM: mitigation measure*
[b] *Number of mitigation measures in the category/sub-category mentioned at least once across the eleven studies*
[c] *Number of mitigation measures within a category or sub-category which were evaluated by a particular study*
[d] *Frequency showing the number of mitigation measures assessed across the eleven studies (including repetitions)*

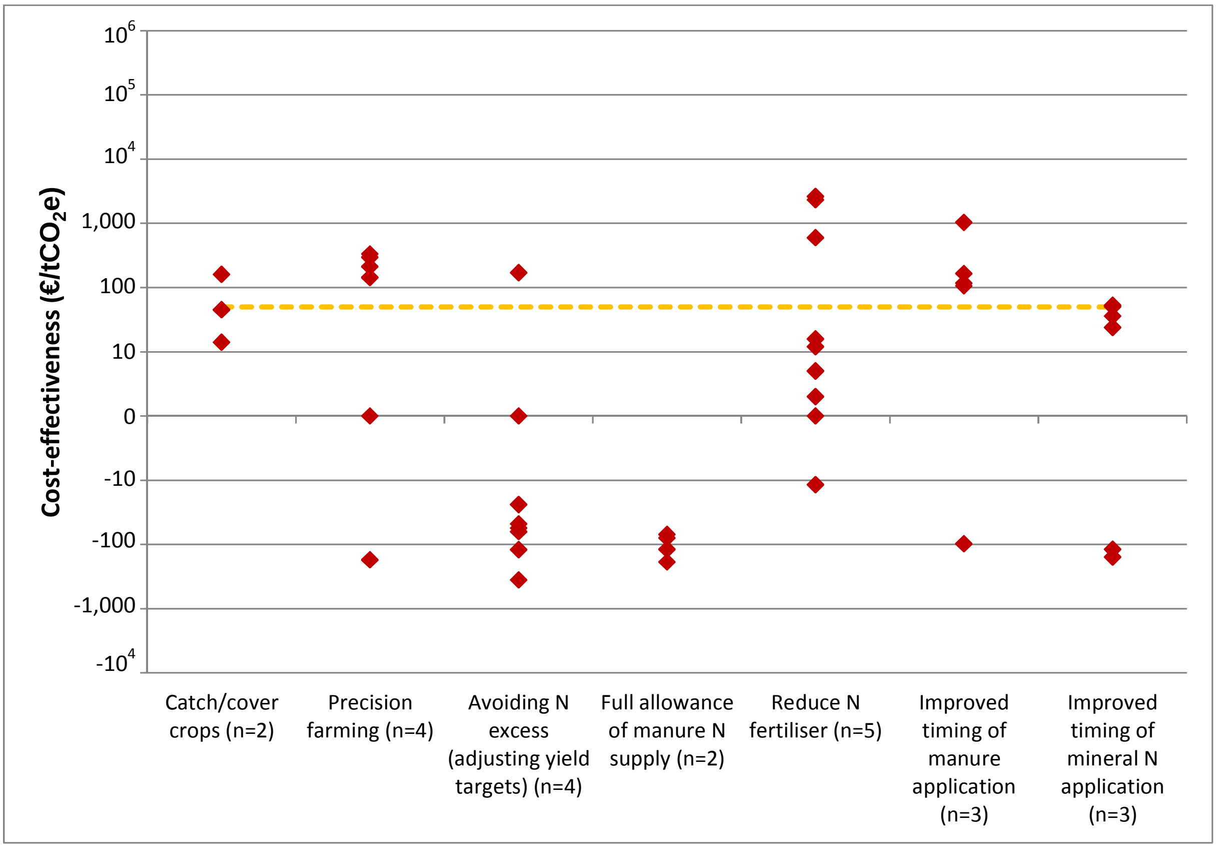

Figure 1 Cost-effectiveness of mitigation measures (dotted line: notional carbon price, n: number of studies providing information)

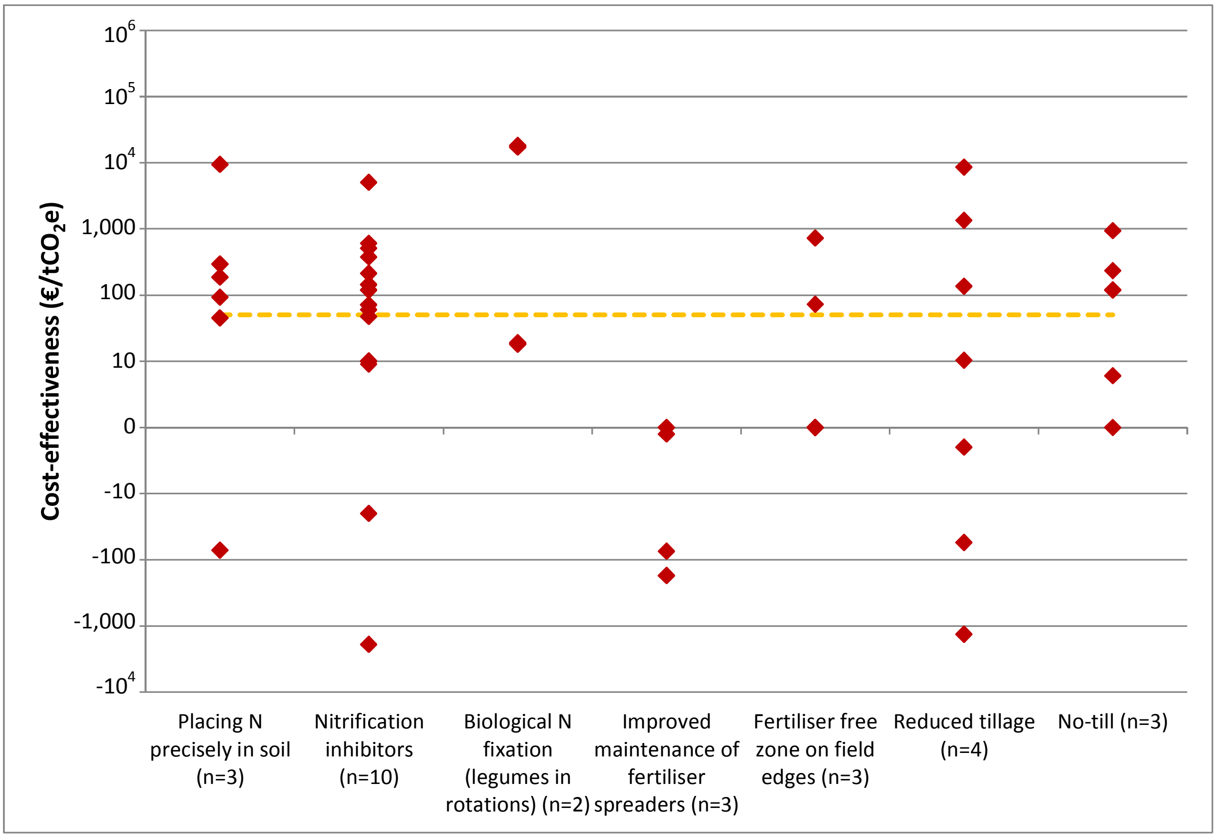

Figure 2 Cost-effectiveness of mitigation measures (dotted line: notional carbon price, n: number of studies providing information)

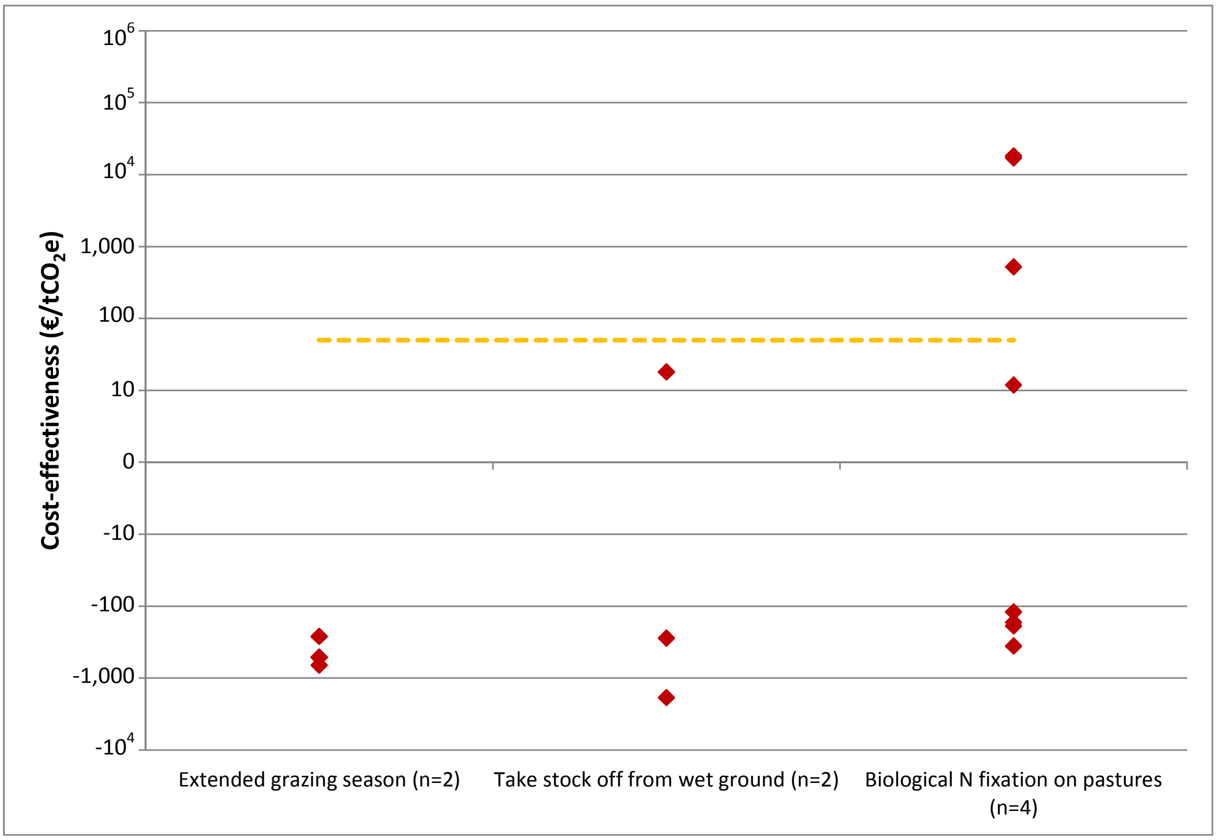

Figure 3 Cost-effectiveness of mitigation measures (dotted line: notional carbon price, n: number of studies providing information)

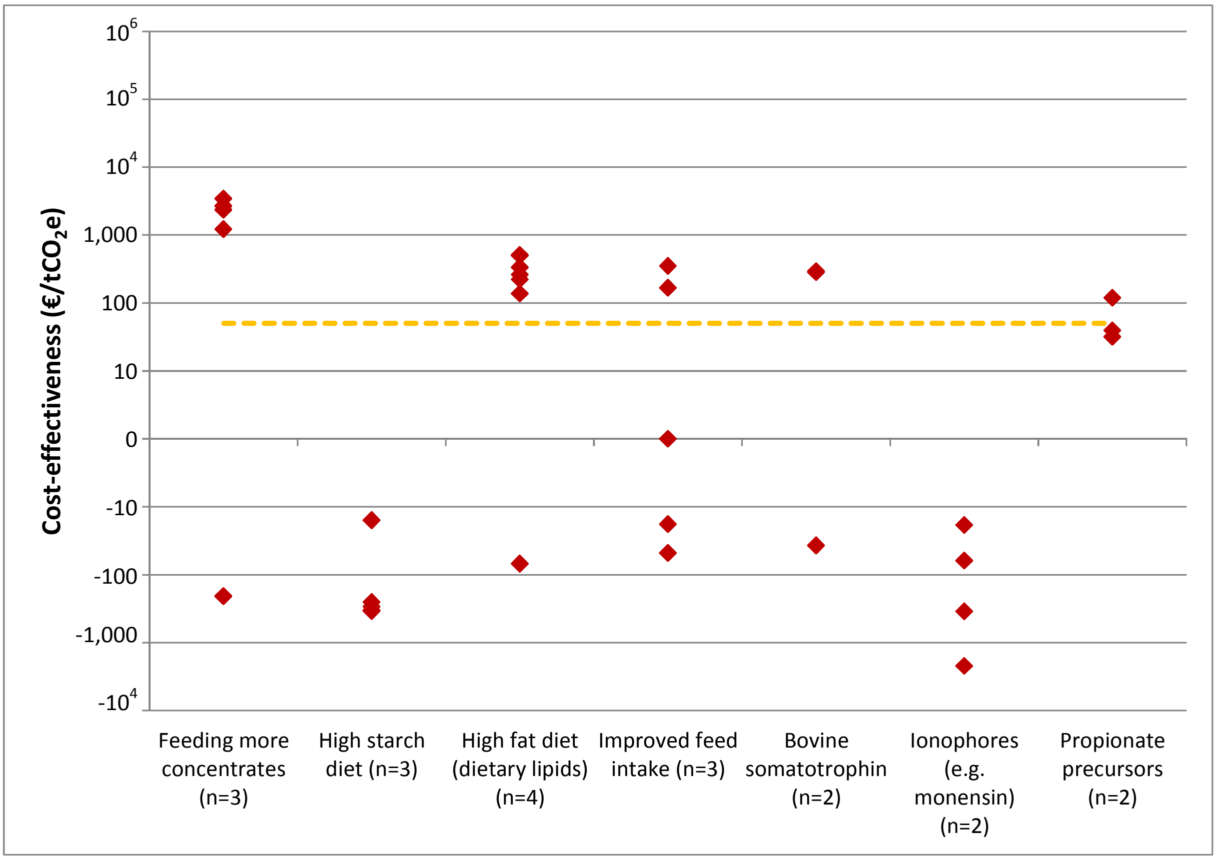

Figure 4 Cost-effectiveness of mitigation measures (dotted line: notional carbon price, n: number of studies providing information)

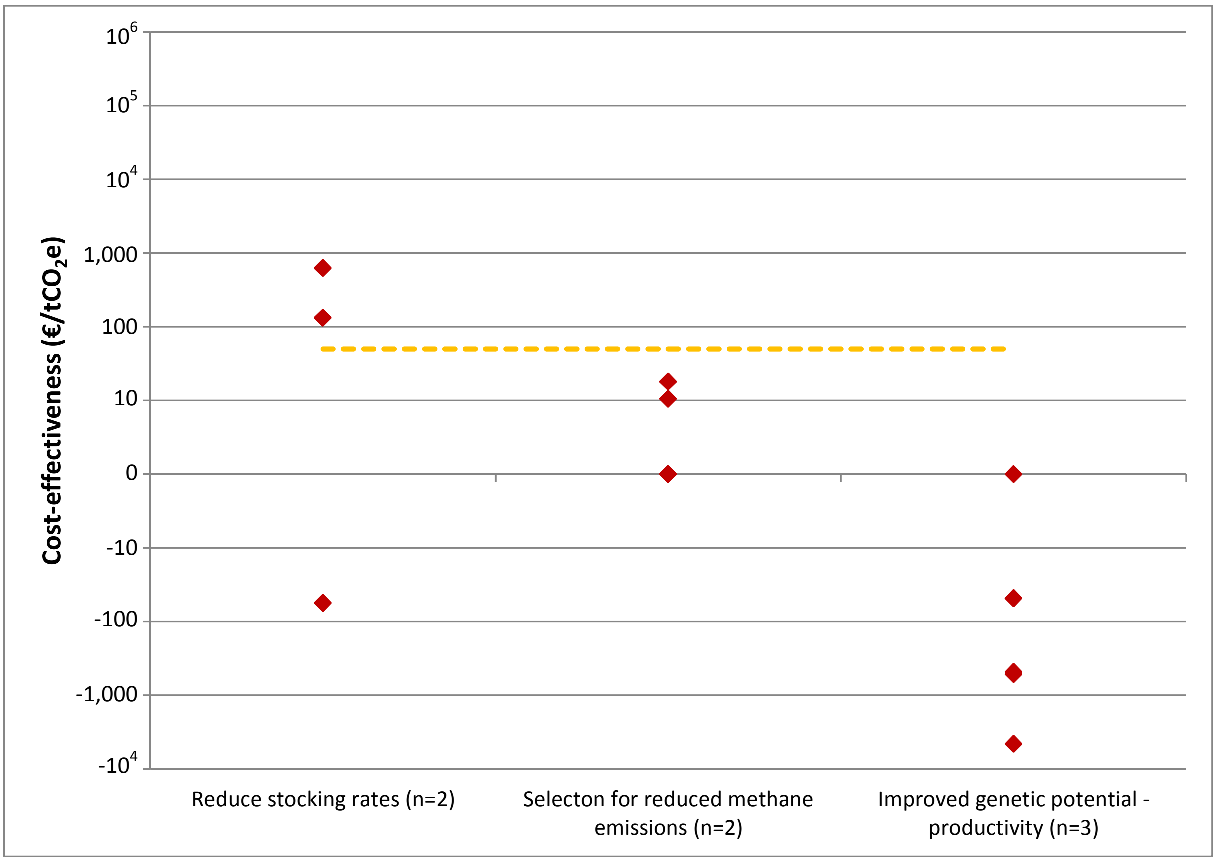

Figure 5 Cost-effectiveness of mitigation measures (dotted line: notional carbon price, n: number of studies providing information)

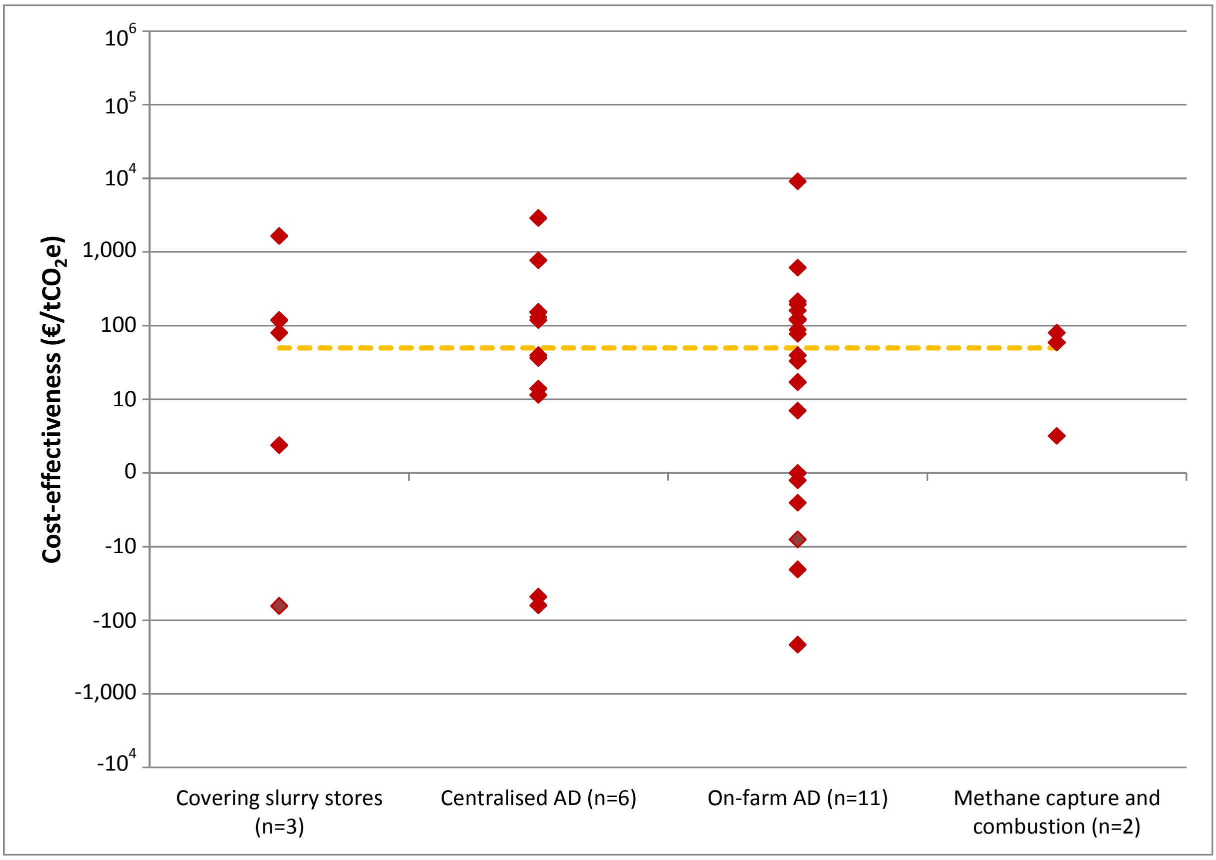

Figure 6 Cost-effectiveness of mitigation measures (dotted line: notional carbon price, n: number of studies providing information)

Lowest and highest cost-effectiveness estimates were recorded for those mitigation measures (less rice cultivation related measures) which appeared at least in two studies, *i.e.* for 31 mitigation measures. These estimates are presented on Figure 1 – Figure 6 (note the log scale on the y axis). The dotted horizontal line represents a notional carbon price of € 50 tCO_2e^{-1}, and the number of studies providing estimates for each measure is indicated in the legend under the x axis. The range of cost-effectiveness estimates for almost all mitigation measures is strikingly wide; the majority of the mitigation measures have both positive and negative values (negative values meaning cost savings), and in most cases the estimates can differ by two or three orders of magnitude or more. There are a number of reasons for the variability between studies. One is the differences in the modelling and calculation approaches the studies use. For example, LCA calculations might attribute very different GHG mitigation potential to certain measures than on-farm GHG calculations do. Another methodological difference which can result in high variability in the cost-effectiveness estimates is the way the interactions are considered. In some studies the mitigation potentials of the measures targeting the same emission source are reduced cumulatively, thus increasing the cost-effectiveness of the measures. An example is the measure 'Biological fixation' in Moran *et al.* (2008), which has a cost-effectiveness of £43 tCO_2e^{-1} in 2022 if considered on its own ('stand-alone cost-effectiveness'), but becomes very expensive (€13,435 tCO_2e^{-1}) if other measures targeting soil N_2O emissions are implemented prior to it. In studies where the issue of interactions is dealt with an allocation assumption (*i.e.* assuming that one each farm only one mitigation measure is implemented to tackle a particular emission source) the mitigation potential of the measures and therefore their cost-effectiveness is not affected. Other drivers of the variability between studies are the difference in geographical locations they cover, the different farm sizes they might use as an average, and further differences in key assumptions about the biophysical efficiency and the financial implications of the measure.

All of the studies reports more than one cost-efficiency estimates for at least one-third of the mitigation measures. In 4 studies all the mitigation measures have more than one cost-effectiveness estimate. The disaggregation is most often done on a spatial basis, *e.g.* for world regions in global studies (Graus *et al.* 2004, Hasegawa and Matsuoka 2010), for countries in EU studies (Amann *et al.* 2008, Bates *et al.* 2009, Hoglund-Isaksson *et al.* 2010) or for states in the case of United States (Biggar *et al.* 2013). It is also common to differentiate – at least for some mitigation measures, like those related to animal feeding – between livestock types, *e.g.* dairy versus beef cattle (Bates *et al.* 2009, Graus *et al.* 2004, Moran *et al.* 2008, Pape *et al.* 2008, Pellerin *et al.* 2013). Some further bases for disaggregation include farm types (Weiske and Michel 2007), crop type (Biggar *et al.* 2013), year of mitigation (Moran *et al.* 2008), discount rate (Moran *et al.* 2008, Pape *et al.* 2008), GHG accounting methodology (Schulte *et al.* 2012). Pellerin *et al.* (2013) also reports a range for some of the cost-effectiveness estimates, though the origin of this range is not well explained. Interestingly, the range between the lowest and highest estimates can be wide even within a study, for example, out of the ten mitigation measures recorded from (Biggar *et al.* 2013) the lowest range of cost-effectiveness estimates is €77 tCO_2e^{-1} ('Covering slurry stores'), while the widest range is close to €5,000 tCO_2e^{-1} ('Nitrification inhibitors'). The widest range within one study is €7,800 tCO_2e^{-1} for the mitigation measure 'Reduced tillage' (Moran *et al.* 2008).

The mitigation measures can be grouped into three categories according to the range their cost-effectiveness estimates cover:

1. Negative and/or small positive cost-effectiveness: these measures are estimated to have either negative cost-effectiveness (providing savings to the farmers), or have a positive cost-effectiveness which is still lower than a threshold carbon price, meaning that though their implementation would cost money, it would be still a cost-effective way to reduce GHG emissions. Here a carbon price threshold of €50 tCO_2e^{-1} is used for the purpose of discussion.

2. Small positive and high positive cost-effectiveness: these measures are estimated to cost money to the farmers, and while in some cases still they can be a cost-effective, they might have cost-effectiveness beyond the threshold carbon price, indicating that their implementation might not only be expensive, but would not be economically efficient – though further consideration of additional impacts might make them desirable.
3. Cost-effectiveness estimates in the whole range (negative, small positive, high positive): the cost-effectiveness values reported for these measures span across the whole range, though for some mitigation measures there is a visible tendency with the estimates falling more into one or the other part of the range.

Table 3 Grouping of the mitigation measures according to their cost-effectiveness estimates

Cost-effectiveness group	Mitigation measures (n)[a]
1. Negative and/or small positive	- Full allowance of manure supply (2) - Improved maintenance of fertiliser spreaders (3) - Extended grazing season (2) - Take stock off from wet ground (2) - High starch diet (3) - Ionophores (2) - Selection for reduced enteric CH_4 emissions (2) - Improved genetic potential – productivity (3)
2. Small positive and high positive	- Catch/cover crops (2) - Biological N fixation in rotations (2) - Fertiliser free zone on field edges (3) - No-till (3) - Proprionate precursors (2) - CH_4 capture and combustion (2)
3. Whole range	*Mostly negative or small positive:* - Avoiding N excess (adjusting yield targets) (4) - Reduce N fertiliser (5) *Mostly high positive:* - Precision farming (4) - Placing N precisely in soil (3) - Improved timing of manure application (3) - Nitrification inhibitors (10) - Feeding more concentrates (3) - High fat diet (4) - Centralised anaerobic digesters (6) *No clear tendency:* - Improved timing of mineral N application (3) - Reduced tillage (4) - Biological N fixation on pastures (2) - Reduce stocking rates (2) - Improved feed intake (3) - Bovine somatotrophin (2) - Covering slurry stores (3) - On-farm anaerobic digesters (11)

[a] *n: number of studies where cost-effectiveness data were available*

Approximately half of the mitigation measures' cost-effectiveness does not spread very wide, seemingly defining clearly whether the measure provides savings (Group 1), or costs money but can be cost-effective (Group 2). The remaining measures have cost-effectiveness estimates in the whole range (Group 3). Among these latter two seem the be mostly cost-effective: 'Avoiding N excess (adjusting yield targets)' and 'Reduce N fertiliser', while four are usually estimated to be too expensive ('Precision farming', 'Placing N precisely in the soil', 'Nitrification inhibitors', 'Centralised anaerobic digesters'). The remaining seven measures in this group show no clear tendency.

Important to note that those mitigation measures which fall into Group 1-2 have only a very limited number of estimates recorded, as they are represented only in two, maximum three studies. On the other hand, the mitigation measures which have been assessed in four or more studies all belong to Group 3, *i.e.* the range of estimates always spreads from negative to high positive.

2.4 Discussion

This review reveals that there are three important areas and issues which are often neglected in studies on the marginal abatement costs and cost-effectiveness of agricultural GHG mitigation. First, mitigation in developing countries have hardly been assessed so far, only a few studies offered estimates for developing countries as part of a global assessment, and one study reported on mitigation in rice production in three Asian countries (Wassmann and Pathak 2007). Still, a significant growth in agricultural production and related GHG emissions are likely to occur in developing nations (Steinfeld *et al.* 2006), and currently the emission intensity of production in these countries is often higher than in developed countries (MacLeod *et al.* 2013, Opio *et al.* 2013). At the same time, food security and poverty alleviation in the face of changing climate and growing population is of utmost importance in these regions (Foresight 2011). Thus, assessing opportunities for mitigating GHG emissions in these regions is a pressing need.

Second, the majority of the studies looked at impacts on emissions within the farm gate, even though changes on farm can have effects on emissions from other parts of the supply chain (like emissions from fertiliser or livestock feed production). Admittedly, exploring sectoral emissions is an important part of planning national and international emission budgets, and by keeping the analysis within the farm gate double-counting of mitigation can be avoided in such an exercise. However, ignoring off-farm emissions poses the risk of emission leakage, for example reducing on-farm enteric methane emissions on a cattle farm by increasing the amount of grains in the feed might result in a net emission increase due to the increased CO_2 emissions from related land-use change (Vellinga and Hoving 2011). Similarly, as demonstrated by Schulte *et al.* (2012), the cost-effectiveness of the mitigation measures can be very different with different system boundaries; increasing emphasis on cost-effectiveness work done by LCA approaches in the future would help to raise awareness to this problem at the policy level.

Finally, not all agricultural emission sources and sinks are considered equally across the studies. Possibly because of the dominance of N_2O and CH_4 emissions in the agricultural sector of the national inventories many studies focus only on these two gases, ignoring CO_2 emissions and C sequestration effects. Some studies look at CO_2 emissions as well, and a growing number of studies also take into account long term changes in soil C stock. CO_2 emissions related to agricultural energy use are important, specifically within some farm types, like dairy cattle and horticulture. Even more important is the soil C stock change related to agricultural activities, and very often mitigation measures targeting soil C have positive effects on soil structure and climate change adaptation. Agricultural MACCs cannot be complete without these effects and mitigation measures.

As presented in Table 2, certain categories and subcategories of mitigation measures are very much favoured across the bottom-up cost-engineering agricultural MACCs, *e.g.* cropland nutrient management, rice management, grazing intensity and timing, livestock feeding practices, and, particularly, anaerobic digestion and CH_4 capture. Others, like organic soils, animal health, waste and energy use have been very much neglected so far. The popularity of the subcategories is only partly a consequence of the perceived efficacy of the mitigation measures, it is also a function of historic research focus (*e.g.* many nitrogen related measures have been earlier identified as ways of reducing ammonia emissions and nitrogen leaching) or perceived novelty of the measure (*e.g.* anaerobic digestion and nitrate feeding). The research gaps highlighted in this review highlight the need for further research. Animal health related mitigation measures can be addressed in bottom-up cost-engineering approaches within the boundaries of the farm gate, while work on organic soils and degraded land necessitates looking beyond current agricultural areas, and waste reduction measures can be best addressed by methods looking at the whole supply chain (cradle to grave LCA analysis).

The cost-effectiveness estimates of the mitigation measures vary greatly both within and between studies. Many drivers of the variability can be explored by comparing the results and the methodologies of the studies, but most of these differences are not clearly stated in the methodology sections of the studies. Beyond the need for clearer description of the studies boundaries and methodologies, an important omission should also be addressed in the future: the lack of uncertainty analysis and sensitivity analysis (though disaggregation by the discount factor can be considered as a sensitivity analysis to the discount factor).

Two measures were identified which showed consistently favourable cost-effectiveness estimates across more than three studies: ‘Avoiding N excess (adjusting yield targets)’ and ‘Reduce N fertiliser’. The latter measure refers to a combination of suboptimal fertilisation (*i.e.* reducing the N fertiliser amount below the economic optimum) and proportional fertiliser reduction (*e.g.* 10%, 20%), where the study did not specify whether this reduction is a reduction only in the excess N or beyond that. Admittedly there is a difficulty in drawing clear boundaries between the mitigation measures in general, particularly in some sub-categories, like ’Nutrient management’. The difficulty is exacerbated by the often inaccurate description of the mitigation measures and the assumptions related to them.

On the other side of the spectrum, still amongst the measures where data are available at least in four studies, are four measures (‘Precision farming’, ‘Nitrification inhibitors’, ‘High fat diet’, ‘Centralised anaerobic digesters’) which, though have a wide cost-effectiveness estimate range, but most often are estimated to have too high cost-effectiveness to be considered economically efficient. All of them have either high upfront costs or high running costs. Examples are the machinery and computer system in ‘Precision farming’, the extended slurry storage for ‘Improved timing of manure application’, the significant investment required for a ‘Centralised anaerobic digesters’, the annual cost of chemicals used as ‘Nitrification inhibitors’, or the increased feed costs in ‘Feeding more concentrates’ and in ‘High fat diet’.

However, many measures with high upfront or running costs still have estimates indicating that the measure can be cost-effective and, in some cases, might provide financial savings. Examples of such measures were ‘Reduced tillage’, ‘No-till’, ‘Covering slurry stores’, and, most notably, ‘On-farm anaerobic digester’.

The limitation of this review is that it considers only those studies which look both at the environmental and economic effects of mitigation, thus it narrows down the evidence base considerably. This means that potentially cost-effective measures (currently in Group 1 and Group 2) might be failed to be identified as consistently cost-effective measures or consistently non-cost-effective measures, due to the current lack of information. The same applies to the long list of measures which are not assessed in any of these studies.

The range of the cost-effectiveness estimates is so large that, on the global scale, no firm conclusions can be drawn on which mitigation measure is better than the other. Mitigation measures which are assessed in more than three studies show a wide range of cost-effectiveness estimates, and *vice versa*, the low number of observations for many measures can be the main reason why they can be categorised more easily. At the same time, the low number of studies limits conducting analysis at a smaller spatial scale or disaggregating the studies in other ways. However, a meta-analysis of the estimates could shed light on some of the drivers of the variability in the estimates. Also, it can be possible to draw some conclusions about individual mitigation options at a regional level. This might be possible by looking at the accumulating evidence on the biophysical effects as analysed in meta-analyses and, at the same time, exploring the private and public cost elements and non-financial barriers in more detail.

The range of estimates is driven only partly by the variability in the systems studied: uncertainty also has an important role. Unfortunately, this uncertainty has not been explored in any of the reviewed studies. Therefore it is of paramount importance that the results of any single study have to be considered only as an indicative value. Additionally, as the cost-effectiveness metric only integrates two features of a mitigation measure (namely costs and mitigation potential), a range of other aspects have also to be considered in a policy development process, for example positive and negative co-effects, the cost and complexity of policy instruments needed to promote uptake and the behavioural barriers to uptake.

Going further, beyond filling in the research gaps identified above, there is a need for developing regional and tailored policy instruments. This could include increasing the availability of farm-specific advice, equipping the farmers and advisors with regionally appropriate information and decision support tools, and, at the same time, promoting the development of monitoring and verification mechanisms, like the use of proxies and simple modelling tools.

However, the value of these studies lies mostly in drawing up an inventory of the likely consequences of the GHG mitigation on farms, discussing possible policy instruments to promote behavioural change and raising awareness among stakeholders by contributing to the public discourse on GHG mitigation.

3. Marginal abatement cost curves for beef production in the Brazilian *Cerrado*

This section is a brief summary of Oliveira Silva *et al.* (2015), attached in Appendix 4: Marginal abatement cost curves for beef production in the Brazilian *Cerrado*.

3.1 Introduction

The expected growth in livestock production poses significant additional pressure on natural resources. Sustainable management will require increasing yields and efficiency in existing ruminant production systems, minimizing competition of land used for food and feed, while maximizing ecosystem services, including mitigation of greenhouse gas (GHG) emissions (Gerber *et al.* 2013, Soussana *et al* 2013, Thornton and Herrero 2010). Brazil is the second world's largest beef producer of the world, with a production predominantly based on pastures mostly in humid and sub-humid tropical climate.

Tropical regions are implicated as potentially offering major opportunities to increase beef productivity and emissions mitigation, as current productivity levels are still relatively low and emission intensities correspondingly high (Gerber *et al.* 2013, Opio *et al.* 2013). More productive pastures can increase soil carbon stocks, providing one of the largest terrestrial carbon sinks (Follett and Reed 2010, Neely *et al.* 2009). In addition, increasing productivity through feed supplementation may significantly reduce direct methane emissions (Berndt and Tomkins 2013, Ruviaro *et al.* 2014).

This paper investigates the cost-effectiveness of livestock mitigation measures applicable in the *Cerrado* core (Central Brazilian Savannah). The paper offers the first MACC analysis using an optimization model for Brazilian beef production. The evaluated measures are pasture restoration, feedlot finishing, supplement concentrates and protein, nitrification inhibitors and pasture irrigation. The analysis uses the outputs of a multi-period Linear Programming model (the Economic Analysis of Greenhouse Gases for Livestock Emissions model- EAGGLE (Oliveira Silva 2013)) to develop a bottom-up or engineering MACC. The analysis accounts for both the private and social costs and benefits (*e.g.* including avoided deforestation) and provides new insights for regional policy intervention.

3.2 Methodology

In our analysis we use a marginal abatement cost curve (MACC) approach to rank the cost-effectiveness of a range of mitigation measures. Agricultural MACCs are used to compare the relative costs of implementing these measures and the amount of mitigation they offer under average farm conditions. MACCs can be used to determine the relative cost-effectiveness of each measure in terms of cost per tonne of CO_2 mitigated. With this information it is possible to define the lowest cost ways to achieve a given GHG reduction target. In our case, the MACC is derived using output from a multi-period linear programming model. We represent the *Cerrado* region as a single production unit (or farm) and seek to maximize production value subject to economic and biophysical constraints.

Overview: The EAGGLE model (Oliveira Silva 2013) is a multi-period linear programming model that represents the complete production cycle (cow-calf, stocking and finishing) on a beef farm. The model allocates farm resources optimally to meet demand projections while maximizing profit. In this analysis, the *Cerrado* beef production system is treated as a single farm.

Outputs: Profit (gross margin) and net GHG emissions are obtained by running the model for a given beef demand projection and associating the resulting animal numbers with standard emissions coefficients, land use conversion emissions (*i.e.* loss of biomass in terms of CO_2e) and changes in soil organic carbon stocks.

Building the MACC: By assuming the adoption of a mitigation measure 'm scenario', the values of the outputs (profit and net emissions) are evaluated relative to a baseline without measure adoption. The abatement potential is calculated as the difference between GHG emissions under the two scenarios. Cost-effectiveness is calculated as the difference between profit, divided by the difference between emissions under the 'm scenario' and the baseline.

3.3 Results and discussion

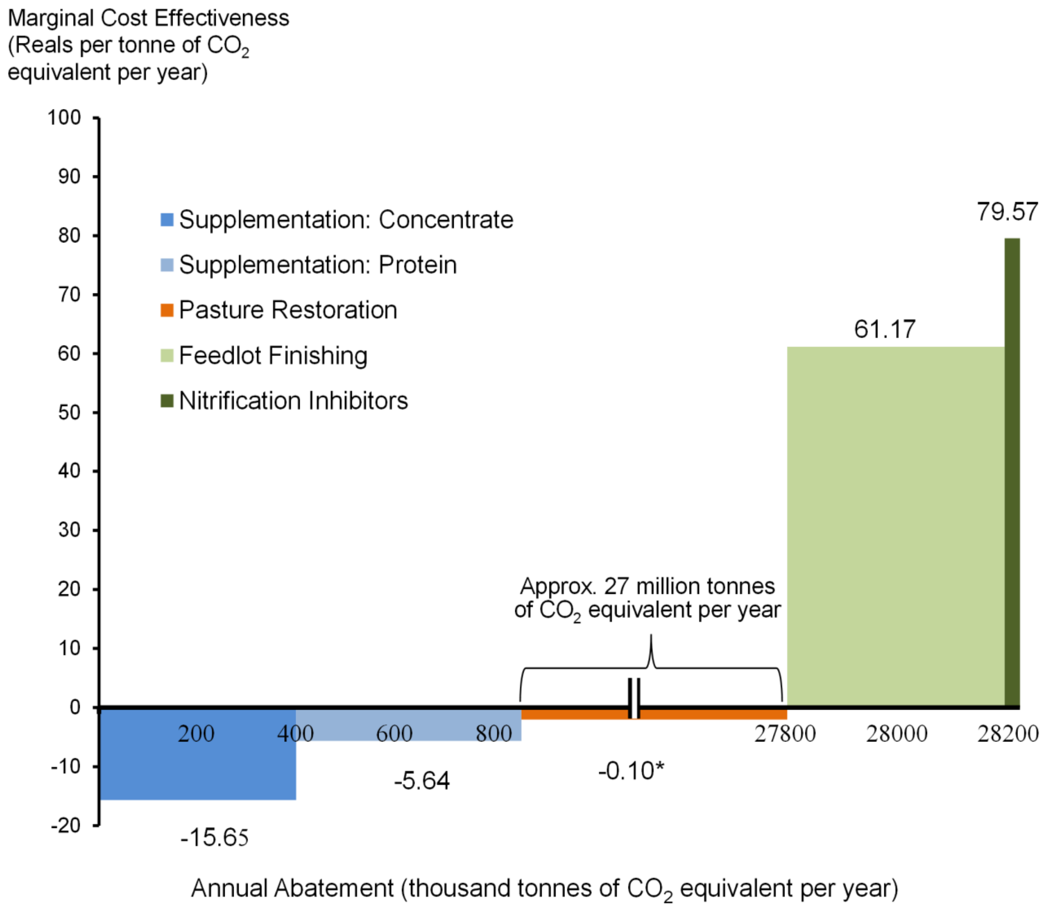

Figure 7 Estimated marginal abatement cost schedule for mitigation measures in *Cerrado* livestock production, 2006 to 2030

* *Not in scale*

By implementing negative-cost measures identified in the MACC, by 2030, regional emissions could be reduced by 27.8 Mt CO_2e yr^{-1}, while the abatement potential of all measures shown by the MACC is 28.2 Mt CO_2e yr^{-1}. Pasture restoration, involving avoided deforestation, offers the largest contribution to these results.

The results who that pasture restoration is a very promising mitigation measure, with a total annual abatement potential of 27 Mt CO_2e at negative costs, *i.e.* providing savings to livestock farmers. Increasing the amount of concentrates and protein in the feed can, similarly, generate savings on the beef farms. Adopting these measures could reduce the Cerrado beef production emissions by 23.7% by 2030.

4. Cost-effectiveness assessment of mitigation options on model farms

4.1 Introduction

Component 3 (Work Packages 9-11) of the AnimalChange project was assessing mitigation options on model and showcase farms in Europe, South America and Africa both from the GHG emission perspective and from their financial performance. The work included the following steps (more details of these steps can be found in research deliverables indicated in brackets):

- Development of FarmAC (Deliverables 9.1, 9.2, 9.3, 9.4)
- Selection of model farms and showcase farms (Deliverables 10.1 and 10.5)
- Selection of mitigation measures (described below)
- Detailed description of mitigation measures for biophysical and economic modelling (described below)
- Biophysical modelling of mitigation measures in FarmAC (Deliverables 10.4 and 10.3)
- Development of the economic assessment tool (described below)

The section is reporting on the selection and description of the mitigation options and on the development of the economic assessment tool. For the latter the methodology is explained, with a future prospect of using this tool to gain deeper insight into the differences in the economic efficiency of GHG mitigation on European farms.

4.2 Identification and description of the mitigation options for modelling

4.2.1 Initial selection for modelling

Work reported in D8.1 'Qualitative overview of mitigation and adaptation options and their possible synergies & trade-offs' developed a list of mitigation and adaptation options, containing 42 mitigation options. On a workshop attended by whole-farm GHG modelling experts 27 of these mitigation options were selected for consideration for biophysical modelling (Table 4), based on three criteria:

- High GHG abatement,
- Whole farm effect as opposed to isolated effect on a single emission source and
- Low perceived difficulty in modelling.

Table 4 Mitigation options initially selected for modelling

Mitigation option
Fertilisation rate
Nitrification inhibitors
Grass-legume swards
Legumes in the rotation
Cover crops
Irrigation

Mitigation option
Restoring degraded lands
Improving pastures
Improving roughage quality
Feeding more maize and less grass
Feeding more fat
Additive nitrate
Balancing amino acids and reduce CP
Increasing housing (grass constant)
Replacement rate cattle
Cover slurry stores
Manure acidification
Anaerobic digestion
Agroforestry
Genetic improvement in dairy cattle
Start the feedlot fattening period at a younger age
Change the grazing management
Clean the pasture from unwanted species
Integrate livestock and crop production
Reducing age at first calving
Optimising calving dates
Using enzymes (phytase)

4.2.2 Selection of five best mitigation options by farm experts

The next step was a further selection, whereby showcase and model farm experts (*i.e.* researchers in AnimalChange Component 3 with in-depth knowledge of regional farming systems) picked the best five options out of the 27 options listed above, considering how they perceive the mitigation options in relation to the following criteria for their particular farms:

- High GHG abatement
- Low cost
- High likely uptake

Farm experts were asked not to consider other criteria at this stage, like scientific relevance to the project, modelling capabilities or data availability. The rankings are presented on Table 6 and Table 7, for European and for South American and African farms, respectively.

Out of the 27 options only one option was not selected by any expert, and that was ‘Nitrification inhibitors’. 21 options were selected for at least two farms, and the most popular choices were the following:

Table 5 Most popular mitigation options from the '5 best' exercise

Overall	Additionally in Europe	Additionally in South America and Africa
Improving pastures	Feeding more maize and less grass	Change grazing management
Improving roughage quality	Feeding more fat	Restoring degraded lands
Fertilisation rate	Reducing age at first calving	Agroforestry
Legumes in the rotation		
Grass-legume swards		
Replacement rate cattle		

The majority of the most popular mitigation options increase the production efficiency of farms, either by more efficient use of nutrient in crop and livestock production ('Improving pastures', 'Improving roughage quality', 'Fertilisation rate', 'Legumes in rotation', 'Grass-legume swards'), or by higher productivity at the herd level ('Replacement rate cattle', 'Reducing age at first calving'). Note that in the option 'Fertilisation rate' was usually understood differently in the regions, in Europe it was considered as decreasing the fertilisation rate while in South America and Africa the opposite was assumed, as current fertilisation rates are very low, and increasing them would increase area-based productivity more than the area-based GHG emissions. All of these options are generally regarded to have low costs, mostly requiring a change in management approach rather than additional investment or annual expenses. The mitigation options most popular in South America and Africa but not in Europe were those which benefit soil quality and soil C stocks – corresponding to the existing agronomic problems in these areas. Interestingly, two mitigation options which are usually estimated to incur increased annual costs were also selected, albeit only in Europe: 'Feeding more maize' and 'Feeding more fat'. Though the first is regarded to result in productivity benefits, which might be higher than the increased costs, the second is mostly considered as an option rather to decrease GHG emissions than to increase productivity. On the other hand, the mitigation option 'Nitrification inhibitors' were not selected by any experts, even though it is commonly considered to have a high mitigation potential – though at an increased annual expense.

Table 6 The best five the mitigation options by farm as selected by farm experts in Europe

			Fertilisation rate	Nitrification inhibitors	Grass-legume swards	Legumes in the rotation	Cover crops	Irrigation	Restoring degraded lands	Improving pastures	improving roughage quality	Feeding more maize and less grass	Feeding more fat	Additive nitrate	Balancing amno acids and reduce CP	Increasing housing (grass constant)	Replacemnt rate cattle	Cover slury stores	Manure acidification	Anaerobic digestion	Agroforestry	Genetic improvement in dairy cattle	Start the feedlot fattening period at a younger age	Change the grazing management	Clean the pasture from unwanted species	Integrate livestock and crop production	Reducing age at first calving	Optimizing calving dates	Using enzymes (Phytase)
Mixed dairy	Europe	Maritime				x						x				x	x					x							
Mixed dairy	Europe	Maritime	x								x			x						x		x							
Mixed dairy	Europe	Continental	x									x											x				x		
Mixed dairy	Europe	Mediterranean	x		x	x					x		x																
Mixed beef	Europe	Maritime	x									x											x				x		
Mixed beef	Europe	Continental	x			x	x						x	x															
Grassland dairy	Europe	Maritime	x		x					x							x					x							
Grassland beef	Europe	Maritime			x					x	x						x					x							
Grassland beef	Europe	Continental				x					x		x														x	x	
Grassland beef	Europe	Mountain			x						x	x															x	x	
Grassland sheep	Europe	Mountain			x					x	x																x	x	
Grassland sheep	Europe	Mediterranean							x	x	x										x			x					
Grassland sheep	Europe	Mediterranean							x	x	x													x	x				
Grassland sheep	Europe	Mediterranean			x			x	x												x								
Pig	Europe	N-Eu	x												x			x	x	x									
Pig	Europe	S-Eu													x				x	x									x

Table 7 The best five the mitigation options by farm as selected by farm experts in South America and Africa

			Fertilisation rate	Nitrification inhibitors	Grass-legume swards	Legumes in the rotation	Cover crops	Irrigation	Restoring degraded lands	Improving pastures	improving roughage quality	Feeding more maize and less grass	Feeding more fat	Additive nitrate	Balancing amno acids and reduce CP	Increasing housing (grass constant)	Replacemnt rate cattle	Cover slury stores	Manure acidification	Anaerobic digestion	Agroforestry	Genetic improvement in dairy cattle	Start the feedlot fattening period at a younger age	Change the grazing management	Clean the pasture from unwanted species	Integrate livestock and crop production	Reducing age at first calving	Optimizing calving dates	Using enzymes (Phytase)
Livestock	Brazil, Amazo	Sub-humid/humid							x												x			x	x	x			
Intensive dairy	Brazil	Sub-humid/humid	x			x	x														x			x		x			
Intensive beef	Brazil	Sub-humid/humid	x			x	x														x			x		x			
Crop livestock	Burkina Faso	Semi-arid grassland				x				x	x					x		x		x									
Crop livestock pastoral	Burkina Faso	Sub-humid				x				x	x					x		x		x									
Extensive / semi-intensive	French Guian	Sub-humid/humid	x			x				x							x				x			x					
Extensive beef	Brazil	Sub-humid/humid							x	x							x						x	x					
Extensive beef	South Africa	Semi-arid grassland							x	x	x						x								x				
Extensive beef	Brazil, Cerrad	Arid	x					x	x	x	x																		
Livestock	Brazil, Amazo	Sub-humid/humid																											
Livestock	Senegal	Semi-arid grassland																											

4.2.3 Selection for modelling across farm types

The objective of this step was to suggest a combination (matrix) of mitigation option x farm for subsequent modelling, based on:

- Experts' choices of five best options
- Maximising the overlap of mitigation options between farm type
- Reducing possible modelling and data availability difficulties
- Considering time and resource constraints

Two additional criteria were also considered: in the final combination one option ('Fertilisation rate') should be modelled on all farms, and two farms (maritime grass-based dairy, maritime mixed dairy) will be modelled with a high number of mitigation options, thus achieving a horizontal and a vertical cross-section. The aim was to achieve a balance in the matrix, trying to keep the experts' choices as far as possible while increasing overlap between farms, and balancing this with the modelling (time and effort) constraints.

4 different mitigation option x farm combinations were developed and evaluated at a workshop by the farm experts and the model developers (Table 8):

- '7 best' was aiming to retain the most from the farm expert's 'five best' choices and proposed to evaluate 7 mitigation options on each farm.
- '4 best local' was proposing to evaluate 4 options on each farm with an emphasis on keeping the expert's original choices.
- '4 best overlap' was also proposing to evaluate 4 options/farm, but with a focus on maximising the overlaps between the farms, *i.e.* to have more options evaluated on multiple farms.
- '3 best easy' was suggesting to assess 3 options on each farm aiming for those which are relatively easier to model.

The final matrix was agreed by the CP3 farm experts and modellers. It was based on the '4 best local' and '4 best overlap' combinations, proposed to have 20 options evaluated, on average 6.5 options/farm (ranging from four to nine options/farm), achieving a good overlap of mitigation options on farms, though at the expense of high total number of modelling runs and the inclusion of a number of the more complex mitigation options. This final matrix is presented on Table 9, and served as the starting point for the farm assessment work. The farm experts used it as a starting point in their modelling and had a choice of adding or leaving out options if needed. The final list of modelled options x farms can be found in Deliverable 10.3.

Table 8 Evaluation of mitigation option x farm combinations

Europe	Number of options to be modelled	Modelled on at least three farms	Number of difficult measures	Total number of runs (farm type X option)	Overlap with '5 best options'
7-local	24	15	7	108	77
4-local	20	9	6	64	54
4-overlap	13	8	3	64	46
3-easy	8	5	1	48	29
Final	16	13	3	112	50
South America and Africa	Number of options to be modelled	Modelled on at least three farms	Number of difficult measures	Total number of runs (farm type X option)	Overlap with '5 best options'
7-local	17	10	8	63	50
4-local	11	6	6	36	31
4-overlap	9	7	5	36	29
3-easy	5	4	1	27	21
Final	10	8	6	51	35
Overall	Number of options to be modelled	Modelled on at least three farms	Number of difficult measures	Total number of runs (farm type X option)	Overlap with '5 best options'
7-local	25	23	8	171	127
4-local	22	15	7	100	85
4-overlap	17	13	6	100	75
3-easy	11	7	2	75	50
Final	20	18	6	163	85

Table 9 Final mitigation option x farm combination (x: mitigation option for that farm to be assessed)

FINAL SET			Fertilisation rate	Nitrification inhibitors	Grass-legume swards	Legumes in the rotation	Cover crops	Irrigation	Restoring degraded lands	Improving pastures	improving roughage quality	Feeding more maize and less grass	Feeding more fat	Additive nitrate	Balancing amno acids and reduce CP	Increasing housing (grass constant)	Replacemnt rate cattle	Cover slury stores	Manure acidification	Anaerobic digestion	Agroforestry	Genetic improvement in dairy cattle	Start the feedlot fattening period at a younger age	Change the grazing management	Clean the pasture from unwanted species	Integrate livestock and crop production	Reducing age at first calving	Optimizing calving dates	Using enzymes (Phytase)
Mixed dairy	Europe	Maritime	x	x								x	x	x					x	x		x					x		
Mixed dairy	Europe	Maritime	x	x								x	x	x					x	x		x					x		
Mixed dairy	Europe	Continental	x	x								x	x	x					x	x		x					x		
Mixed dairy	Europe	Mediterranean	x	x								x	x	x					x	x		x					x		
Mixed beef	Europe	Maritime	x	x								x	x	x					x	x		x					x		
Mixed beef	Europe	Continental	x	x								x	x	x					x	x		x					x		
Grassland dairy	Europe	Maritime	x	x	x					x							x					x		x			x		
Grassland beef	Europe	Maritime	x	x	x					x		x					x					x		x			x		
Grassland beef	Europe	Continental	x	x						x	x		x																
Grassland beef	Europe	Mountain	x	x	x					x	x																		
Grassland sheep	Europe	Mountain	x	x	x					x	x																		
Grassland sheep	Europe	Mediterranean	x	x						x	x													x					
Grassland sheep	Europe	Mediterranean	x	x						x	x													x					
Grassland sheep	Europe	Mediterranean	x	x	x					x																			
Pig	Europe	N-Eu	x	x											x			x	x	x									
Pig	Europe	S-Eu	x	x											x			x	x	x									
Livestock	Brazil, Amazon	Sub-humid/humid	x			x			x	x											x			x		x			
Intensive dairy	Brazil	Sub-humid/humid	x			x			x	x											x			x		x			
Intensive beef	Brazil	Sub-humid/humid	x			x			x	x											x			x		x			
Crop livestock	Burkina Faso	Semi-arid grassland	x			x				x										x									
Crop livestock pastoral	Burkina Faso	Sub-humid	x			x				x										x									
Extensive / semi-intensive	French Guiana	Sub-humid/humid	x			x											x							x					
Extensive beef	Brazil	Sub-humid/humid	x						x	x	x													x		x			
Extensive beef	South Africa	Semi-arid grassland	x						x	x	x						x							x					
Extensive beef	Brazil, Cerrado	Arid	x						x	x	x													x		x			
Livestock	Brazil, Amazon	Sub-humid/humid																											
Livestock	Senegal	Semi-arid grassland																											

4.2.4 Description of mitigation options for biophysical and economic modelling

The biophysical modelling work in Component 3 was done by farm experts, therefore a common understanding of the mitigation options had to be achieved. This common understanding had to cover the mitigation rationale, the agronomic details and the cost elements of the mitigation option. Additional to that, agreement had to be made on the boundaries of the mitigation options (*e.g.* in case an option would reduce the animal feed available on farm, is the whole-farm response to reduce stocking rates or to increase the amount of feed bought in?), and, as a continuous process, the fine details of the biophysical modelling implementation had to be shared amongst the experts.

While acknowledging that the mitigation measures would be implemented somewhat differently on the farms, common guidelines on the mitigation measures were developed to help to make the results as comparable as possible. A brief description of the options was prepared (see Land use change (including deforestation), degrading or restoring pasture will affect the soil carbon (C) stocks. These changes are calculated by EAGGLE: the model estimating the annual C stock under pasture and crops for each land use. The total accumulated C under soils is given by the sum of the C stock of each pasture DMP levels, soya and corn.

2.1 Carbon sequestration through pasture management

Depending on the DMP, the C flux may change significantly. The EAGGLE model works with equilibrium values of the C stock for each type of pasture and crops. The higher the pasture productivity, the higher the C equilibrium value (Table 2). The equilibrium values were calculated exogenously, using simulations from the CENTURY model (Parton *et al.*, 1987) applied to *Cerrado* biophysical characteristics and using the annual DMP calculated for each pasture category.

Table 2: Annual dry matter productivity and equilibrium C stock values.

Pasture/Crops	DM[1] ($t.ha^{-1}.yr^{-1}$)	Carbon stock equilibrium[2] ($t.ha^{-1}$)
A	19.6	84.3
B	17.6	82.7
C	12.6	62.3
D	8.7	45.2
E	5.8	32.4
F	3.9	26.1
Corn (Silage)	3.8	45.0
Corn(Grain)	9.0	40.0
Soybean	2.5	45.0

[1] Estimated using the models published by Tonato *et al.* (2010)

[2] According to Parton (1987)

EAGGLE accounts for the annual carbon stocks per each land use in column 1, Table 2. The model transfers the accumulated carbon from year *t-1* to year *t* and calculates the variation of soil C in year *t*.
Letting $C_{t,lu}$ be the soil carbon stock (tons) under the land use *lu*, where $lu \in \{A, B, C, D, E, F, Soybeans, Corn(silage), Corn(grain)\}$.Then $C_{t,lu}$ can be expressed by:

$C_{t,lu} = \varphi(t,lu) + \Delta C_{t,lu}$ (Eq. 1)

And

$\Delta C_{t,lu}= f(\varepsilon_{lu}, C_{t-1,lu})$ (Eq. 2)

Eq. (1) is composed of the carbon transference term, $\varphi(t,lu)$, and the C sequestration term, $\Delta C_{t,lu}$. The term φ(t,lu) accounts the transference of C from other uses to land use *lu* in year *t*; *e.g*., if *lu* is equal pasture *B*, and one hectare of soybeans is converted in year *t* into one hectare of pasture level *B*, the carbon previously stocked under soybeans has to be transferred to pasture *B*. Similarly, if some hectares are converted from pasture *B* to pasture *A*, or degraded to *C*, then part of the C stock from *B* has to be proportionally transferred from *B* to these other uses. The sequestration term, $\Delta C_{t,lu}$ is written as a function of the distance between the previous C stock $C_{t-1,lu}$, and the C stock equilibrium value, ε_{lu}. Hence the further the previous stock is from the equilibrium value, the more C will be up taken. Conversely, if due to the land use change, or degradation, the C stock becomes greater than the equilibrium value, there will be negative C sequestration, *i.e.,* a loss of C stock. These modelling approaches follow the concepts suggested by Eggleston *et al*. (2006) and Vuichard *et al*. (2007). The extended version of Eq. (1) and (2) are presented in Oliveira Silva (2013).

2.2 Deforestation due to cattle ranching

For pasture area we use the projections published by (Gouvello *et al.*, 2010) combined with an endogenous deforestation term. Let LU_t be the total area at year *t*; a_t the Gouvello *et al.* (2010) projections; and D_t the endogenous term that represents further area expansion. Then for every year:

$LU_t = a_t + D_t$ (Eq. 3)

The deforested area will cause a loss of carbon stocks in natural vegetation and influence soil C; and directly influences the transference term in eq. (1), *i.e*., loss of soil organic matter (SOM). Both vegetation carbon stocks and SOM are accounted by EAGGLE to represent the emissions associated with deforestation.
There is limited quantitative research on the dynamics of pasture productivity following deforestation. In accordance with the best available information, the model allocates new converted areas into the system in pasture category *C*(the highest without nitrogen fertilization), as soil carbon also can increase or decrease values after deforestation (Maia *et al.,* 2009) and pasture productivity is relatively high after conversion due to higher soil organic matter mineralization (Martha Jr, 2007).In this analysis, we assumed the cost of opening new areas is zero because the cost of conversion the *Cerrado* into pastures can be offset by timber sales and land value appreciation(Bowman, 2013).
Another assumption is that the model cannot discard land endogenously, neither does it allow fallow in any year of the planning period. This assumption is based on the fact that cattle ranchers are not allowed to let their properties be unproductive; otherwise the land can be confiscated by the government for Agrarian Reform (Federal Law 8.629 - www.planalto.gov.br/ccivil_03/leis/l8629.htm).

2.3 Baseline construction

Land use change scenarios need to be mapped onto a plausible baseline for land use activity. The baseline scenario is based on national forecasts of beef demand and grassland area for Brazil, from 2006 to 2030 (Gouvello *et al.*, 2010). The assumption is that the attributable *Cerrado* pasture area and beef demand share are a fixed proportion of the national projections. In 2006, the *Cerrado* pasture area represented 34% of the national total(IBGE, 2014).The model then assumes that *Cerrado* pasture area corresponds to 34% of Brazil's pasture area, and this proportion is constant during the studied period (2006-2030). Similarly, as there is no data for regional demand, we assumed demand to be proportional to area, *i.e*., demand for *Cerrado* is also equivalent to 34% of national demand, this percentage is very close to the 35% figure estimated by Anualpec (2010).

In the model, increased productivity occurs by means of investments in technologies, *e.g*., pasture restoration, supplementation and feedlot animals. The baseline scenario has limited adoption of these measures, implying constant productivity. We assumed that pasture restoration is allowed in the baseline only to avoid degradation, but it is constrained to maintain productivity at 2006 levels (10 t-DM.ha^{-1}.yr^{-1}) (Appendix S2). Combining this constraint with projected increased demand pushes the model to open new areas if it is necessary to meet the growing demand for beef.
The current adoption rate of feedlot finishing in Brazil is around 10% of the total herd (Anualpec, 2010). We assumed this proportion to be constant in the baseline, a rate that is in counterpoint to a higher level of penetration of this measure in a mitigation counterfactual.

2.4 GHG emissions sources

The EAGGLE model calculates GHG emissions using emissions factors for activities within the farm gate. GHG emissions associated with the farm activities are: (a) CH_4 from cattle enteric fermentation (CH_4 from excreta is not accounted); (b) N_2O from cattle excreta; (c) N_2O direct emissions from N fertilization; (d) CO_2 from deforestation; and (e) CO_2 from pasture degradation and land use change from pasture to crops.

Items (a) and (b) depend on herd composition: each age cohort of males and females (heifer or cow) has an associated emission factor of CH_4 and N_2O calculated using Tier 2 methodology (Eggleston *et al*., 2006), see Table S1 and Table S2. Due to the lack of studies in Brazilian conditions, for (c), we used the Tier 1 IPCC default factor of 1% (Eggleston *et al*., 2006). The emissions from (d) are calculated using coefficient of loss of natural vegetation per deforested area. The average carbon loss of natural vegetation due to deforestation was estimated as 34.6 tons of C per hectare, in accordance to Eggleston *et al*. (2006) and Bustamante *et al.* (2012). For (e), the emissions are calculated according to Eq. (1) and (2).

2.5 Mitigation Measures

The selection of GHG mitigation measures was based on literature review and expert opinion regarding the relevance and applicability of the technologies to Brazilian livestock production and conditions. The measures evaluated are: concentrate supplementation, protein supplementation, pasture restoration, nitrification inhibitors and feedlot finishing. Although the latter is already in the baseline, we investigated a higher adoption rate of this technology.
Modelling assumptions for these measures related to the effects the measures have upon the gross margin and emissions are detailed in Table 3.

Table 3: Selected livestock mitigation measures

Mitigation measure	Description	Cost[1]	Unit	Reduces emissions by:	Adoption rate target
Feedlot finishing	When cattle weight is around 80% of the slaughter weight it is removed from pasture and grass to feedlot on a diet with ration of balanced protein and energy content	9.12	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	15% of the total finished animals
Nitrification inhibitors	Application of Agrotain Plus® together with urea used as fertilizer; 3g per Kg of applied nitrogen[2]	61.44	$\$.t^{-1}$	Reduced conversion of nitrogen to the GHG nitrous oxide (nitrification)	Optimized
Pasture restoration	Improving pasture forage productivity by soil chemical and mechanical treatment. As described in Section 2.1	Table 1	$\$.ha^{-1}$	Avoiding the need for additional pasture land and increasing organic carbon sequestration	Optimized
Supplementation concentrate	Feeding cattle via grazing and a ration with a high energy content. Grazing steers with 421 kg of LW can be selected for concentrate supplementation. The supplementation takes 2 months and the final weight is 490 kg	3.07	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	Optimized
Supplementation protein	Feeding cattle via grazing and a ration with a high protein content. Calves (189 kg) can be selected (only in March) to be supplemented with protein. The steers are finished after 15 months, with 481 kg	1.15	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	Optimized

[1]Supplementations non-feed cost, for feed costs (ration formulation, see Table 4)

[2]Cost and Application ratio suggested manufacturer (http://www.agrotain.com/us/home).

2.5.1 Concentrate and protein supplementation

Both measures involve supplementing the feed of grazing steers; *e.g.*, feed is composed of forage and supplements. It is expected that these measures reduce emissions since animals gain weight faster and take less time to be finished.

Table 4: Rations (supplements) formulation and costs.

Crop	Ration Formulation (%)[1]			Cost[2] (US$.kg^{-1})
	Feedlot	Concentrate	Protein	
Corn (grain)	83	80	15	PBF
Corn (Silage)	11	0	0	PBF
Soybeans	5	17	39	PBF
Urea	0	2	12	1.19
Mineral Salt	1	1	19	0.84
NaCl	0	0	15	1.19

[1]Rations were formulated by using the software Invernada (minimum cost ration formulator) (Barioni, 2011)

[2]PBF = Produced By the Farm, *i.e*., the crops produced by EAGGLE (according to the dynamics in section 2.2.2) are stored and used to formulate the rations.

Biological coefficients, *e.g*., mortality rate, weight, DM intake, and emissions factor for steers fed with supplementations can be found in Table S2.

2.5.2 Pasture restoration

This measure works in the model by avoiding deforestation and because restoration boosts carbon soil uptake. Details of the modelling and Costs are explained in section 2.2.2. In contrast to the baseline scenario, to evaluate this measure, the fixed DMP baseline constraint was removed.

2.5.3 Nitrification Inhibitors

The measure works by avoiding a proportion of the Nin fertilizer or manure being converted into N_2O, *i.e.* nitrification and denitrification35 process (Abbasi and Adams, 2000). To date there have been no studies detailing the reduction in N_2O emissions for Brazilian pastures when nitrogen inhibitors are applied. A 50% reduction of direct N_2O emissions is assumed in this paper -as found by Giltrap *et al.* (2011) for a New Zealand study. We assumed that this measure is applicable only over the N used for pasture and crops fertilization. The reason is that most of the Brazilian herd is based on a grazing systemwhere it is unfeasible to apply inhibitors to animal excreta.

2.5.4 Feedlot finishing

Like supplementation, this measure works by reducing the cattle finishing time since feedlot animals are fed only by ration (with the formulation descried in Table 4). Only steers can be selected to model in the feedlot system. The adoption rate was arbitrarily assumed to be 15% of the total finished herd, since in the baseline the adoption rate is 10% of the total finished herd, the measure can be stated as: increasing by 50% over the baseline adoption rate.

2.6 Marginal abatement cost curve

A MACC can be used to represent the relative cost-effectiveness of different abatement options and the total amount of GHG that can be abated by applying mitigation measures over and above a baseline scenario. The aim is to identify the most economically efficient manner to achieve emissions reduction targets, where the cheapest units of greenhouse gas should be abated first (Moran *et al*., 2010).
MACC analysis can be derived by means of a top-down analysis – which usually makes use of a general equilibrium model and emissions are calculated endogenously, or by a bottom-up or engineering analysis (MacLeod *et al*., 2010). This paper take a bottom-up approach, where the individual abatement potential of measures and their costs are individually modelled using the EAGGLE detailed equations.
The MACC can be presented in form of a histogram, where the C abatement potential lies on the x-axis, and the cost per tons of abatement in the y-axis. The abatement potential of a measure *m* (AP_m) is calculated as the annual average of the difference between the

business-as-usual (baseline) total GHG emissions (E_{BAU}) and the total emissions under the mitigation measure scenario (E_m) during the production period T:

$$AP_m = \frac{E_{BAU} - E_m}{T} \qquad \text{(Eq.4)}$$

The cost-effectiveness of measure m (CE_m), therefore, is calculated by:

$$CE_m = \frac{GM_{BAU} - G_m}{AP_m} \qquad \text{(Eq. 5)}$$

Where GM_{BAU} and GM_m are, respectively, the gross margin in the baseline scenario and the gross margin in the scenario with the measure m implemented.

As observed in Eq.4 and Eq.5, AP_m and CE_m are average values across the planning period.

1. Results

3.1 Baseline Emissions

In the baseline scenario, livestock production in the *Cerrado* accounts for an average of 121.5Mt $CO_2e.yr^{-1}$, from 2010 to 2030. This value includes enteric fermentation, animal waste (emissions from excreta), soil fertilization emissions, pasture (due to the loss in C stocks), and deforestation driven by cattle production (Fig. 1). The accumulated emissions from 2010 to 2020 account for about 1,249Mt CO_2e or 2,551Mt CO_2e from 2010 to 2030.

In relative terms, enteric fermentation makes the biggest contribution to the total: 66% of emissions, followed by deforestation, with 26%. The results also show that pasture degradation is a considerable source 100 of emissions, accounting for an average of 8.35 Mt $CO_2e.yr^{-1}$ (an average of 0.06 t $CO^2e.ha^{-1}.yr^{-1}$), the equivalent to 4% of emissions or the same proportion as animal waste (Fig.2).

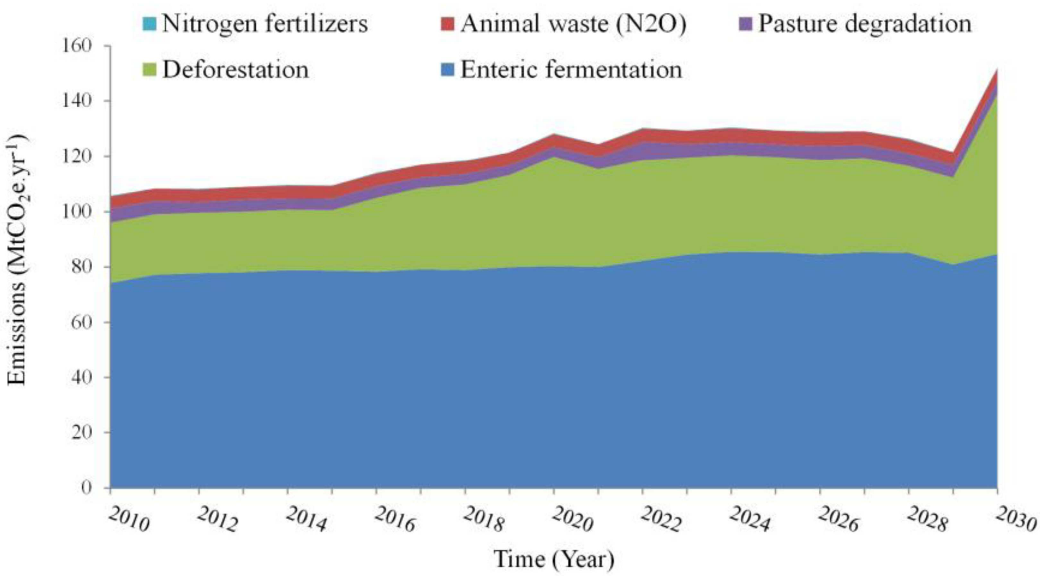

Figure 1: *Cerrado* baseline emissions 2010-2030

Gouvello *et al.* (2010) suggests that total national GHG emissions from energy, transport, waste, livestock and agriculture, will be around 1.70 Gt CO_2e, for 2030. The results presented here suggest that beef production in the *Cerrado* will be responsible for about 152 Mt CO_2e in 2030, corresponding to 9% of total national GHG emissions.

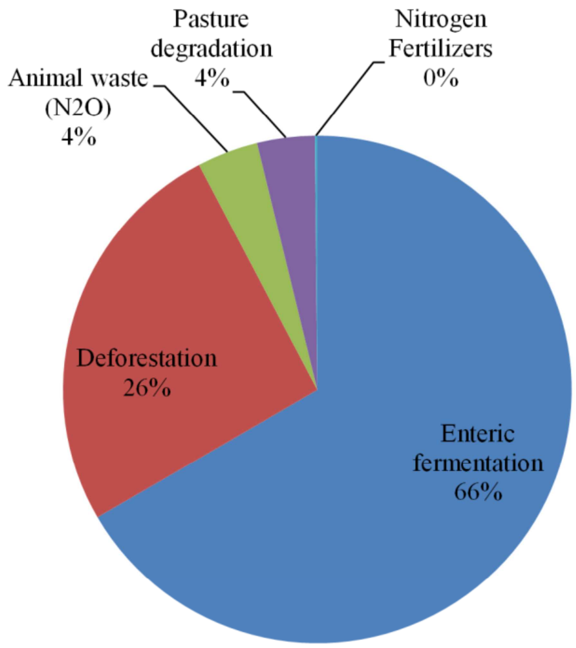

Figure 2: Share of emissions from 2010 to 2030 for the Brazilian *Cerrado*.

In the baseline scenario, without increasing productivity, an average deforestation rate of 246.1 10^3 ha.yr^{-1} would be required to meet the beef demand.
Emissions attributed to the use of fertilizers were not significant, accounting for an average of 0.2 Mt CO_2e.yr^{-1}. This was expected, since small amounts of N are used to fertilize *Cerrado* pasture soils (Martha Jr *et al*., 2007; Cederberg *et al*., 2009).

3.2 Cost-effectiveness analysis

For policy purposes it is important to detail the relative cost of emissions mitigation measures. Three of the five mitigation measures simulated, - concentrate supplementation, protein supplementation, and pasture restoration - have negative cost-effectiveness: US$-8.01. kt CO_2e^{-1}, US$-2.88. kt CO_2e^{-1} and US$-0.05. kt CO_2e^{-1}, respectively (Figure 3). Adopting these measures implies cost savings while reducing emissions. These measures work by balancing the loss of DM production during the dry months. The *Cerrado* biome is predominantly seasonal tropical, meaning dry winters and rainy summers, with lower pasture productivity during the dry months. If cattle are supplemented with concentrates or protein they can be finished earlier, thereby reducing emissions.

Due to the large applicable area (approximately 60 M ha), and given the current low productivity of 10 t DM.ha^{-1}.yr^{-1}, pasture restoration provides the biggest opportunity for reducing emissions in the region.

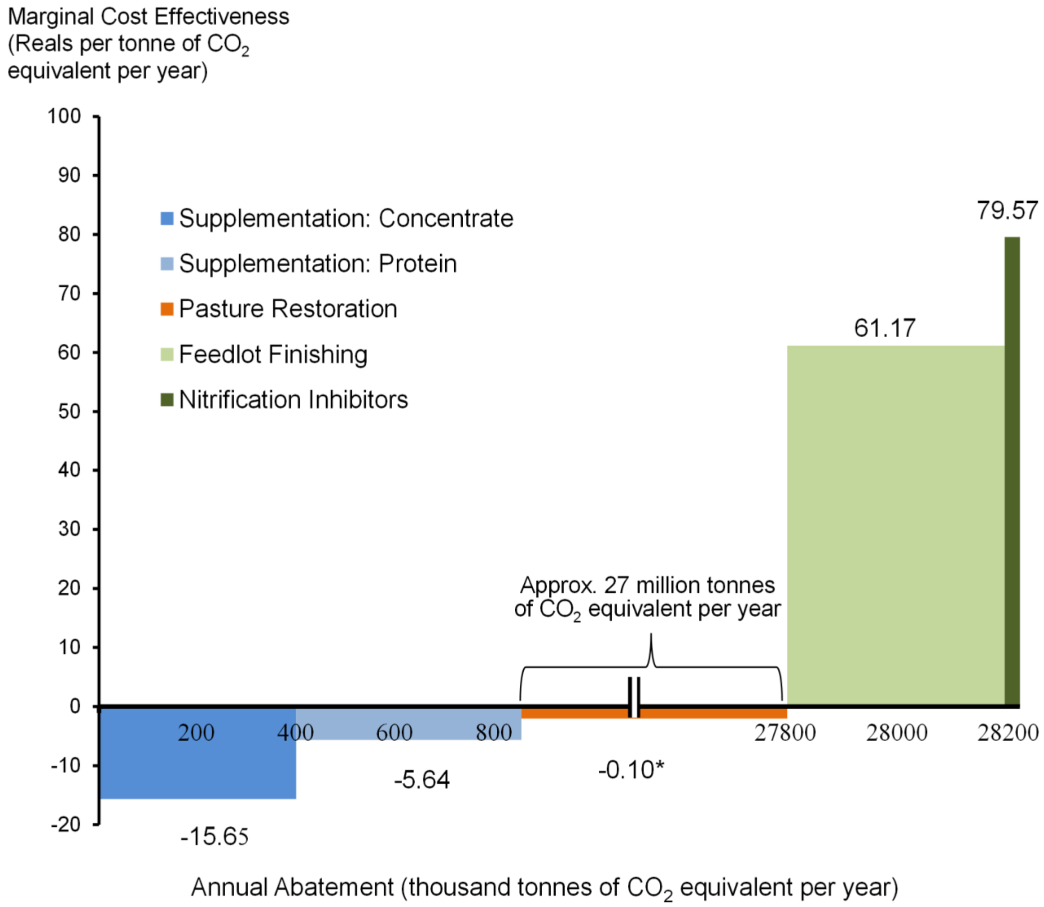

Figure 3: Marginal abatement cost curve: mitigation measures for *Cerrado* livestock production from 2006 to 2030. * Not in scale

The abatement potential (AP) for pasture restoration is 26.9 Mt $CO_2e.yr^{-1}$,comprising of two components: C sequestration and avoided deforestation, the latter accounting for 96% of this AP. Pasture restoration would improve the *Cerrado* average productivity from 10 to 11.2 t $DM.ha^{-1}.yr^{-1}$, an increase of 12% relative to the baseline. This increase would lead to an average C sequestration rate of 0.32 t $CO_2e.ha^{-1}.yr^{-1}$.This is a low C uptake potential when compared to values found by Maia *et al*. (2009), which showed that C sequestration rates of 2.24 t $CO_2e.ha^{-1}.yr^{-1}$ can be achieved in well-managed pastures in *Cerrado*. The carbon sequestration rate however, reflect the 2006-2030 period, after which, and in the long term, as pastures are intensified it will eventually reach equilibrium and therefore no more carbon is likely to be sequestered.

The AP of feedlot finishing is 470 kt $CO_2e.yr^{-1}$, but the measure cost-effectiveness US$ 13.32 t CO_2e^{-1} is high relative to t supplementation.
Nitrification inhibitors are the least cost-effective measure considered. But this analysis only considered the application to N used for pasture and crops fertilization and excluded the application to animal excreta.

The results indicate that restoring degraded lands is the biggest opportunity for reducing emissions in the *Cerrado*. The AP of this measure is about 20 times greater than all the other measures combined.

An important assumption underpinning the MACC relates to the assumed measure adoption rates. With exception of feedlot finishing, the adoption rates are optimized, meaning the rates that maximizes the gross margin in the model.

Table 5: Mitigation measures adoption rate.

Mitigation Measure	Adoption rate	Unit
Supplementation: concentrate	12	%[1]
Supplementation: protein	2.2	%
Pasture restoration	314.7	10^3 ha.yr^{-1}
Feedlot finishing	15	%
Nitrification inhibitors	12.78	g.ha^{-1}.yr^{-1}

[1]Adoption rates for feedlot, protein and concentrate supplementation are calculated as the percentage of the total finished animals. The adoption rate of pasture restoration is the annual average area of restored pasture.

2. Discussion

To meet increasing domestic and export demand, the government of Brazil recognizes the need to foster sustainable agricultural intensification, which implies increased resource productivity while minimizing significant domestic and global external costs implicit in GHG emissions and deforestation. The results presented here suggest that a significant contribution to this objective can be made by targeting specific measures to improve yield. Specifically, pasture restoration, supplements and feedlot measures could reduce sector emissions by 24.1% by 2030. Moreover, by adopting only negative-cost measures (Fig. 3), it is possible to abate about 23.7% of baseline livestock emissions in the *Cerrado*, up to 2030. According to our results the restoration of degraded pastures offers the greatest abatement potential, involving the restoration of an average of 314.7 10^3 ha.yr^{-1} in *Cerrado* grasslands.

Currently, it has been estimated that 50 % to 80 % of pastures in the Amazon and *Cerrado* are degraded (Macedo *et al.*, 2014; Peron & Evangelista, 2004; Zimmer *et al.*, 1994). Achieving a higher rate is likely to entail some initial investment costs to promote modified production practices and this is the purpose of the government's ABC program. ABC is an ambitious plan created to stimulate farmers and ranchers to adopt mitigation measures including restoration of degraded pastures, helping the country to meet the reduction targets presented at COP 15. ABC is the biggest sustainable agriculture fund running in Brazil, with a key objective of disbursing subsidized credit to the agricultural sector. The plan currently targets the recovery of 15 Mha in 10 years, which will lead to reductions up to 104 Mt CO_2e, roughly 64% of the program total mitigation potential. But it does not include other relevant measures such as feed supplementation measures, which would normally be considered as privately profitable anyway.

The outcome of the ABC plan remains to be evaluated, but initial indications suggest that uptake of credit has been slower than anticipated (Claudio, 2012). Recent evidence from the Amazon Environmental Research Institute suggests that several institutional barriers have retarded the program, including a lack of publicity and information about the aims and the benefits of the program, difficulties in complying with program requirements, a lack of technical assistance, and producer scepticism about the private economic benefits of measures that are predominantly designed to address global external costs (Stabile *et al.*, 2012).

Producers also perceive transaction costs in program compliance and a lack of basic infrastructure (Rada, 2013) that is needed to support increased productivity. In short, the ABC plan is confronting similar behavioural barriers in relation to non-adoption, identified in other mitigation studies, *e.g*. Moran *et al*. (2013), which need to be addressed before wider measure adoption can be expected.

3. Conclusion

This paper highlight show resource efficiency measures can be enacted (notionally within farm gate) in the *Cerrado* biome to help reconcile competing objectives of private yield improvements and the reduction of external costs. The analysis responds to the need to demonstrate the possibilities for sustainable intensification, allowing Brazil to meet economic growth ambitions for the sector.

The key finding from the use of the EAGGLE economic optimization model is the representation of the cost-effectiveness of key mitigation measures. Specifically, that pasture restoration is the most promising mitigation measure in terms of abatement potential volume and that it offers a cost saving for the livestock sector. By adopting these measures – pasture restoration, concentrate and protein supplementations – the *Cerrado* could reduce 23.7% of its emissions by 2030, while the total abatement potential of adopting all measures is 24.1%.

The analysis presented here has a number of caveats that potentially warrant further research. These include a more detailed representation of the biophysical heterogeneity of the *Cerrado* biome, more detailed treatment of the deforestation (and hence land sparing) processes and relaxation of the assumed equilibrium supply and demand conditions in the optimization model.

Nevertheless by highlighting cost-effective policy options, this paper contributes to our understanding of sustainable intensification processes as relevant to Brazilian livestock production.

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Appendix. Supplementary material

Appendix S1: Description of inputs and costs
Appendix S2: Model calibration
Supplementary Tables: Tables S1-S8

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Appendix 5: Mitigation options – brief descriptions for biophysical and economic modelling), and more detailed agronomic/biophysical descriptions were also prepared for ten options (see Appendix 6: Detailed description of mitigation options for biophysical and economic modelling).

4.3 Methodology

4.3.1 Economic assessment

For the economic assessment of the mitigation options a calculator approach is used, as the method which can align most with the FarmAC modeling. It is a static approach, estimating the on-farm net technical cost of the mitigation option as the difference in costs and income streams between the baseline and the mitigation scenario. The cost-effectiveness of the mitigation option is calculated by dividing the net technical cost with the GHG emission difference between the mitigation and the baseline scenario:

$$CE_m = \frac{\sum_i Costs_{m,i} - \sum_j Income_{m,j}}{GHG_m - GHG_0}$$

Where CE_m: cost-effectiveness of mitigation option *m*

$Costs_m$: main technical costs of implementing mitigation option *m*
$Income_m$: main income streams of implementing mitigation option *m*
GHG_m: GHG emissions when implementing mitigation option *m*
GHG_0: GHG emissions in the baseline scenario

The calculator uses GHG emission and resource use and production data directly from FarmAC. These data are complemented with additional information on some management aspects not available in FarmAC and also with income and cost information. The farm experts are used as the primary source of the information on cost and selling/buying prices, or, if data are not available form them then data from the Eurostat database is used where possible. For mitigation options requiring capital investment the annualised capital cost and the annual maintenance cost are also included in the total costs.

Most of this information is provided by the farm experts, while some can be derived from Eurostat database. The livestock herd data are stock data, with no flow information, *i.e.* the income and cost calculations are based on the average annual number of animals in the herd. The variable costs (including veterinary costs, insemination costs, water and energy costs and excluding feed costs and labour costs), the labour requirement and the labour costs are provided by the farm experts for each livestock category. The milk and meat production data are derived from FarmAC at an aggregate level. The milk, livestock and meat selling prices are sourced from the Eurostat database or, if available, can be provided by the experts. The feed costs are calculated on a whole farm level, as explained below.

The crop activities are modelled as rotations in FarmAC, and the economic tool calculates the annual average crop activities for each crop based on the length of the rotation and the frequency of a crop used in the rotation. The nitrogen fertiliser use is derived from FarmAC, and the price is either provided by farm experts or Eurostat data are used. Other variable cost elements and labour requirements are provided by farm experts. The variable costs include seed costs, other fertiliser costs, plant protection costs, machinery and fuel costs (including on-farm processing, like crop drying and silage and hay production costs) and insurance. The amount of the exported and imported crop products (including animal feed) is available at the aggregated level from FarmAC. Corresponding buying or selling prices are either provided by farm experts or sourced from the Eurostat database and are used to calculate the cost of crop products purchased and the income from the sold crop products.

4.3.2 Description of the farms and the financial data

Cost-effectiveness assessment was carried out on two maritime grass-based cattle farms from the Component 3 model farms, with the following mitigation options as seen in Table 10:

- M-EU-004 Maritime Grassland Dairy – Irish Average National Dairy
- M-EU-002 Maritime Grassland Beef – Irish Average National Beef

Table 10 Mitigation options assessed on the two maritime model farms

Irish Average National Dairy	Irish Average National Beef
Reducing inorganic N fertiliser use	Reducing inorganic N fertiliser use
Introducing white clover into the sward	Introducing white clover into the sward
Increasing grass and grass silage quality	Increasing grass and grass silage quality
Improving total genetic merit of dairy cows	
	Earlier finishing of beef heifers and steers

Irish Average National Dairy	Irish Average National Beef
Application of nitrification inhibitors	Application of nitrification inhibitors
Extending the length of the grazing season	Extending the length of the grazing season
Increasing inorganic N fertiliser use	Increasing inorganic N fertiliser use
Combined measure: genetic improvement and longer grazing	
	Combined measure: earlier finishing and longer grazing
Combined measure: white clover and reduced N fertiliser use	Combined measure: white clover and reduced N fertiliser use

The detailed description of the farms and the GHG, N cycle and C cycle results are reported in AnimalChange Deliverable10.3. Key farm data are presented in Table 11 and Table 13, for the dairy and beef farm, respectively. Key production and emission FarmAC results can be found in Table 13 and Table 14, for the dairy and beef farm, respectively.

Table 11 Key farm data of the Irish Average National Dairy Farm by mitigation options

	Baseline	Reduced N	Clover	Pasture quality	Genetic impr.	Nitrification inhibitors	Longer grazing	Increased N	Genetic imp. + Longer gr.	Clover + Reduced N
Farm size [ha]	35.2	35.2	35.2	35.2	35.2	35.2	35.2	35.2	35.2	35.2
Grazed pasture [ha]	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.8
Grass silage [ha]	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Number of cows [head]	66.00	66.00	74.91	66.00	66.00	67.98	66.00	67.69	66.00	73.02
Urea used [kg N/yr/farm]	2,532	2,401	2,532	2,532	2,532	2,637	2,530	2,653	2,530	2,401
CAN used [kg N/yr/farm]	2,686	2,547	2,686	2,686	2,686	2,798	2,684	2,815	2,684	2,547
Concentrate imported [kg DM/y/farm]	49,126	49,126	55,754	49,126	49,126	50,599	49,501	50,383	49,501	54,348
Grass silage imported [kg DM/y/farm]	1,851	3,932	0	1,851	1,851	1,901	2,182	1,891	2,182	0

Table 12 Key farm data of the Irish Average National Beef Farm by mitigation options

	Baseline	Reduced N	Clover	Pasture quality	Earlier finishing	Nitrification inhibitors	Longer grazing	Increased N	Earlier finishing + Longer gr.	Clover + Reduced N
Farm size [ha]	35.2	35.2	35.2	35.2	35.2	35.2	35.2	35.2	35.2	35.2
Grazed pasture [ha]	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.8	21.8
Grass silage [ha]	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Number of cows [head]	66.00	66.00	74.91	66.00	66.00	67.98	66.00	67.69	66.00	73.02
Urea used [kg N/yr/farm]	2,532	2,401	2,532	2,532	2,532	2,637	2,530	2,653	2,530	2,401
CAN used [kg N/yr/farm]	2,686	2,547	2,686	2,686	2,686	2,798	2,684	2,815	2,684	2,547
Concentrate imported [kg DM/y/farm]	49,126	49,126	55,754	49,126	49,126	50,599	49,501	50,383	49,501	54,348
Grass silage imported [kg DM/y/farm]	1,851	3,932	0	1,851	1,851	1,901	2,182	1,891	2,182	0

Table 13 Key production and emission results for the Irish Average National Dairy Farm by mitigation options (source: FarmAC, D10.3)

	Baseline	Reduced N	Clover	Pasture quality	Genetic impr.	Nitrification inhibitors	Longer grazing	Increased N	Genetic impr. + Longer gr.	Clover + Reduced N
Milk produced [t/yr/farm]	328	328	388	338	344	338	332	337	349	378
Meat exported [t LW/farm/y]	0.660	0.660	0.749	0.660	0.660	0.680	0.660	0.677	0.660	0.730
Total protein exported [t protein/farm/y]	10.9	10.9	12.9	11.2	11.5	11.3	11.2	11.2	11.7	12.6
GHG emissions [kg CO2e/farm/y]	336,667	341,616	354,562	336,280	336,011	337,517	336,925	337,835	333,883	352,126
NH3 emissions [kg N/farm/y]	1,543	1,533	1,534	1,535	1,534	1,564	1,526	1,571	1,516	1,506
N leaching [kg N/farm/y]	3,883	3,892	2,600	3,855	3,816	3,816	3,939	3,877	3,822	2,591
GHG mitigation [kg CO2e/farm/y]		-4,950	-17,895	386	655	-851	-258	-1,168	2,784	-15,459
GHG mitigation % [% of baseline]		-1.5%	-5.3%	0.1%	0.2%	-0.3%	-0.1%	-0.3%	0.8%	-4.6%
NH3 mitigation [kg N/farm/y]		11	9	9	9	-20	18	-27	27	38
N leaching mitigation [kg N/farm/y]		-10	1,283	27	67	67	-56	6	61	1,292

Table 14 Key production and emission results for the Irish Average National Beef Farm by mitigation options (source: FarmAC, D10.3)

	Baseline	Reduced N	Clover	Pasture quality	Earlier finishing	Nitrification inhibitors	Longer grazing	Increased N	Earlier finishing + Longer gr.	Clover + Reduced N
Milk produced [t/yr/farm]	0	0	0	0	0	0	0	0	0	0
Meat exported [t LW/farm/y]	21.871	21.871	26.740	22.311	21.867	22.552	22.198	22.156	22.193	26.390
Total protein exported [t protein/farm/y]	4.7	4.5	5.8	4.8	4.6	4.9	4.6	4.8	4.5	5.7
GHG emissions [kg CO_2e/farm/y]	319,072	318,928	286,181	318,966	299,122	313,309	314,264	314,918	295,307	286,126
NH_3 emissions [kg N/farm/y]	1,272	1,272	1,426	1,268	1,175	1,326	1,253	1,313	1,152	1,402
N leaching [kg N/farm/y]	2,934	2,897	2,560	2,934	2,728	2,845	2,858	2,924	2,646	2,507
GHG mitigation [kg CO_2e/farm/y]		144	32,891	106	19,950	5,763	4,808	4,154	23,765	32,946
GHG mitigation % [% of baseline]		0.0%	10.3%	0.0%	6.3%	1.8%	1.5%	1.3%	7.4%	10.3%
NH_3 mitigation [kg N/farm/y]		-1	-154	4	97	-54	19	-41	120	-130
N leaching mitigation [kg N/farm/y]		37	374	1	207	90	76	11	289	428

The relevant cost elements and their respective values are presented in Table 15.

Table 15 Financial elements

	Unit	Value	Scenario
Urea price	EUR(2011)/t N	878	All scenarios
CAN price	EUR(2011)/t N	1,185	All scenarios
Reseeding frequency	/year	0.125	All, except 'Pasture quality'
Reseeding frequency	/year	0.13	Scenario 'Pasture quality'
Reseeding cost	EUR(2011)/ha	250	All scenarios
Clover seed amount	kg/ha	5	Scenario 'Clover'
Clover seed price	EUR(2011)/kg	8	Scenario 'Clover'
DCD application rate	kg/ha/y	10	Scenario 'Nitrification inhibitors'
DCD application rate	kg/ha/y	7	Scenario 'Nitrification inhibitors'
DCD price	EUR(2011)/kg	7	Scenario 'Nitrification inhibitors'
Concentrate price	EUR(2011)/t fresh matter	284	All scenarios
Grass silage price	EUR(2011)/t fresh matter	30	All scenarios
Milk price	EUR/kg, actual butterfat	0.34	All scenarios
Average heifer/steer (200-250kg) price	EUR/kg LW	1.90	All scenarios
Urea price	EUR(2011)/t N	878	All scenarios

4.4 Results

The results from the economic assessment are presented in Table 16 and Table 17. The GHG mitigation, mitigation cost and emission intensity results are also shown on figures 8 and 9.

Table 16 Key costs, cost-effectiveness results and emission intensities for the Irish Average National Dairy Farm by mitigation options

	Baseline	Reduced N	Clover	Pasture quality	Genetic impr.	Nitrification inhibitors	Longer grazing	Increased N	Genetic impr. + Longer gr.	Clover + Reduced N
N fertiliser costs [EUR(2011)/farm/y]	5,408	5,128	5,408	5,408	5,408	5,634	5,404	5,667	5,404	5,128
Feed costs [EUR(2011)/farm/y]	21,115	21,427	23,973	21,115	21,115	21,747	21,281	21,654	21,281	23,362
Income from milk [EUR(2011)/farm/y]	113,087	113,087	133,745	116,335	118,730	116,476	114,483	115,980	120,196	130,375
Income from meat [EUR(2011)/farm/y]	1,254	1,254	1,423	1,254	1,254	1,292	1,254	1,286	1,254	1,387
Income from crops [EUR(2011)/farm/y]	0	0	0	0	0	0	0	0	0	0
Crop net costs of mitigation [EUR(2011)/farm/y]	0	-280	176	44	0	2,690	-3	260	-3	-104
Livestock net costs of mitigation [EUR(2011)/farm/y]	0	312	-17,658	-3,248	-5,644	-2,725	-1,231	-2,327	-6,944	-14,929
Net costs of mitigation [EUR(2011)/farm/y]	0	32	-17,482	-3,204	-5,644	-36	-1,234	-2,068	-6,948	-15,033
GHG CE [EUR(2011)/t CO2e]	NA	NA	NA	-8,293	-8,613	NA	NA	NA	-2,495	NA
NH3 CE [EUR(2011)/t N]	NA	3,008	-1,847,271	-366,106	-610,478	NA	-69,062	NA	-256,723	-398,029
N leaching CE [EUR(2011)/t N]	NA	NA	-13,629	-117,274	-84,602	-532	NA	-374,656	-113,764	-11,639
GHG EI [kg CO2e/kg protein]	30.80	31.25	27.43	29.91	29.29	29.99	30.21	30.16	28.54	27.98
GHG EI change % [% of baseline]		1.5%	-10.9%	-2.9%	-4.9%	-2.6%	-1.9%	-2.1%	-7.3%	-9.2%

Table 17 Key costs, cost-effectiveness results and emission intensities for the Irish Average National Beef Farm by mitigation options

	Baseline	Reduced N	Clover	Pasture quality	Earlier finishing	Nitrification inhibitors	Longer grazing	Increased N	Earlier finishing + Longer gr.	Clover + Reduced N
N fertiliser costs [EUR(2011)/farm/y]	3,815	3,653	3,815	3,815	3,530	4,106	3,707	3,961	3,424	3,653
Feed costs [EUR(2011)/farm/y]	10,878	11,255	12,466	10,878	9,708	11,204	10,695	11,006	9,708	12,314
Income from milk [EUR(2011)/farm/y]	0	0	0	0	0	0	0	0	0	0
Income from meat [EUR(2011)/farm/y]	41,554	41,554	50,805	42,392	41,548	42,849	42,175	42,097	42,166	50,141
Income from crops [EUR(2011)/farm/y]	1,063	875	1,230	1,063	953	1,100	988	1,083	953	1,210
Crop net costs of mitigation [EUR(2011)/farm/y]	0	27	69	59	-174	3,558	-33	126	-280	-72
Livestock net costs of mitigation [EUR(2011)/farm/y]	0	377	-7,484	-837	-1,163	-931	-804	-399	-1,782	-6,990
Net costs of mitigation [EUR(2011)/farm/y]	0	404	-7,415	-778	-1,338	2,628	-836	-272	-2,062	-7,062
GHG CE [EUR(2011)/t CO2e]	NA	2,806	-225	-7,353	-67	456	-174	-66	-87	-214
NH3 CE [EUR(2011)/t N]	NA	NA	NA	-205,304	-13,739	NA	-44,484	NA	-17,151	NA
N leaching CE [EUR(2011)/t N]	NA	10,874	-19,818	-1,499,010	-6,477	29,314	-10,982	-25,380	-7,143	-16,507
GHG EI [kg CO2e/kg protein]	67.58	70.48	49.55	66.55	65.01	64.40	67.76	65.71	65.45	50.34
GHG EI change % [% of baseline]		4.3%	-26.7%	-1.5%	-3.8%	-4.7%	0.3%	-2.8%	-3.2%	-25.5%

Figure 8 GHG mitigation, mitigation cost and emission intensity effects of the mitigation options (Irish Average National Dairy Farm). Note that negative mitigation values mean increase in GHG emissions; positive cost values mean costs to the farmers.

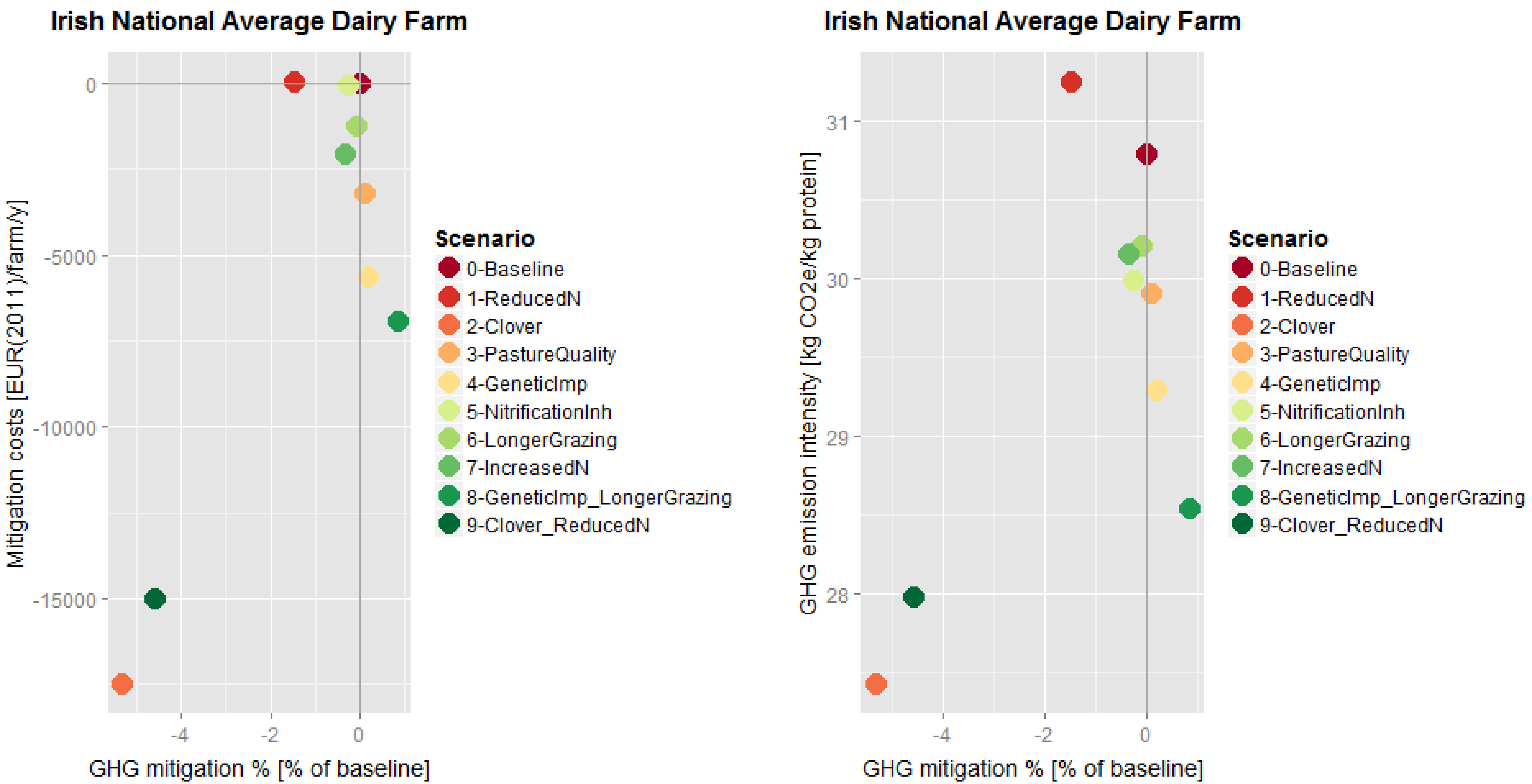
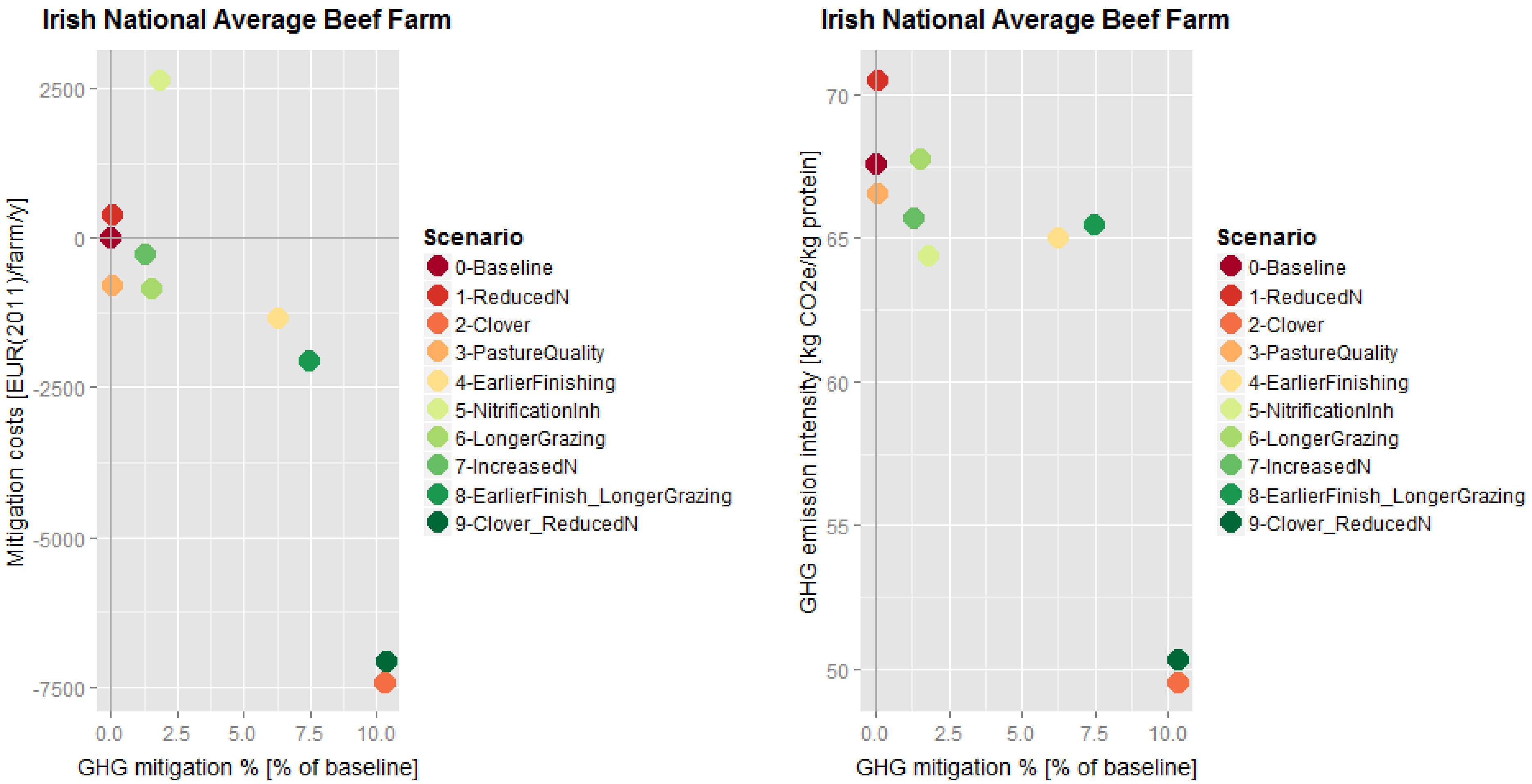


Figure 9 GHG mitigation, mitigation cost and emission intensity effects of the mitigation options (Irish Average National Beef Farm). Note that negative mitigation values mean increase in GHG emissions; positive cost values mean costs to the farmers.



As D10.3 highlighted already, these grass based farms there is not much scope for significant GHG abatement. The results presented here show that on the dairy farm all but two options actually increase GHG emissions: Improving pasture quality and Genetic improvement (also in combination with Longer grazing period) decrease emissions by 0.1-0.8%. Nevertheless, as these options, with the exception of Reducing N use, increase production more than they increase GHG emissions, the emission intensity of the farm improves in all cases, apart from the Reducing N use option. The GHG emissions are reduced by every option on the beef farm, the effects is between 0.03% and 10.3%, for Improving pastures and Clover-grass mixture, respectively. The emission intensity of the farm also improves for all options except Reduced N use and Longer grazing season, as in these cases a slight drop in crop production counter-balances the small improvement in GHG emissions.

These farm management options are usually accompanied with financial savings, according to the cost calculations, except for Reduced N use, where the loss in income results in a total loss to the farmer and Nitrification inhibitors, where the additional expense on DCD makes the option expensive on the beef farm (€2,628/ha) and just about cost neutral on the dairy farm (€32/ha). Regarding the emission intensity improvements and the financial implication, the Clover option (and the Clover and Reduced N combination) are the most promising options, though on the dairy farm they increase total emissions. The biggest (still very small) mitigation on the dairy farm and the second biggest mitigation on the beef farm can be achieved by Genetic improvement and Earlier finishing, respectively, both of them at negative costs.

4.5 Concluding remarks

The mitigation option selection by farm experts revealed that there are big differences between farms (and also amongst farmer experts) regarding which mitigation option is considered the best in terms of GHG efficacy, costs and likely uptake. These differences origin mostly from the climatic, soil, agronomic differences, differences in the financial structure of the farms and in the regional prices, but also from the different personal perceptions. Such ranking exercise can reveal big heterogeneity among farmers as well, with surprisingly low number of explanatory factors identifiable behind the ranking (Glenk *et al.* 2014). The heterogeneity in the experts' choices of mitigation measrues to be modelled on farms and in their implementation of mitigation measrues in the biophysical modelling (see Deliverables 10.4 and 10.3).

The calculator approach in the economic assessment has certain benefits compared to other methdologies, like whole farm economic modelling. This approach follows the management changes in FarmAC directly, thus providing strong consistency between the biophysical and the eocnomic results. Particularly when comparing mitigation options implemented on different farms, this approach makes it easier to understand the finanical and GHG implications of the underlying agronomic and farm management processes. Additionally, as the farm experts are heavily involved in the assessment process, the cost elements of the mitigation options can be represeneted in details. On the other hand, obtaining detailed information on local prices can prove challenging, in which case the assessment has to rely on regional or national statistical data.

This approach is capable of estimating the finanical implications of the mitigation *ceteris paribus*, *i.e.* assuming that the farm activities change only as much as to accomodate the mitigaiton option. For example, if due to a mitigation option the gross margin of a particular crop drops below a substitute crop, in reality the farmer might switch, still, this assessment assumes that the cropping structure is kept and the gross margin falls. Thus, it gives the pure technical cost of the mitigation option, without any opportunity costs. Due to these particular features, this approach does not predict potetnial structural changes happening on farms, neither does it assess potential shifts in agricultural production at the regional or national scale.

Most of the mitigation options assessed on thsee two farms were low-cost options, often providing high savings in costs (*e.g.* fertiliser costs) or increased revenues (*e.g.* increased milk production). Not surprisingly, the cost-effectiveness results are mostly negative, indicating potential 'win-win' options, if at not at the farm GHG level, but at least regarding emission intensity and the finances. The existence of win-win options have been debated though, as profit maximising theory suggests that farms should be already operating at the maximum efficiency, there is no action should exist wich provides net savings. There are various explanations why these options appear repeatedly in various assessments, and there is a need for further exploring the potential barriers or hidden costs associated with these options.

The scientific literature on agricultural GHG mitigation and the cost-effectiveness of mitigation options reveals that there is great variability in the economic assessment of agricultural mitigation, partly as a result of the biophysical, agronomic and economic differences between regions and farms, and partly due to the uncertainties and the consequent differences in modeling assumptions. Whole farm GHG modelling and accompanying economic asssessment might shed light on the practicalities on the implementation of the options on farms. It can reveal important details about potential synergies and trade-offs between on-farm GHG emission sources, while providing an improved assessment of the financial knock-on effects of implementation, *i.e.* consequences on resource requirements and production. Additionally, the specificities of farm types and farming systems are presented in a focused way with such assessments.

The whole-farm effects are often only very roughly estimated in the regional and national GHG cost-effectiveness assessments, as there is a research gap in looking at whole farm GHG mitigation. Moreover, there is very limited information available on the GHG synergies and trade-offs of mitigation options at the farm level, which is a key information in the marginal abatement cost curves. Such synergies and trade-offs have to be considered to avoid the double-counting of mitigation effects at the national scale. Future research agenda should continue focusing on whole-farm assessments, partly as a way to feed into economic modelling at a bigger spatial scale, and partly as a way to inform regional policy makers about the potetnial differnces between farm types and the most cost-effective mitigation option packages.

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Appendix 1: List of studies reviewed

Table 18 List of studies reviewed

ID	Reference	Short reference
1	Schneider, U.A. (2000) Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. Dissertation, Texas A&M University	Schneider 2000
2	Graus, W., Harmelink, M. and Hendriks, C. (2004) Marginal GHG-abatement curves for agriculture, Report No EEP03039, Ecofys, Utrecht, the Netherlands	Graus *et al.* 2004
3	Perez Dominguez, I. (2004). Greenhouse gases: Inventories, abatement costs and markets for emission permits in European agriculture - A modelling approach, EU, Rheinischen Friedrich-Wilhelms-Universitet zu Bonn	Perez Dominguez 2004
4	De Cara, S., Houze, M. and Jayet, P. A. (2005) Methane and nitrous oxide emissions from agriculture in the EU: A spatial assessment of sources and abatement costs. Environmental & Resource Economics 32 (4), 551-583	De Cara *et al.* 2005
5	DeAngelo, B. J., de la Chesnaye, F. C., Beach, R. H., Sommer, A. and Murray, B. C. (2006) Methane and nitrous oxide mitigation in agriculture. Energy Journal 27, 89-108	DeAngelo *et al.* 2006
6	Hediger, W. (2006) Modeling GHG emissions and carbon sequestration in Swiss agriculture: An integrated economic approach. International Congress Series 1293, 86-95	Hediger 2006
7	Lucas, P. L., van Vuuren, D. P., Olivier, J. G. J. and den Elzen, M. G. J. (2007) Long-term reduction potential of non-CO_2 greenhouse gases. Environmental Science & Policy 10 (2), 85-103	Lucas *et al.* 2007
8	Schneider, U. A., Mccarl, B. A. and Schmid, E. (2007) Agricultural sector analysis on greenhouse gas mitigation in US agriculture and forestry. Agricultural Systems 94, 128-140	Schneider *et al.* 2007
9	Wassmann, R. and Pathak, H. (2007) Introducing greenhouse gas mitigation as a development objective in rice-based agriculture: II. Cost-benefit assessment for different technologies, regions and scales. Agricultural Systems 94 (3), 826-840	Wassman & Pathak 2007
10	Weiske, A. and Michel, J. (2007) Greenhouse gas emissions and mitigation costs of selected mitigation measures in agricultural production, Report No MEACAP WP3 D15a, Institute for Energy and Environment (IE)	Weiske & Michel 2007
11	Amann, M., Hoglund-Isaksson, L., Winiwarter, W., Tohka, A., Wagner, F., Schopp, W., Bertok, I. and Heyes, C. (2008) Emission scenarios for non-CO_2 greenhouse gases in the EU-27 - Mitigation potentials and costs in 2020, IIASA	Amann *et al.* 2008
12	Beach, R. H., DeAngelo, B. J., Rose, S., Li, C., Salas, W. and DelGrosso, S. J. (2008) Mitigation potential and costs for global agricultural greenhouse gas emissions. Agricultural Economics 38 (2), 109-115	Beach *et al.* 2008
13	Environmental Protection Agency - Queensland Office of Climate Change (2008) An enhanced Queensland marginal abatement cost curve Queensland	Queensland EPA 2008
14	Pape, D., Moffroid, K. and Thompson, V. (2008) Analysis of the potential and costs for greenhouse gas emission reductions within the New Zealand agricultural sector, ICF International, Ministry of Agriculture and Forestry	Pape *et al.* 2008
15	Moran, D., MacLeod, M., Wall, E., Eory, V., Pajot, G., Matthews, R., McVittie, A., Barnes, A., Rees, R., Moxey, A., Williams, A. and Smith, P. (2008) UK marginal abatement cost curves for the agriculture and land use, land-use change and forestry sectors out to 2022, with qualitative analysis of options to 2050, Report No RMP4950, Committee on Climate Change, SAC	Moran *et al.* 2008
16	Neufeldt, H. and Schafer, M. (2008) Mitigation strategies for greenhouse gas emissions from agriculture using a regional economic-ecosystem model. Agriculture Ecosystems & Environment 123 (4), 305-316.	Neufeldt & Shcafer 2008

ID	Reference	Short reference
17	Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M. and Smith, J. (2008) Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B-Biological Sciences 363 (1492), 789-813	Smith *et al.* 2008
18	Bates, J., Brophy, N., Harfoot, M. and Webb, J. (2009) Agriculture: methane and nitrous oxide, Report No Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC), AEA Energy & Environment	Bates *et al.* 2009
19	Golub, A., Hertel, T., Lee, H. L., Rose, S. and Sohngen, B. (2009) The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry. Resource and Energy Economics 31 (4), 299-319	Golub *et al.* 2009
20	Naucler, T. and Enkvist, P. A. (2009) Pathways to Low Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve, McKinsey & Company	Naucler & Enkvist 2009
21	Durandeau, S., Gabrielle, B., Godard, C., Jayet, P. A. and Le Bas, C. (2010) Coupling biophysical and micro-economic models to assess the effect of mitigation measures on greenhouse gas emissions from agriculture. Climatic Change 98 (1), 51-73	Durandeau *et al.* 2010
22	Hasegawa, T. and Matsuoka, Y. (2010) Global methane and nitrous oxide emissions and reduction potentials in agriculture. Journal of Integrative Environmental Sciences 7 (sup1), 245-256	Hasegawa & Matsuoka 2010
23	Hoglund-Isaksson, L., Winiwarter, W., Wagner, F., Klimont, Z. and Amann, M. (2010) Potentials and costs for mitigation of non-CO_2 greenhouse gas emissions in the European Union until 2030. Results. Report to the European Commission, DG Climate Action Contract no. 07.030700/2009/545854/SER/C5, IIASA	Hoglund-Isaksson *et al.* 2010
24	Leip, A., Weiss, F., Wassenaar, T., Perez, I., Fellmann, T., Loudjani, P., Tubiello, F., Grandgirard, D., Monni, S. and Biala, K. (2010) Evaluation of the livestock sector's contribution to the EU greenhouse gas emissions (GGELS) - Final Report, Administrative Arrangements AGRI-2008-0245 and AGRI-2009-0296, Joint Research Centre, European Commission	Leip *et al.* 2010
25	De Cara, S. and Jayet, P. A. (2011) Marginal abatement costs of greenhouse gas emissions from European agriculture, cost effectiveness, and the EU non-ETS burden sharing agreement. Ecological Economics 70 (9), 1680-1690	De Cara & Jayet 2011
26	Vellinga, T. V., de Haan, M. H. A., Schils, R. L. M., Evers, A. and van den Pol-van Dasselaar, A. (2011) Implementation of GHG mitigation on intensive dairy farms: Farmers' preferences and variation in cost effectiveness. Livestock Science 137 (1-3), 185-195	Vellinga *et al.* 2011
27	Perez Dominguez, I., Fellmann, T., Witzke, H. P., Jansson, T., Oudendag, D., Gocht, A. and Verhoog, D. Fellmann, T. (ed) (2012) Agricultural GHG emissions in the EU: an exploratory economic assessment of mitigation policy options, Report No 25288 EN, European Commission, Joint Research Centre, Institute for Propesctive Technological Studies	Perez Dominguez *et al.*2012
28	Schulte, R. P., Crosson, P., Donnellan, T., Farrelly, N., Finnan, J., Lalor, S. T., Lanigan, G., O'Brien, D., Shalloo, L. and Thorne, F. Schulte, R. P. and Donnellan, T. (ed) (2012) A marginal abatement cost curve for Irish agriculture, Teagasc	Schulte *et al.* 2012
29	Van Amstel, A. R. (2012). Methane: Its role in climate change and options for control, global, Wageningen University	van Amstel 2012
30	Wagner, F., Amann, M., Borken-Kleefeld, J., Cofala, J., Hoglund-Isaksson, L., Purohit, P., Rafaj, P., Schopp, W. and Winiwarter, W. (2012) Sectoral marginal abatement cost curves: implications for mitigation pledges and air pollution co-benefits for Annex I countries. Sustain Sci 7 (2), 169-184	Wagner *et al.* 2012

ID	Reference	Short reference
31	Cornet, M., Duerinck, J., Laes, E., Lodewijks, P., Meynaerts, E., Pestiaux, J., Renders, N. and Vermuelen, P. (2013) Scenarios for a low carbon Belgium by 2050, CLIMACT, VITO	Cornet *et al.* 2013
32	Biggar, S., Man, D., Moffroid, K., Pape, D., Riley-Gilbert, M., Steele, R. and Thompson, V. (2013) Greenhouse gas mitigation options and costs for agricultural land and animal production within the United States, Report No Contract No. AG-3142-P-10-0214, ICF International, U.S. Department of Agriculture Climate Change Program Office Washington, DC	Biggar *et al.* 2013
33	Pellerin, S., Bamiere, L., Angers, D., Beline, F., Benoit, M., Butault, J. P., Chenu, C., Colnenne-David, C., De Cara, S., Delame, N., Dureau, M., Dupraz, P., Faverdin, P., Garcia-Launay, F., Hassouna, M., Henault, C., Jeuffroy, M. H., Klumpp, K., Metay, A., Moran, D., Recous, S., Samson, E. and Savini, I. (2013) How can French agriculture contribute to reducing greenhouse gas emissions? Abatement potential and cost of ten technical measures, INRA	Pellerin *et al.* 2013
34	Reisinger, A. and Ledgard, S. (2013) Impact of greenhouse gas metrics on the quantification of agricultural emissions and farm-scale mitigation strategies: a-áNew Zealand case study. Environmental Research Letters 8, 025019	Reisinger & Legard 2013
35	EPA (2013) Global mitigation of non-CO_2 greenhouse gases: 1990-2030, Report No EPA-430-R-13-011, United States Environmental Protection Agency, Office of Atmospheric Programs, Washington DC	EPA 2013
36	Whittle, L., Hug, B., White, S., Heyhoe, E., Harle, K., Mamun, E. and Ahammad, H. (2013) Costs and potential of agricultural emissions abatement in Australia, Report No ABARES technical report 13.2, Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Canberra	Whittle *et al.* 2013
37	Lengers, B., Britz, W. and Holm-Muller, K. (2013) Comparison of GHG-Emission Indicators for Dairy Farms with Respect to Induced Abatement Costs, Accuracy, and Feasibility. Applied Economic Perspectives and Policy 35 (3), 451-475	Lengers *et al.* 2013

Appendix 2: Long list of mitigation measures

Table 19 List of mitigation measures

Cropland management

Agronomy

Improved crop varieties
Extending the perennial phase of crop rotations
Reducing bare fallow
Adding nutrients when deficient
Adopting systems less reliant on inputs (nutrients, pesticides etc)
Catch/cover crops
Keep pH at an optimum for plant growth (*e.g.* liming)
Reduce liming
Changing from winter to spring cultivars
Agroforestry (with low tree density)
Hedges
Cultivated crops to increase soil C (*e.g.* deep-rooted or permanent plants)
Other

Nutrient management

Precision farming
Avoiding N excess (adjusting yield targets)
Use a fertiliser recommendation system
Analyse manure prior to application
Full allowance of manure N supply
Use the right form of mineral N fertiliser
Split fertilisation (baseline amount of N fertiliser but divided into smaller increments)
Reduce N fertiliser
Improved timing of manure application
Improved timing of mineral N application
Improved timing of slurry and poultry manure application
Separate slurry applications from fertiliser applications by several days
Use composts, straw-based manures in preference to slurry
Mix nitrogen rich crop residues with other residues of higher C:N ratio
Placing N precisely in soil
Trailing hose
Trailing shoe
Injection
Incorporate manure after application
Low trajectory slurry application
Increasing rate of infiltration into soil (dilution of manure, application of water after spreading)
Controlled release fertilisers
Nitrification inhibitors
Production of natural nitrification inhibitors by plants
Application of urease inhibitor
Plant varieties with improved N-use efficiency
Genetically improve the efficacy of nitrogen uptake and use by plants
Biological N fixation (legumes in rotations)
Applying organic input on cropland instead of on grassland
Improved maintenance of fertiliser spreaders
Modify soil microbial communities to reduce N_2O into N2 (*e.g.* incorporation of Rhizobia strains)
Do not apply fertiliser at high-risk areas
Fertiliser free zone on field edges
Optimisation of fertiliser distribution geometry
Water buffer strips
Other

Structural and management changes

Tightening the N cycles (regionally optimised plant and animal production)
Relocate high N-input cropping to drier, cooler areas
Less monoculture
Other

Soil and water management

Reduced tillage
No-till
Retain crop residues
Plough in early spring, spread crop residues evenly and control compaction
Avoid burning of residues
Burying biochar
Improved irrigation
Land drainage
Loosen compacted soils / Prevent soil compaction
Prevent soil erosion
Other

Rice management

Aeration of rice-growing soil (*e.g.* reduce the depth of paddy fields, empty them several times per year)
Shallow flooding of rice
Mid-season drainage of rice
Off-season rice straw
Alternate flooding of rice
Rice straw compost
Application of phosphogypsum to rice
Direct wet seeding of rice
Replace urea with AN for rice
Sulphate amendments for rice
Changing fertiliser type for rice (in general)
Other uses of rice straw
Low methane rice cultivars
Continuous flooding of rice
Other

Orchards

Convert to trellis system
Other

Grazing land management
Grazing intensity and timing
Reduce N on the most intensive permanent and temporary grasslands
Increase stocking density on medium productivity grassland
Intensive grazing (cattle are frequently rotated between pastures)
Extended grazing season
Take stock off from wet ground
Reduce stocking density
Other
Increased productivity
In general
Fertilisation
Pasture renovation
Avoid fertiliser applications prior to pasture renovation
Biological N fixation (grass-legume mixtures)
Species introduction (including legumes)
New forage plant varieties for improved nutritional characteristics
New forage plant varieties to buffer grass growth
Increasing digestibility (forage quality)
Higher sugar content grasses
Increase the lifespan of temporary grassland
Improved irrigation
Other
Fire management
Fire management
Management of organic soils
Avoid drainage of wetlands / conversion of peatlands
Avoiding row crops and tubers
Avoiding deep ploughing
Maintaining a shallower water table - peat
Maintaining a shallower water table - arable
Other
Restoration of degraded lands
In general
Erosion control
Revegetation
Nutrient amendments
Organic amendments (manures, biosolids, composts, etc.)
Reducing tillage
Retaining crop-residues
Conserving water
Other
Livestock management
Feeding practices
Feeding more concentrates (replacing forages)
High starch diet
Balance diet for energy and protein (*e.g.* reducing protein, increasing carbohydrates)
Reduce protein intake (without AA supplementation)
Reduce protein intake and provide AA supplementation
Target specific livestock nutrient requirements
High fat diet (dietary lipids)
Estimating potential CH_4 production from feeds
Mechanical treatment of feed
Chemical treatment of low quality feed
Feeding total mixed ration
Precision feeding (+ feed analysis)
Multiphase feeding
Improved feed conversion (increasing energy content and digestibility)
Continuing conventional dietary improvement
Increase body fat at slaughter
Food industry co-products as feed
Improved feed intake
Bovine somatotropin
Increased milking frequency
Other
Specific agents and dietary additives
In general
Higher salt content of the diet
Plant extracts
Essential oils
Tannins
Saponins
Ionophores (*e.g.* monensin)
Antibiotics
Propionate precursors
Nitrate
Nitrification inhibitors fed directly
Hexose partitioning
Directly fed probiotic microbes (*e.g.* yeast products)
Manipulation of rumen archaea and bacteria
Directly fed microbes (acetogens, CH_4 oxidisers)
Antimethanogens
Genetic modification of rumen microflora
Vaccination against methanogens
Halogenated methane analogues
Defaunating agents
Naturally occurring plant compounds (new species/GM)
Chicory
Allicin
Glycerol
Other
Animal health
Better health planning
Improve hygiene & supervision at lambing
Improve ewe nutrition in late gestation to increase lamb survival
Anti-parasitics
Other
Structural and management changes
Reduction in the number of replacement heifers / Improved fertility management
Multi use of cows (milk, calves and meat)
More feed production on farm scale or local level
Organic farming
Winter management of cattle (collected and re-utilised excreta)
Increase of grazing in comparison to housing
Increase of housing in comparison to grazing
Reduce stocking rates
Skipping the stocker phase
Other

Breeding, genetics, herd structure
Improved genetic potential in general
Selecton for reduced methane emissions
Selection for non-productive traits (*e.g.* longevity, fertility)
Improved genetic potential - productivity
Use semen of high economic breeding value
Cloning
GM livestock
Artificial insemination
Using sexed semen
Twinning
Transgenic manipulation
Use cows with lower yield but which can produce beef calves
Develop mixed breeds or industrial cross-breeding
Switching breeds
Other

Housing and manure

Housing
New low-emission livestock and poultry housing systems
Filtration of animal house emissions
Decreasing of air velocity above manure
Cooling the manure covered surfaces
Cages and aviaries instead of floor systems for layer hens
Keeping surfaces, manure and animals dry
Partly or fully slatted floors
Deep litter systems
Switch between solid manure and slurry systems
Other

Manure storage and handling
Cooling of manure storage
Frequent manure removal to outside (cooler) storage
Covering manure heaps
Lowering the filling level of slurry storage
Covering slurry stores
Semi-permeable
Impermeable
Allowing the build-up of natural crust on cattle slurry
Separating solids from slurry
Composting solid manure (also after slurry separation)
Switch from anaerobic to aerobic facilities
Minimising of stirring slurry
Manure acidification
Reducing the surface per unit volume of slurry or FYM (e.g tanks instead of lagoons)
Increasing the carbon content of the manure (adding straw)
Compaction of FYM
Comminution of FYM
Increased frequency of slurry spreading
Drying of manure (esp. poultry)
Incinerate poultry litter
Other

Anaerobic digestion and CH_4 *capture*
AD
Centralised AD
On-farm AD
Methane capture and combustion
Other

Land use change
Shelter belts/riparian zones/buffer strips
Arable to grassland
Arable to woodland
Arable to set-aside
Grassland to woodland
Drained croplands - wetlands
Afforestation
Permanent revegetation of set-aside
Restoration of peatlands
Avoid conversion of woodlands
Biomass crops
Sylvopastoral systems
Other

Energy and waste

Transport
Increased fuel efficiency
Other transport

Heating and electricity
Increased heating efficiency (livestock houses and greenhouses)
Move heated greenhouses to areas where the can utilise waste heat
Improved crop-drying
Efficient cooling of milk
Efficient ventilation and cooling
Efficient lighting
Other

Waste
Reduce waste during transport, processing and storage
Other

Electricity generation
Use of renewable electricity
Biomass combustion
Solar energy
Wind power
Solar water heating
Small-scale hydro-electric power
Ground-source or air-source heat pumps
Other

Other energy and waste
Other energy and waste

Appendix 3: Overview of the studies

Table 20 Overview of the studies' characteristics

ID	Scope	Resolution	Emission boundaries[a]	Interactions[b]	Methodology[c]	CE available?[d]
1	US	Sub-national region	On-farm	Not specified	2	No
2	Global	World region	On-farm	Yes	3	Yes
3	EU-15	Sub-national region	On-farm	No	1	No
4	EU-15	Sub-national region	On-farm	No	1	No
5	Global	World region	On-farm	Measure allocation	3	No
6	Switzerland	Sub-national region	On-farm	Not specified	1	No
7	Global	World region	On-farm + some LCA elements	No	3	No
8	US	Sub-national region	On-farm	No	2	No
9	Philippines, China, India	Sub-national region	On-farm	Not specified	3	No
10	NW Germany	Farm	On-farm	Not specified	3	Yes
11	EU-27	Country	On-farm	Measure allocation	3	Yes
12	Global	Global	On-farm	Measure allocation	3	No
13	Queensland (Australia)	Sub-national region	On-farm	Yes	2	No
14	New Zealand	Country	On-farm	Not specified	3	Yes
15	UK	Country	On-farm	Yes	3	Yes
16	Germany	Sub-national region	On-farm	Yes	1	No
17	Global	World region	On-farm	Not specified	3	No
18	EU-27	World region	On-farm	Not specified	3	Yes
19	Global	World region	On-farm	No	2	No
20	Global	Global	On-farm	Not specified	3	No
21	France	Sub-national region	On-farm	Yes	1	No
22	Global	World region	On-farm	Yes	3	Yes
23	Kyoto Annex I countries	Country	On-farm + some LCA elements	Yes	3	Yes
24	EU-27	Sub-national region	LCA	Yes	1	No
25	EU-24	Sub-national region	On-farm	No	1	No
26	the Netherlands	Farm	On-farm	No	3	Yes
27	EU-27	Sub-national region	On-farm	Yes	1	No
28	Ireland	Country	LCA	Yes	3	Yes
29	Global	Global	On-farm	Yes	2	No

ID	Scope	Resolution	Emission boundaries[a]	Interactions[b]	Methodology[c]	CE available?[d]
30	Kyoto Annex I countries	Country	On-farm + some LCA elements	Measure allocation	3	No
31	Belgium	Country	On-farm	Not specified	3	No
32	US	Farm	On-farm	Not specified	3	Yes
33	France	Country	On-farm + some LCA elements	Yes	3	Yes
34	New Zealand	Farm	LCA	Not specified	3	No
35	Global	Country	On-farm	Measure allocation	3	No
36	Australia	Farm	On-farm	Measure allocation	3	No
37	Germany	Farm	On-farm	Yes	3	No

[a] *'On-farm': emissions within the farm gate are considered, On-farm + other: some off-farm emissions are considered, 'LCA': off-farm emissions (usually pre-farm or up to the retailers) are considered*

[b] *'Yes': interactions between mitigation measures are taken into account, 'Measure allocation': mitigation measures are allocated so that simultaneous implementation of measures do not happen, 'No': interactions are not taken into account, 'Not specified': the study does not specify whether interactions are considered*

[c] *1: micro-economic modelling,2: equilibrium models, 3: bottom-up cost-engineering*

[d] *Whether cost-effectiveness estimates for individual mitigation measures are presented or not*

Appendix 4: Marginal abatement cost curves for beef production in the Brazilian *Cerrado*

Developing a Nationally Appropriate Mitigation Measure from the greenhouse gas GHG abatement potential from livestock production in the Brazilian *Cerrado*

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Abstract
Brazil is one of the first major developing countries to commit to a national greenhouse gas (GHG) emissions target that requires a reduction of between 36.1% and 38.9% relative to baseline emissions by 2020. The country intends to submit agricultural emissions reductions as part of this target, with livestock production identified as offering significant abatement potential. Focusing on the *Cerrado* core (central Brazilian savannah), this paper investigates the cost-effectiveness of this potential, which involves some consideration of both the private and social costs and benefits (*e.g.* including avoided deforestation) arising from specific mitigation measures that may form part of Brazil's definition of Nationally Appropriate Mitigation Measures (NAMAs). The analysis was made using the EAGGLE optimization model (Economic Analysis of Greenhouse Gases for Livestock Emissions), which helps to define abatement costs. A baseline projection suggests that, the region will emit 2.6 Gt from 2010 to 2030, the equivalent of 9% of the country´s total net emissions. By implementing negative-cost measures identified in a marginal abatement cost curve (MACC), by 2030, regional emissions could be reduced by around 24%. Pasture restoration, involving avoided deforestation, offers the largest contribution to these results. As the Brazilian *Cerrado* is seen as model for transforming other global savannahs, the results offer a significant contribution by identifying alternatives for increasing productivity whilst minimizing national and global external costs.

Keywords: climate change; marginal abatement cost curves; mitigation measures; sustainable intensification; grassland restoration; linear programming.

Highlights

- Around 66% of emissions in the region are due to enteric fermentation in livestock.
- 24% of emissions can be reduced by adopting negative-cost (cost-saving) measures.
- Pasture restoration has the biggest abatement potential (27.8 Mt $CO_2e.yr^{-1}$).

4. Introduction

Global demand for livestock products is projected to grow by 70 per cent by 2050 (Gerber *et al*., 2013). This is expected to generate significant additional pressure on producers and on natural resources. Sustainable management (or intensification) will require increasing yields and efficiency in existing ruminant production systems, minimizing competition of land used for food and feed, while maximizing ecosystem services, including mitigation of greenhouse gas (GHG) emissions (Gerber *et al*., 2013; Soussana *et al*., 2013; Thornton and Herrero, 2010).

Tropical regions are implicated as potentially offering major opportunities to increase beef productivity and emissions mitigation, as current productivity levels are still relatively low and emission intensities correspondingly high (Opio *et al*., 2013; Henderson and & Steinfeld, 2013).

More productive pastures can increase soil carbon stocks, providing one of the largest terrestrial carbon sinks (Follett and Reed, 2010; Neely *et al*., 2009), in a pool that is a more stable form than the aerial components of forests (Soussana *et al*., 2010). But potential carbon sequestration in soils under grasslands far from offset the loss of above ground vegetation in the majority of tropical areas, and therefore natural vegetation should be preserved.

Brazil is the world's second largest beef producer – 9.3 $Mt.yr^{-1}$ (14.7 % of the world's total), and the largest exporter in 2012-13 (FAO, 2014). Production is predominantly pasture-based in a grassland area of approximately 170 M ha (IBGE, 2014), mostly in a humid or sub-humid tropical climate.

But beef production can entail significant trade-offs, that must be managed to minimize external costs. These include the controlled expansion of agricultural area, associated deforestation, cost-effective greenhouse gas mitigation, and land competition between food and biofuels.

Analysis of historical data (Martha *et al*., 2012) and scenario studies conducted by the World Bank (Gouvello *et al*., 2010) suggests that improving beef productivity has the highest potential to buffer the expansion of other agricultural activities, avoiding further deforestation. Increasing pasture productivity can also boost soil carbon sequestration, particularly when carried out in currently degraded grasslands (Bras *et al*., 2013; Ruviaro *et al*., 2014). In addition, increasing productivity through feed supplementation may significantly reduce direct methane emissions (Berndt and Tomkins, 2013; Ruviaro *et al*., 2014).

In this context and based on its previous National Plan on Climate Change, at the Conference of the Parties 15 (COP 15), Brazil has proposed Nationally Appropriate Mitigation Actions (NAMAs) as part of its commitment to the United Nations Framework Convention on Climate Change (http://www.mmechanisms.org/e/namainfo/index.html). Over the period 2010-2020, the NAMAs establish targets for the reduction of Amazon deforestation by 80% and by 40% in the *Cerrado* (Brazilian Savannah), through the adoption of pasture recovery (15 million ha), and from integrated crop-livestock-forestry systems (4 million ha). With these cattle-related measures, Brazil expects to reduce net emissions by between 101 and 126 Mt CO_2-e, by2020, which account for 61% -73% of all mitigation in agricultural practices by the NAMA route. The NAMA proposal is enacted as part of the ambitious ABC (Agricultura de Baixo Carbono - Low Carbon Agriculture) program, which offers low interest credit lines to farmers adopting mitigation technologies (Mozzer, 2011). This paper investigates the cost-effectiveness of these livestock mitigation measures applicable in the *Cerrado* core (Central Brazilian Savannah); a region that contains around 35% of the Brazilian herd (Anualpec, 2010).The region is considered as central in Brazil's ascendance in global production (The Economist, 2010; The New York Times, 2007) and is still regarded as the most important region for expanding beef production in Brazil (Ferraz and Felício, 2010). It is seen as a potential model for transforming other savannahs (Morris *et al*., 2012; The World Bank, 2009).

The analytical focus is significant because there is currently little research clearly demonstrating that mitigation through livestock management can be delivered at relatively low cost. The paper offers the first bottom-up cost-effectiveness analysis using an optimization model for Brazilian beef production. The measures evaluated are pasture restoration, feedlot finishing, supplement concentrates and protein and nitrification inhibitors. The analysis uses the outputs of a multi-period Linear Programming model (the Economic Analysis of Greenhouse Gases for Livestock Emissions model-EAGGLE; Oliveira Silva, 2013), to develop a bottom-up or engineering marginal abatement cost curve (MACC), to represent the relative cost-effectiveness of measures and their cumulative abatement potential above a baseline of business as usual (Moran *et al*., 2010). The analysis examines the direct emissions of measures enacted within the notional farm gate rather than wider life cycle impacts, and accounts for both the private and social costs and benefits (e.g. including avoided deforestation).

The paper offers new insights for regional policy and is structured as follows. Section two outlines the modelling structure and relevant optimization assumptions underlying the cost-effectiveness analysis. Section three describes the MACC calculation, while section four sets out results. Sections five and six offer a discussion and conclusions.

5. Modelling methods for mitigation cost-effectiveness

2.7 Model Overview

Abatement potential and cost-effectiveness of measures were derived using the EAGGLE model; a Multi-Period Linear Programming model that simulates a whole cycle (cow-calf, stocking and finishing) beef production farm, accounting for: (i) herd dynamics, (ii) financial resources, (iii) feed budgeting, (iv) Land use: pasture recovery dynamics and crops, and (v) Soil carbon stock dynamics.

The model optimizes the use of the farm resources (capital, cattle, land) while meeting demand projections and maximizing profit. In this context EAGGLE is used to simulate beef production treating the *Cerrado* region as a single farm. The farm activities (i-iii) are modelled using monthly time steps, while (iv&v) are modelled using annual time steps. EAGGLE represents animals in age cohorts k; a steer of age cohort $k=1$, is a calf aged 6 months, and 189 kg of live weight (LW). After 3 months in the system, age cohort k is transferred to age cohort $k+1$, now with 222 kg of LW. The final weight is 454kg, corresponding to $k=9$ (33 months), when the animal is sold and removed from the system.

The same cohorts apply to heifers, although these can also accommodate breeding rates, where a heifer generates 1 calf per 18 month cycle, comprising 9 months of pregnancy, 6 months of lactation (Millen *et al*., 2011), plus 3 months of non-lactation and non-pregnancy. Half of the calves born are allocated to steers and the other half are allocated to heifers, both of age cohort $k=1$. After 4 cycles, the cows are removed from the system and slaughtered, *i.e*., used to meet demand.

EAGGLE also simulates feedlot finishing, and thus allows the reduction of the finishing time. The model can remove steers from exclusive grazing, inserting the animals into feedlot systems; generally only males are confined in Brazil (Millen *et al*., 2009; Costa Junior *et al*., 2013). For all cattle categories, *i.e*., male, female, male in feedlot and breeding females, the corresponding age cohort is associated with specific parameters: weight, death rate, dry matter (DM) intake, selling and purchase prices, emissions factors for CH_4 from enteric fermentation and emissions factors for N_2O from excreta. The associated coefficient values are detailed in Table S1 and Table S2.

The gross margin of the *Cerrado* single region farm is maximized and calculated as the difference between the income and expenses. Income derives exclusively from the sale of finished cattle, 454kg of LW for steers and 372 of LW for heifers. Farm expenses are composed of investment and maintenance costs. Maintenance costs are (i) farm maintenance and (ii) animal non-feed maintenance. Costs for (i) include working animals, machinery and equipment, veterinary equipment telephone device, fuel, taxes and fees, totalling US$ 25.00 $ha^{-1}.yr^{-1}$ (See Table S8 details). Costs for (ii) were calculated for each age cohort and it is composed of cost of mineral salt and expenses with health (vaccines), and animal identification (Table S1).

2.8 Land use dynamics

The model simulates land use dynamics by allocating the total area across pastures or crops; the latter being used for grain and silage production to be used for the formulation of ration for feedlot and supplementation for grazing cattle. EAGGLE allocates land into pasture, soybeans and corn. In the case of pasture, the model allocates land into different productivity levels. Pasture degradation and restoration rates are key model processes that have a bearing on overall system productivity and hence emissions intensity of production.

2.8.1 Grassland degradation

Pasture degradation can be defined as the loss of vigour and productivity of forage. To represent the degradation process, EAGGLE defines six levels of Dry Matter Productivity (DMP) levels categories (Table 2): *A*, *B*, *C*, *D*, and *F*, where level *A* is pasture of highest productivity, and level *F* is fully degraded. If no action is taken to maintain or improve productivity of a fraction of the area in a given category, it is relocated to a lower productivity category. So, after a period of time (assumed as two years herein) category *A* degrades to category *B*, *B* degrades to *C*, and so on, until pasture *F*, thus completing a 10-year full degradation (with no management interventions).
The DMP of the pastures levels were calculated exogenously using a model that estimates seasonal pasture growth according to soil, species and climate conditions (Tonato *et al*., 2010).

2.8.2 Land use change and pasture restoration

To offset the degradation process the model can allow for grassland restoration through improved forage quality by direct restoration (by chemical and mechanical treatment) or indirect restoration (by rotating with crops). For example, in a given year a pasture *A* will degrade to *B*, the optimal solution might be letting half of pasture A to degrade, and half be maintained to level *A*. Furthermore, EAGGLE works simultaneously with a composition of pasture DMP levels; *e.g*., in a given year *t*, the composition can be 4% of *A*, 10 % of *B*, 85% of *C*, and 1% of soybeans. Then, at year *t+1*, the composition can change by any combination among the pasture DMP levels and crops.
For each type of land use change or restoration, there is an associated cost (Table 1). Costs were calculated accounting for the amount of inputs (*e.g.*, nitrogen, limestone, micronutrients, forage seeds, and machinery) needed to maintain or increase the DMP level in the target pasture production category. For details of applied inputs, see Table S3-S7.

Table 1: Costs of land use change, pasture maintenance and restoration. The table can be read as “the cost from land use *X* to land use *Y*”, where *X* and *Y* can be any pasture DMP level or crops.

Cost of land use change/pasture restoration Cost[1] (US \$ 2012.ha^{-1})										
		To land use								
		A	B	C	D	E	F	Corn (Silage)	Corn (Grain)	Soybeans
From land use	A	112.4	0.0	0.0	0.0	0.0	0.0	1352.6	600.0	345.4
	B	149.9	72.7	0.0	0.0	0.0	0.0	1502.5	749.9	495.3
	C	399.3	249.4	15.0	0.0	0.0	0.0	1751.9	999.3	744.7
	D	630.0	480.0	230.7	9.4	0.0	0.0	1982.6	1229.9	975.3
	E	724.6	574.6	325.2	94.6	5.6	0.0	2077.2	1324.5	1069.9
	F	767.0	617.1	367.7	137.1	42.5	5.6	2119.6	1367.0	1112.4
	Corn (Silage)	269.8	200.9	125.1	125.1	125.1	125.1	1630.7	1060.6	971.8
	Corn (Grain)	269.8	200.9	125.1	125.1	125.1	125.1	1736.4	981.9	992.6
	Soybean	269.8	200.9	125.1	125.1	125.1	125.1	1736.4	981.9	1017.7

[1]See Appendix S1 for calculation details.

Land use change (including deforestation), degrading or restoring pasture will affect the soil carbon (C) stocks. These changes are calculated by EAGGLE: the model estimating the annual C stock under pasture and crops for each land use. The total accumulated C under soils is given by the sum of the C stock of each pasture DMP levels, soya and corn.

2.9 Carbon sequestration through pasture management

Depending on the DMP, the C flux may change significantly. The EAGGLE model works with equilibrium values of the C stock for each type of pasture and crops. The higher the pasture productivity, the higher the C equilibrium value (Table 2). The equilibrium values were calculated exogenously, using simulations from the CENTURY model (Parton *et al.*, 1987) applied to *Cerrado* biophysical characteristics and using the annual DMP calculated for each pasture category.

Table 2: Annual dry matter productivity and equilibrium C stock values.

Pasture/Crops	DM[1] ($t.ha^{-1}.yr^{-1}$)	Carbon stock equilibrium[2] ($t.ha^{-1}$)
A	19.6	84.3
B	17.6	82.7
C	12.6	62.3
D	8.7	45.2
E	5.8	32.4
F	3.9	26.1
Corn (Silage)	3.8	45.0
Corn(Grain)	9.0	40.0
Soybean	2.5	45.0

[1] Estimated using the models published by Tonato *et al.* (2010)
[2] According to Parton (1987)

EAGGLE accounts for the annual carbon stocks per each land use in column 1, Table 2. The model transfers the accumulated carbon from year *t-1* to year *t* and calculates the variation of soil C in year *t*.
Letting $C_{t,lu}$ be the soil carbon stock (tons) under the land use *lu*, where $lu \in \{A, B, C, D, E, F, Soybeans, Corn(silage), Corn(grain)\}$. Then $C_{t,lu}$ can be expressed by:

$$C_{t,lu} = \varphi(t,lu) + \Delta C_{t,lu} \quad \text{(Eq. 1)}$$

And

$$\Delta C_{t,lu} = f(\varepsilon_{lu}, C_{t-1,lu}) \quad \text{(Eq. 2)}$$

Eq. (1) is composed of the carbon transference term, $\varphi(t,lu)$, and the C sequestration term, $\Delta C_{t,lu}$. The term φ(t,lu) accounts the transference of C from other uses to land use *lu* in year *t*; *e.g.*, if *lu* is equal pasture *B*, and one hectare of soybeans is converted in year *t* into one hectare of pasture level *B*, the carbon previously stocked under soybeans has to be transferred to pasture *B*. Similarly, if some hectares are converted from pasture *B* to pasture *A*, or degraded to *C*, then part of the C stock from *B* has to be proportionally transferred from *B* to these other uses. The sequestration term, $\Delta C_{t,lu}$ is written as a function of the distance between the previous C stock $C_{t-1,lu}$, and the C stock equilibrium value, ε_{lu}. Hence the further the previous stock is from the equilibrium value, the more C will be up taken. Conversely, if due to the land use change, or degradation, the C stock becomes greater than the equilibrium value, there will be negative C sequestration, *i.e.,* a loss of C stock. These modelling approaches follow the concepts suggested by Eggleston *et al*. (2006) and Vuichard *et al*. (2007). The extended version of Eq. (1) and (2) are presented in Oliveira Silva (2013).

2.10 Deforestation due to cattle ranching

For pasture area we use the projections published by (Gouvello *et al.*, 2010) combined with an endogenous deforestation term. Let LU_t be the total area at year *t*; a_t the Gouvello *et al.* (2010) projections; and D_t the endogenous term that represents further area expansion. Then for every year:

$$LU_t = a_t + D_t \quad \text{(Eq. 3)}$$

The deforested area will cause a loss of carbon stocks in natural vegetation and influence soil C; and directly influences the transference term in eq. (1), *i.e.*, loss of soil organic matter (SOM). Both vegetation carbon stocks and SOM are accounted by EAGGLE to represent the emissions associated with deforestation.
There is limited quantitative research on the dynamics of pasture productivity following deforestation. In accordance with the best available information, the model allocates new converted areas into the system in pasture category *C*(the highest without nitrogen fertilization), as soil carbon also can increase or decrease values after deforestation (Maia *et al.,* 2009) and pasture productivity is relatively high after conversion due to higher soil organic matter mineralization (Martha Jr, 2007).In this analysis, we assumed the cost of opening new areas is zero because the cost of conversion the *Cerrado* into pastures can be offset by timber sales and land value appreciation(Bowman, 2013).
Another assumption is that the model cannot discard land endogenously, neither does it allow fallow in any year of the planning period. This assumption is based on the fact that cattle ranchers are not allowed to let their properties be unproductive; otherwise the land can be confiscated by the government for Agrarian Reform (Federal Law 8.629 - www.planalto.gov.br/ccivil_03/leis/l8629.htm).

2.11 Baseline construction

Land use change scenarios need to be mapped onto a plausible baseline for land use activity. The baseline scenario is based on national forecasts of beef demand and grassland area for Brazil, from 2006 to 2030 (Gouvello *et al.*, 2010). The assumption is that the attributable *Cerrado* pasture area and beef demand share are a fixed proportion of the national projections. In 2006, the *Cerrado* pasture area represented 34% of the national total(IBGE, 2014).The model then assumes that *Cerrado* pasture area corresponds to 34% of Brazil's pasture area, and this proportion is constant during the studied period (2006-2030). Similarly, as there is no data for regional demand, we assumed demand to be proportional to area, *i.e*., demand for *Cerrado* is also equivalent to 34% of national demand, this percentage is very close to the 35% figure estimated by Anualpec (2010).

In the model, increased productivity occurs by means of investments in technologies, *e.g*., pasture restoration, supplementation and feedlot animals. The baseline scenario has limited adoption of these measures, implying constant productivity. We assumed that pasture restoration is allowed in the baseline only to avoid degradation, but it is constrained to maintain productivity at 2006 levels (10 t-DM.ha^{-1}.yr^{-1}) (Appendix S2). Combining this constraint with projected increased demand pushes the model to open new areas if it is necessary to meet the growing demand for beef.
The current adoption rate of feedlot finishing in Brazil is around 10% of the total herd (Anualpec, 2010). We assumed this proportion to be constant in the baseline, a rate that is in counterpoint to a higher level of penetration of this measure in a mitigation counterfactual.

2.12 GHG emissions sources

The EAGGLE model calculates GHG emissions using emissions factors for activities within the farm gate. GHG emissions associated with the farm activities are: (a) CH_4 from cattle enteric fermentation (CH_4 from excreta is not accounted); (b) N_2O from cattle excreta; (c) N_2O direct emissions from N fertilization; (d) CO_2 from deforestation; and (e) CO_2 from pasture degradation and land use change from pasture to crops.

Items (a) and (b) depend on herd composition: each age cohort of males and females (heifer or cow) has an associated emission factor of CH_4 and N_2O calculated using Tier 2 methodology (Eggleston *et al*., 2006), see Table S1 and Table S2. Due to the lack of studies in Brazilian conditions, for (c), we used the Tier 1 IPCC default factor of 1% (Eggleston *et al*., 2006). The emissions from (d) are calculated using coefficient of loss of natural vegetation per deforested area. The average carbon loss of natural vegetation due to deforestation was estimated as 34.6 tons of C per hectare, in accordance to Eggleston *et al*. (2006) and Bustamante *et al.* (2012). For (e), the emissions are calculated according to Eq. (1) and (2).

2.13 Mitigation Measures

The selection of GHG mitigation measures was based on literature review and expert opinion regarding the relevance and applicability of the technologies to Brazilian livestock production and conditions. The measures evaluated are: concentrate supplementation, protein supplementation, pasture restoration, nitrification inhibitors and feedlot finishing. Although the latter is already in the baseline, we investigated a higher adoption rate of this technology.
Modelling assumptions for these measures related to the effects the measures have upon the gross margin and emissions are detailed in Table 3.

Table 3: Selected livestock mitigation measures

Mitigation measure	Description	Cost[1]	Unit	Reduces emissions by:	Adoption rate target
Feedlot finishing	When cattle weight is around 80% of the slaughter weight it is removed from pasture and grass to feedlot on a diet with ration of balanced protein and energy content	9.12	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	15% of the total finished animals
Nitrification inhibitors	Application of Agrotain Plus® together with urea used as fertilizer; 3g per Kg of applied nitrogen[2]	61.44	$\$.t^{-1}$	Reduced conversion of nitrogen to the GHG nitrous oxide (nitrification)	Optimized
Pasture restoration	Improving pasture forage productivity by soil chemical and mechanical treatment. As described in Section 2.1	Table 1	$\$.ha^{-1}$	Avoiding the need for additional pasture land and increasing organic carbon sequestration	Optimized
Supplementation concentrate	Feeding cattle via grazing and a ration with a high energy content. Grazing steers with 421 kg of LW can be selected for concentrate supplementation. The supplementation takes 2 months and the final weight is 490 kg	3.07	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	Optimized
Supplementation protein	Feeding cattle via grazing and a ration with a high protein content. Calves (189 kg) can be selected (only in March) to be supplemented with protein. The steers are finished after 15 months, with 481 kg	1.15	$\$.head^{-1}.mth^{-1}$	Shorter animal life cycle by increasing weight gain	Optimized

[1]Supplementations non-feed cost, for feed costs (ration formulation, see Table 4)

[2]Cost and Application ratio suggested manufacturer (http://www.agrotain.com/us/home).

2.13.1 Concentrate and protein supplementation

Both measures involve supplementing the feed of grazing steers; *e.g.*, feed is composed of forage and supplements. It is expected that these measures reduce emissions since animals gain weight faster and take less time to be finished.

Table 4: Rations (supplements) formulation and costs.

Crop	Ration Formulation (%)[1]			Cost[2] (US$.kg^{-1})
	Feedlot	Concentrate	Protein	
Corn (grain)	83	80	15	PBF
Corn (Silage)	11	0	0	PBF
Soybeans	5	17	39	PBF
Urea	0	2	12	1.19
Mineral Salt	1	1	19	0.84
NaCl	0	0	15	1.19

[1]Rations were formulated by using the software Invernada (minimum cost ration formulator) (Barioni, 2011)

[2]PBF = Produced By the Farm, *i.e*., the crops produced by EAGGLE (according to the dynamics in section 2.2.2) are stored and used to formulate the rations.

Biological coefficients, *e.g*., mortality rate, weight, DM intake, and emissions factor for steers fed with supplementations can be found in Table S2.

2.13.2 Pasture restoration

This measure works in the model by avoiding deforestation and because restoration boosts carbon soil uptake. Details of the modelling and Costs are explained in section 2.2.2. In contrast to the baseline scenario, to evaluate this measure, the fixed DMP baseline constraint was removed.

2.13.3 Nitrification Inhibitors

The measure works by avoiding a proportion of the Nin fertilizer or manure being converted into N_2O, *i.e.* nitrification and denitrification35 process (Abbasi and Adams, 2000). To date there have been no studies detailing the reduction in N_2O emissions for Brazilian pastures when nitrogen inhibitors are applied. A 50% reduction of direct N_2O emissions is assumed in this paper -as found by Giltrap *et al.* (2011) for a New Zealand study. We assumed that this measure is applicable only over the N used for pasture and crops fertilization. The reason is that most of the Brazilian herd is based on a grazing systemwhere it is unfeasible to apply inhibitors to animal excreta.

2.13.4 Feedlot finishing

Like supplementation, this measure works by reducing the cattle finishing time since feedlot animals are fed only by ration (with the formulation descried in Table 4). Only steers can be selected to model in the feedlot system. The adoption rate was arbitrarily assumed to be 15% of the total finished herd, since in the baseline the adoption rate is 10% of the total finished herd, the measure can be stated as: increasing by 50% over the baseline adoption rate.

2.14 Marginal abatement cost curve

A MACC can be used to represent the relative cost-effectiveness of different abatement options and the total amount of GHG that can be abated by applying mitigation measures over and above a baseline scenario. The aim is to identify the most economically efficient manner to achieve emissions reduction targets, where the cheapest units of greenhouse gas should be abated first (Moran *et al*., 2010).
MACC analysis can be derived by means of a top-down analysis – which usually makes use of a general equilibrium model and emissions are calculated endogenously, or by a bottom-up or engineering analysis (MacLeod *et al*., 2010). This paper take a bottom-up approach, where the individual abatement potential of measures and their costs are individually modelled using the EAGGLE detailed equations.
The MACC can be presented in form of a histogram, where the C abatement potential lies on the x-axis, and the cost per tons of abatement in the y-axis. The abatement potential of a measure *m* (AP_m) is calculated as the annual average of the difference between the business-as-usual (baseline) total GHG emissions (E_{BAU}) and the total emissions under the mitigation measure scenario (E_m) during the production period *T*:

$$AP_m = \frac{E_{BAU} - E_m}{T} \qquad \text{(Eq.4)}$$

The cost-effectiveness of measure *m* (CE_m), therefore, is calculated by:

$$CE_m = \frac{GM_{BAU} - G_m}{AP_m} \qquad \text{(Eq. 5)}$$

Where GM_{BAU} and GM_m are, respectively, the gross margin in the baseline scenario and the gross margin in the scenario with the measure *m* implemented.

As observed in Eq.4 and Eq.5, AP_m and CE_m are average values across the planning period.

6. Results

6.1 Baseline Emissions

In the baseline scenario, livestock production in the *Cerrado* accounts for an average of 121.5Mt $CO_2e.yr^{-1}$, from 2010 to 2030. This value includes enteric fermentation, animal waste (emissions from excreta), soil fertilization emissions, pasture (due to the loss in C stocks), and deforestation driven by cattle production (Fig. 1). The accumulated emissions from 2010 to 2020 account for about 1,249Mt CO_2e or 2,551Mt CO_2e from 2010 to 2030.

In relative terms, enteric fermentation makes the biggest contribution to the total: 66% of emissions, followed by deforestation, with 26%. The results also show that pasture degradation is a considerable source 100 of emissions, accounting for an average of 8.35 Mt $CO_2e.yr^{-1}$ (an average of 0.06 t $CO^2e.ha^{-1}.yr^{-1}$), the equivalent to 4% of emissions or the same proportion as animal waste (Fig.2).

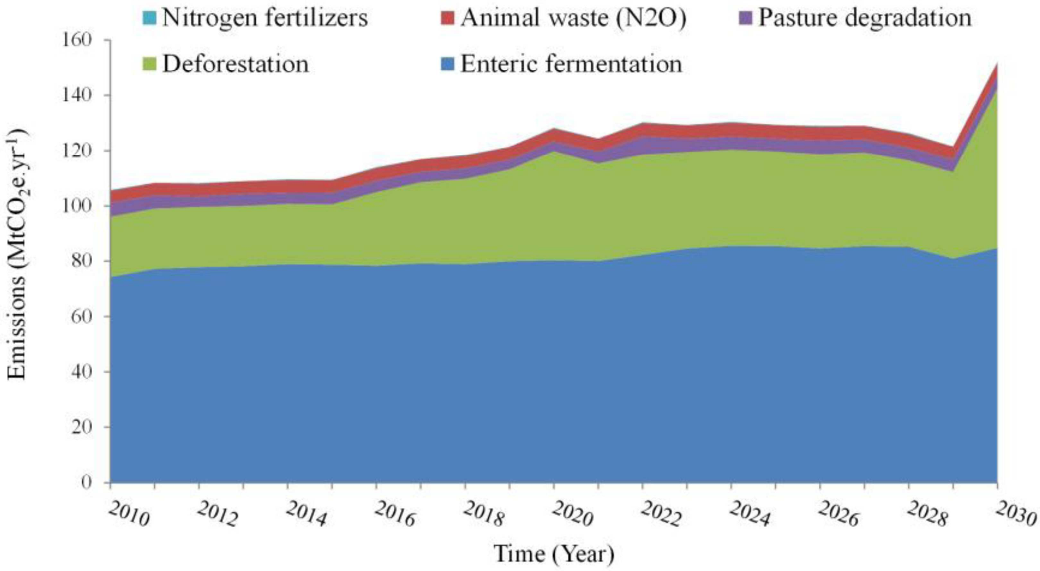

Figure 1: *Cerrado* baseline emissions 2010-2030

Gouvello *et al.* (2010) suggests that total national GHG emissions from energy, transport, waste, livestock and agriculture, will be around 1.70 Gt CO_2e, for 2030. The results presented here suggest that beef production in the *Cerrado* will be responsible for about 152 Mt CO_2e in 2030, corresponding to 9% of total national GHG emissions.

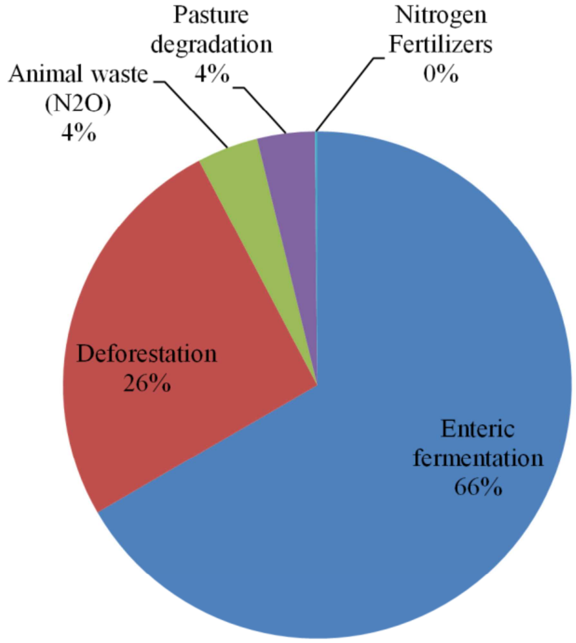

Figure 2: Share of emissions from 2010 to 2030 for the Brazilian *Cerrado*.

In the baseline scenario, without increasing productivity, an average deforestation rate of 246.1 10^3 $ha.yr^{-1}$ would be required to meet the beef demand.

Emissions attributed to the use of fertilizers were not significant, accounting for an average of 0.2 Mt $CO_2e.yr^{-1}$. This was expected, since small amounts of N are used to fertilize *Cerrado* pasture soils (Martha Jr *et al*., 2007; Cederberg *et al*., 2009).

6.2 Cost-effectiveness analysis

For policy purposes it is important to detail the relative cost of emissions mitigation measures. Three of the five mitigation measures simulated, - concentrate supplementation, protein supplementation, and pasture restoration - have negative cost-effectiveness: US$-8.01. kt CO_2e^{-1}, US$-2.88. kt CO_2e^{-1} and US$-0.05. kt CO_2e^{-1}, respectively (Figure 3). Adopting these measures implies cost savings while reducing emissions. These measures work by balancing the loss of DM production during the dry months. The *Cerrado* biome is predominantly seasonal tropical, meaning dry winters and rainy summers, with lower pasture productivity during the dry months. If cattle are supplemented with concentrates or protein they can be finished earlier, thereby reducing emissions.

Due to the large applicable area (approximately 60 M ha), and given the current low productivity of 10 t $DM.ha^{-1}.yr^{-1}$, pasture restoration provides the biggest opportunity for reducing emissions in the region.

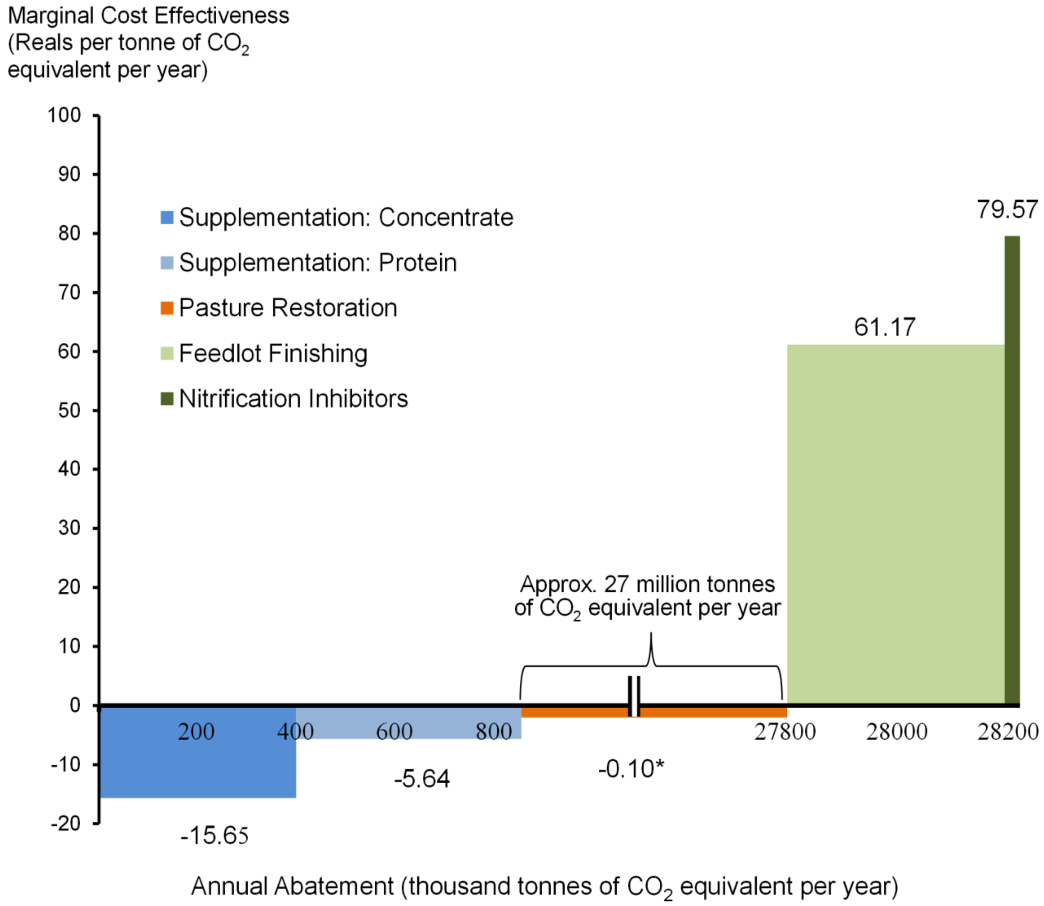

Figure 3: Marginal abatement cost curve: mitigation measures for *Cerrado* livestock production from 2006 to 2030. * Not in scale

The abatement potential (AP) for pasture restoration is 26.9 Mt $CO_2e.yr^{-1}$,comprising of two components: C sequestration and avoided deforestation, the latter accounting for 96% of this AP. Pasture restoration would improve the *Cerrado* average productivity from 10 to 11.2 t $DM.ha^{-1}.yr^{-1}$, an increase of 12% relative to the baseline. This increase would lead to an average C sequestration rate of 0.32 t $CO_2e.ha^{-1}.yr^{-1}$.This is a low C uptake potential when compared to values found by Maia *et al*. (2009), which showed that C sequestration rates of 2.24 t $CO_2e.ha^{-1}.yr^{-1}$ can be achieved in well-managed pastures in *Cerrado*. The carbon sequestration rate however, reflect the 2006-2030 period, after which, and in the long term, as pastures are intensified it will eventually reach equilibrium and therefore no more carbon is likely to be sequestered.

The AP of feedlot finishing is 470 kt $CO_2e.yr^{-1}$, but the measure cost-effectiveness US$ 13.32 t CO_2e^{-1} is high relative to t supplementation.
Nitrification inhibitors are the least cost-effective measure considered. But this analysis only considered the application to N used for pasture and crops fertilization and excluded the application to animal excreta.

The results indicate that restoring degraded lands is the biggest opportunity for reducing emissions in the *Cerrado*. The AP of this measure is about 20 times greater than all the other measures combined.

An important assumption underpinning the MACC relates to the assumed measure adoption rates. With exception of feedlot finishing, the adoption rates are optimized, meaning the rates that maximizes the gross margin in the model.

Table 5: Mitigation measures adoption rate.

Mitigation Measure	Adoption rate	Unit
Supplementation: concentrate	12	%[1]
Supplementation: protein	2.2	%
Pasture restoration	314.7	10^3 $ha.yr^{-1}$
Feedlot finishing	15	%
Nitrification inhibitors	12.78	$g.ha^{-1}.yr^{-1}$

[1]Adoption rates for feedlot, protein and concentrate supplementation are calculated as the percentage of the total finished animals. The adoption rate of pasture restoration is the annual average area of restored pasture.

7. Discussion

To meet increasing domestic and export demand, the government of Brazil recognizes the need to foster sustainable agricultural intensification, which implies increased resource productivity while minimizing significant domestic and global external costs implicit in GHG emissions and deforestation. The results presented here suggest that a significant contribution to this objective can be made by targeting specific measures to improve yield. Specifically, pasture restoration, supplements and feedlot measures could reduce sector emissions by 24.1% by 2030. Moreover, by adopting only negative-cost measures (Fig. 3), it is possible to abate about 23.7% of baseline livestock emissions in the *Cerrado*, up to 2030. According to our results the restoration of degraded pastures offers the greatest abatement potential, involving the restoration of an average of 314.7 10^3 $ha.yr^{-1}$ in *Cerrado* grasslands.

Currently, it has been estimated that 50 % to 80 % of pastures in the Amazon and *Cerrado* are degraded (Macedo *et al*., 2014; Peron & Evangelista, 2004; Zimmer *et al.*, 1994). Achieving a higher rate is likely to entail some initial investment costs to promote modified production practices and this is the purpose of the government's ABC program. ABC is an ambitious plan created to stimulate farmers and ranchers to adopt mitigation measures including restoration of degraded pastures, helping the country to meet the reduction targets presented at COP 15. ABC is the biggest sustainable agriculture fund running in Brazil, with a key objective of disbursing subsidized credit to the agricultural sector. The plan currently targets the recovery of 15 Mha in 10 years, which will lead to reductions up to 104 Mt CO_2e, roughly 64% of the program total mitigation potential. But it does not include other relevant measures such as feed supplementation measures, which would normally be considered as privately profitable anyway.

The outcome of the ABC plan remains to be evaluated, but initial indications suggest that uptake of credit has been slower than anticipated (Claudio, 2012). Recent evidence from the Amazon Environmental Research Institute suggests that several institutional barriers have retarded the program, including a lack of publicity and information about the aims and the benefits of the program, difficulties in complying with program requirements, a lack of technical assistance, and producer scepticism about the private economic benefits of measures that are predominantly designed to address global external costs (Stabile *et al*., 2012).

Producers also perceive transaction costs in program compliance and a lack of basic infrastructure (Rada, 2013) that is needed to support increased productivity. In short, the ABC plan is confronting similar behavioural barriers in relation to non-adoption, identified in other mitigation studies, *e.g*. Moran *et al*. (2013), which need to be addressed before wider measure adoption can be expected.

8. Conclusion

This paper highlight show resource efficiency measures can be enacted (notionally within farm gate) in the *Cerrado* biome to help reconcile competing objectives of private yield improvements and the reduction of external costs. The analysis responds to the need to demonstrate the possibilities for sustainable intensification, allowing Brazil to meet economic growth ambitions for the sector.

The key finding from the use of the EAGGLE economic optimization model is the representation of the cost-effectiveness of key mitigation measures. Specifically, that pasture restoration is the most promising mitigation measure in terms of abatement potential volume and that it offers a cost saving for the livestock sector. By adopting these measures – pasture restoration, concentrate and protein supplementations – the *Cerrado* could reduce 23.7% of its emissions by 2030, while the total abatement potential of adopting all measures is 24.1%.

The analysis presented here has a number of caveats that potentially warrant further research. These include a more detailed representation of the biophysical heterogeneity of the *Cerrado* biome, more detailed treatment of the deforestation (and hence land sparing) processes and relaxation of the assumed equilibrium supply and demand conditions in the optimization model.

Nevertheless by highlighting cost-effective policy options, this paper contributes to our understanding of sustainable intensification processes as relevant to Brazilian livestock production.

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Appendix. Supplementary material

Appendix S1: Description of inputs and costs
Appendix S2: Model calibration
Supplementary Tables: Tables S1-S8

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Appendix 5: Mitigation options – brief descriptions for biophysical and economic modelling

General assumptions

- We are modelling the current situation, so no forecasts are needed.
- When the total production of feedstuff changes at farm, we will adjust the stocking rate accordingly rather than buying in/selling feed or changing the milk yield or weight gain rate.
- We're going to use typical farms rather than best practice farms, as i) not much difference can be seen for many mitigation measures if the farm is already best practice, ii) "average"/"typical" farms are more useful for policy development.

Fertilisation rate

Change mineral N application ±50 kg N ha^{-1} y^{-1} relative to current practice. We only consider inorganic N in this mitigation measure, leaving the organic N practice unchanged. (Note that subsequently manure N is going to change due to the change in yield, so the organic N will be different.) The stocking rate is adjusted to the yield. If there is a need to increase P or K fertilisation, information on that is needed too (amount and cost).

Input variables/parameters affected:

- Grass production, crop yield
- Machinery and fuel use for fertilisation (including N, P and K)
- Labour requirement for fertilisation (including N, P and K)

Nitrification inhibitors

Nitrification inhibitors (NIs) are applied onto cropland or pasture to slow down the conversion of NH_4^+ to NO_3^- in the soil and thus reduce N leaching and N_2O emissions from inorganic and organic fertilisers and grazing. Commonly used NIs include dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP). The application rate of DCD and DMPP usually range between 7 to 30 kg ha^{-1} and 0.5 to 5 kg ha^{-1}, respectively, and in this modelling exercise it should be defined based on the baseline N fertilisation rate. We assume no change in the fertilisation rate. NI application might increase yield and the N content of the plant.

Input variables/parameters affected:

- Machinery and fuel use for fertilisation
- Labour requirement for fertilisation
- Grass production, crop yield
- Crop/grass N content

More legumes in grass swards

Clover (or other appropriate legumes) is sown along with grass, so that the legume content of the grass will be kept at a constant level of 20-30 % DM. The measure is applicable on rotational, temporary and permanent grasslands. We will assume stitching the legumes into the grass – where it is not feasible, we can model immediate reseeding, and assume that reseeding was due anyway. As the legume content of the sward might be decreasing over time, more frequent reseeding/stitching in might be required. The N fertilisation is kept constant if the baseline is less than 75 kg ha^{-1}, or reduced to 75 kg ha^{-1} (one application in the spring) if it's more than that. We'll assume no change in the N content, energy content and digestibility of the grass mix. Yield is reduced, so stocking rate is reduced.

The measure is going to affect soil N_2O emissions, cattle/sheep diet and rumen emissions, manure N and VS content (so storage emissions), N_2O emissions from manure spreading.

Input variables/parameters affected:

- Type of legume
- Grass yield
- Seed cost
- Frequency of reseeding
- N fertiliser amount
- Machinery and fuel use for fertilisation and extra seeding
- Labour requirement for fertilisation and extra seeding

Legumes in the rotation

The proportion of legumes (could be grain legumes or fodder legumes, *e.g.* alfalfa) in the rotation is increased to 10% of the land area. The measure is applicable on arable land. Legumes will either replace a crop in the rotation or reduce the amount of all the other crops. The N fertilisation requirements within the rotation are reduced. The legumes are either used to replace imported N in the animal feed, or if the animals are already eating local protein sources then the legumes are sold. In the first case the N-content of the diet has to be balanced by reducing the N-content of the concentrates, replacing soya at the first place (LCA for related emissions).

The measure is going to affect soil N_2O emissions, cattle diet and rumen emissions, manure N and VS content (so storage emissions), N_2O emissions from manure spreading.

Input variables/parameters affected:

- Rotation pattern, crop outputs
- Yield (legume and subsequent crop)
- Seed cost (both the legumes and the crop it is replacing)
- N fertiliser amount
- Machinery and fuel use for fertilisation and changed rotation pattern
- Labour requirement for fertilisation, changed rotation pattern and changed feed mix
- Diet energy and N content
- Off-farm emissions from concentrates replaced (changes in concentrates and GHG emissions from concentrates production)

Cover crops

Cover crops are sown in between main crops. The applicability of this measure depends on the rotational pattern. The type and timing of the cover crop depends on local circumstances. 100% of the crop is ploughed in when the main crop is seeded. The N fertilisation need of the next crop decreased.

The measure is going to affect soil N_2O emissions and NO_3^- leaching in winter (leaching reduced, but N_2O might increase) and soil C stocks.

Input variables/parameters affected:

- Crop pattern
- Yield of subsequent crop
- Seed cost
- Field operations from seeding (machinery, labour, fuel)
- N fertiliser amount of subsequent crop
- Machinery and fuel use for fertilisation and cover crops
- Labour requirement for fertilisation and cover crops

Irrigation

Can be applied to crops or grass, but the type of land (whether grassland or arable land) should be kept constant. Water harvesting and storage should also be considered where applicable. The changes in the fertilisation needs are to be defined.

Input variables/parameters affected:

- Yield
- Water cost (installation of water storage if applicable)
- Irrigation installation, maintenance and fuel costs
- Labour requirement
- Fertilisation needs

Restoring degraded lands

This option is only considered for the non-European regions. The main focus is on improving the soil quality and soil C content.

Improving permanent pastures

We consider three main ways of improving pastures:

a. Changing the species mix or the varieties.
b. Removing unwanted species.
c. Supplying P and K if needed.

These can be implemented in combination or alone, depending on the local circumstances.

Improving roughage quality

We consider two main ways of improving roughage quality:

a. Changing the species mix or the varieties.
b. Better cutting regime.

These can be implemented in combination or alone, depending on the local circumstances.

We consider this option only for the non-European regions.

Feeding more maize/sorghum and less grass

Increase the part of area dedicated to maize/sorghum production on farm so that the DM intake from maize:grass is I) 50:50 and II) 25:75. Maintain constant the area dedicated to roughage production. Adapt stocking rate (and thereby milk/meat production) according to the change in the forage production and quality.

This measure will only be about maize or sorghum, not silage wheat or barley. For farms where it is not economic to grow these crops, we don't model this measure.

This option can change many GHG emissions: enteric CH_4, manure CH_4, N_2O emissions, ammonia emissions, C sequestration, CO_2 fossil source.

Input variables/parameters affected:

- Change in land use (grass and maize/sorghum areas)
- Diet (grass, maize and concentrates), energy and N content
- Off-farm emissions from concentrates replaced (changes in concentrates and GHG emissions from concentrates production)
- Mineral fertilization and manure production
- Milk production and composition
- Average selling price of milk
- Time spent indoor

Feeding more fat

Increase the proportion of specific unsaturated fats to 5% in the concentrate compounds to reduce the enteric methane emission of ruminants. With a moderate addition of lipids in the diets, no negative effects on digestibility, rumen ecosystem or milk yield are expected. Diet energy and N content is assumed to be constant. Milk composition might change (increase in fat content). The supplement must be fed with the concentrates, in substitution to another concentrate compound. We assume that the additive is bought in (too special to be easily produced at farm). LCA emissions will be assigned to the additive.

Input variables/parameters affected:

- Type and amount of supplement
- Cost of feed (including the cost of replaced feedstuff)
- Milk composition (fat)
- Average price of milk

Additive nitrate

Add 1% nitrate to the diet, replacing either urea or other N sources. Diet energy and N content is assumed to be constant.

Input variables/parameters affected:

- Type and amount of supplement

- Cost of feed
- Enteric CH_4 emission factor

Balance amino acids and reduce CP in pigs

Reduce the CP content of the diet without changing animal performance by using phase feeding and amino acids supplementation. Diet energy and N content is assumed to be constant.

The expected change in GHG emissions concerns mainly N_2O either directly or indirectly (NH_3).

Input variables/parameters affected:

- Feed composition
- Cost of feed

Increasing housing while keeping the proportion of grass in the feed constant

Animals spend more time indoors, though not 100%. (Still to decide on the target housing rate.) The cut grass will be fed fresh, and if that is not feasible, then as hay or silage, depending on local circumstances. The manure collected in houses will be spread, plus a little bit more inorganic N to compensate for gaseous losses through storage. Leaching on the field is assumed to be constant.

The expected change in GHG emissions concerns mainly manure management (N_2O, CH_4, NH_3) and C sequestration. Fossil energy is also concerned (CO_2).

Input variables/parameters affected:

- Time spent indoor
- Proportion of grass grazed / cut / hay / silage
- Diet energy and N content
- Mineral fertilization and manure production
- Machinery, fuel and energy use for fertilisation and cutting grass (and preparing hay/silage)
- Labour requirement for fertilisation and cutting grass (and preparing hay/silage)

Replacement rate dairy cattle

Increase stocking rate of cows and decrease the stocking rate of heifers (still to decide the target replacement rate). The total area of forage production is kept constant. This option will only be considered in dairy farms, otherwise it will be necessary to consider that the heifers will be reared in another herd. Milk yield is kept constant, but the production per cow has to consider the change in primiparous cows due to a lower replacement rate.

Many emissions can be changed (CH_4, N_2O, NH_3, CO_2), but productions (milk and meat) are also modified.

Input variables/parameters affected:

- Replacement rate
- Change in concentrate and forage system according to the diet the different animal classes, and, accordingly, change in land use (grass versus crops)
- Off-farm emissions from concentrates replaced (changes in concentrates and GHG emissions from concentrates production)
- Diet energy and N content
- Milk production and composition
- Average milk selling price

Cover slurry stores/manure heaps

Covering of slurry tanks or manure heap by an impervious cover.

Impacts: C degradation, NH_3 emission, N_2O emission & N_2 emission from storage, CH_4 emission from storage.

Input variables/parameters affected:

- Type of cover
- Investment and maintenance of cover
- Storage CH_4, NH_3, N_2O and N_2 emission factors

Manure acidification

Acidify slurry to pH 5.5 using sulphuric acid, using add-on technology to existing stores. Applicability is affected by the type of the concrete in the livestock house and by the type of the manure store.

Impacts: C degradation in storage, NH_3 emission, N_2O emission & N_2 emission from storage, CH_4 emission from storage, NH_3, N_2O and N_2 emission from field-applied manure.

Input variables/parameters affected:

- Investment and maintenance of acidification equipment
- Labour requirement
- Storage CH_4, NH_3, N_2O and N_2 emission factors
- Manure spreading NH_3 emission factor

Anaerobic digestion

Anaerobically digest slurry and/or farm yard manure. (Still to decide the size of the digester, whether manure is imported (*i.e.* centralised anaerobic digestion) or not (on-farm anaerobic digestion), whether any supplementary substrate is used, and whether the supplementary substrate is bought in or home-grown.)

Impacts: C degradation, CH_4 emission from storage, NH_3 emission, N_2O emission & N_2 emission in storage, NH_3 emission from field-applied manure.

Input variables/parameters affected:

- Size of digester

- Investment, maintenance and income (electricity price and subsidies) from AD (including labour costs)
- Land use and stocking rate changes (if supplementary substrate is used and grown on farm)
- Amount and type of supplementary substrate bought in
- Manure import (if assumed), distance of manure imported from
- Storage CH_4, NH_3, N_2O and N_2 emission factors
- Manure spreading NH_3 emission factor
- AD technical details, like
    - Farm electricity use (baseline)
    - Farm gas use which can be replaced by electricity
    - Farm oil use which can be replaced by electricity
    - Lifetime of the AD plant
    - % of biogas as CO_2
    - % of biogas as CH_4
    - Methane leakage
    - Efficiency of electricity production in the AD plant
    - Efficiency of heat production in the AD plant
    - Typical GHG emissions per kWh of electricity generation (grid average)

Appendix 6: Detailed description of mitigation options for biophysical and economic modelling

Reducing N fertilisation

For farm modelling in the Animal Change project, Component 3
Authors: Bob Rees and Vera Eory (SRUC)

Questions

Do we assume a change in N_2O EF, i.e. higher EF for N above Navailmax?

A number of recent studies have shown that when N_2O emissions are scaled according to yield, minimum levels of emission intensity can be identified at nitrogen fertiliser rates that that may differ from the economic optimum (Figure 4) (Hoben *et al.*, 2011; Pappa *et al.*, 2011). However, such relationships are not consistent in some studies have shown fairly linear relationships between emission intensity of N_2O and fertiliser application rates (Thorman *et al.*, 2013).

How to set NavailMax? Is NavailMax expected to be constant within an AEZ?

Approach 1

NavailMax = N(economic optimum), NyieldMax = Nyield(economic optimum)

Rational: As FarmAC is using a linear N-response function with a NyieldMax at NavailMax. N response curves are more or less exponential, and the argument in this mitigation option is that though in the baseline situation available mineral N is likely to be below the point where the yield is maximised (because the economic N optimum is always below that point), still the N response curve's slope is low enough to allow for only a small decrease in the yield given a decrease in N mineral N. As the exponential curve will not be reproduced in FarmAC, it is important to set NavailMax in a way that it captures this. Therefore it might be needed to set NavailMax not at the maximum yield, but slightly below, *e.g.* at the economic optimum (available in fertiliser recommendations).

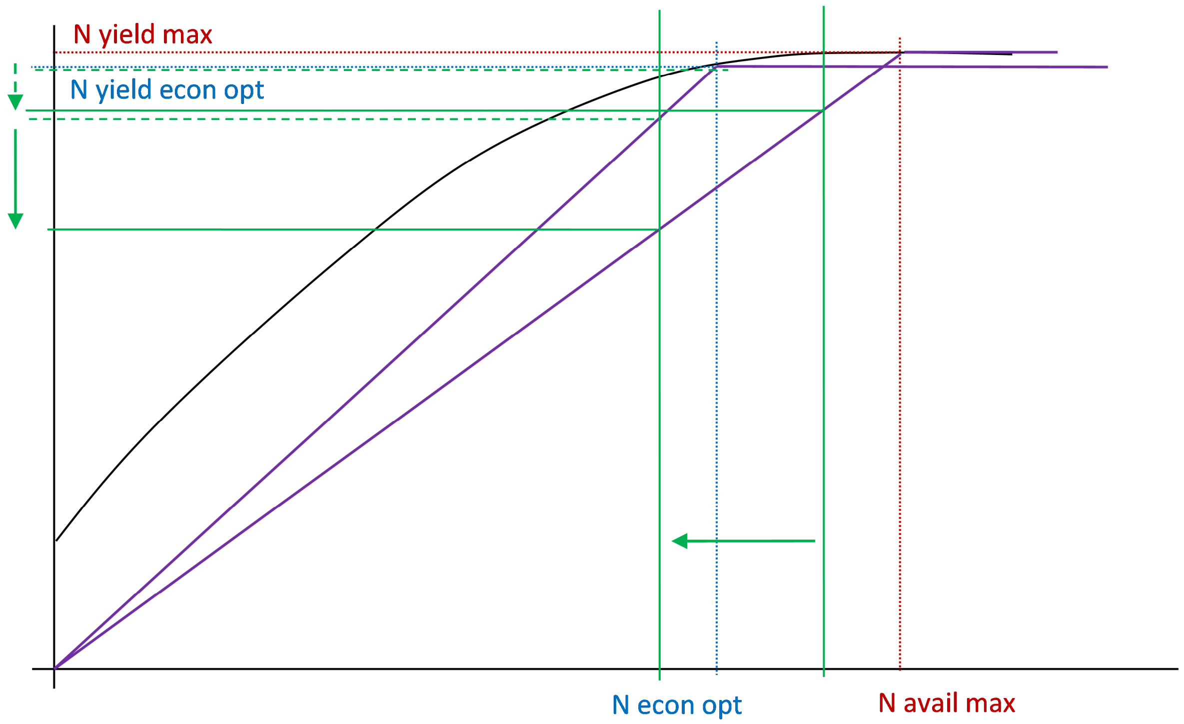

Figure 1. Effects of defining NavailMax on the changes in Nyield as the function of Navailable

In this case experts don't need to give any information to FarmAC on this measure.

Financial information is still needed (especially in the case of increasing fertilisation in non-European countries) on whether there is change in the cost of other fertilisers and the cost of spreading (or machine runs).

Approach 2

Another alternative is to ask experts to provide a value about how much the yield changes given a ±50 kg N/ha change in the available N (see an example below). But that would imply that this information has to overwrite the original response function in FarmAC. Would it be feasible?

We should ask these data anyway to crosscheck them with the modelled yields.

Data to be provided by regional experts

Estimate the economic optimum N application (kg N available / ha) and the corresponding yield (kg DM / ha) for each crop in the agroecological zone. Provide these as the FarmAC model parameters NavailMax and NyieldMax, respectively:

NavailMax = N-available(economic optimum)

NyieldMax = Nyield(economic optimum)

These values might be available in fertiliser recommendations, or in scientific papers.

NOTE: the NavailMax parameter of FarmAC refers to total available mineral N, and not only to the applied N. The fertiliser recommendations might provide the N(economic optimum) as applied N. In this case, find estimates about the corresponding soil nitrogen supply (SNS), and calculate NavailMax as:

NavailMax = SNS + N-applied(economic optimum).

For reference, make a note on the fertiliser N price: grain N price ratio (it is a key assumption in the economic optimum calculations).

Explaining SNS: SNS is the amount of nitrogen in the soil that is available for uptake by the crop throughout its entire life, taking account of nitrogen losses. The SNS includes Soil Mineral Nitrogen (SMN):

SNS = SMN + estimate of mineralisable soil nitrogen

SMN is the nitrate-N plus ammonium-N content of the soil within the potential rooting depth of the crop, allowing for nitrogen losses.

Mineralisable soil nitrogen is the estimated amount of nitrogen which becomes available for crop uptake from mineralisation of soil organic matter and crop debris during the growing season after sampling for SMN. (Defra, 2011)

EXAMPLE (winter wheat, UK)

Parameter	Value	Unit	Farm type/AEZ	Reference
NavailMax, winter wheat	324	kg N ha^{-1}	All farms, EU maritime	(Kindred *et al.*, 2010; Kindred *et al.*, 2012; Sylvester-Bradley *et al.*, 2009)
NyieldMax, winter wheat	195	kg N ha^{-1}	All farms, EU maritime	

Calculations used:

NavailMax = N-applied(opt) + SNS = 324 kg N ha^{-1}

SNS = 110 kg N ha-1 (assumption, based on (Kindred *et al.*, 2012))

N-applied(opt) = [ln(k – c) – ln(b * ln(r))] / ln(r) = 214 kg N ha^{-1} (Kindred *et al.*, 2010)

where k: fertiliser N price : grain N price ratio of 5, k = 0.005

c: the slope of the response beyond the region of maximum curvature, c = -0.002

b: the change in yield from the maximum if no fertiliser N was applied, b = -6.0

r: the shape of the response in the region of maximum curvature, r = 0.99

Note, that though NavailMax = 324 kg N ha^{-1}, the optimum N applied is 214 kg N ha^{-1}

NyieldMax = Yield(opt) * 1000 kg/t * GrainN = 162 kg N ha^{-1}

Yield(opt) = 0.85 * (a + b * rN + c * N) = 7.94 t N ha^{-1} (Kindred *et al.*, 2010) where 0.85: conversion factor (85% DM to 100% DM)

a: the asymptote, or maximum achievable yield, a = 10.47 t N ha^{-1}

N: N applied, here N = N-applied(opt) = 214 kg N ha^{-1}

GrainN: grain N content (%DM), GrainN = 2.04% (assumption, based on (Sylvester-Bradley *et al.*, 2009))

Data to be provided by local experts

1. Estimate how much the yield changes (kg DM ha^{-1}) given a ±50 kg N ha^{-1} change in the applied N (synthetic + organic). The change should be relative to the farm baseline.
2. Is there any change in the cost of other fertilisers and the cost of spreading (or machine runs)? (Especially in regions where N is currently under-applied, and the +50 kg N ha^{-1} increase is substantial.

EXAMPLE (winter wheat, UK)

1. Yield change:

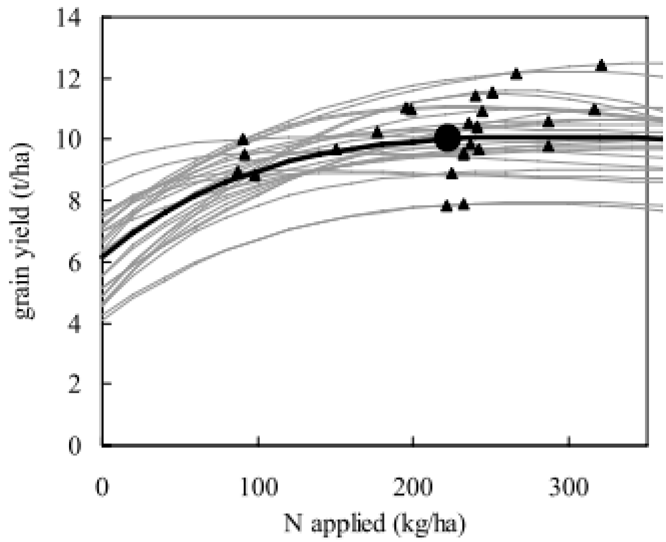

Figure 2. Response curves (NOTE: N applied, not N available) from wheat trials in 2005-7 (modern varieties), and an 'average' curve (bold line) fitted to their average yields (Sylvester-Bradley *et al.*, 2008)

'Average' yield curve (Kindred *et al.*, 2010):

Y=10.47-6.0*⟦0.99⟧^N-0.002*N (see above for more on the parameters)

where Y: yield at 85% DM

N: N applied (kg N ha^{-1})

If the baseline N applied (manure + inorganic) = 200 kg N ha^{-1}, and yield = 7.88 t DM ha^{-1}:

N applied = 150 kg N ha^{-1} → Y = 7.52 t DM ha^{-1} (-4.6%)

N applied = 250 kg N ha^{-1} → Y = 8.06 t DM ha^{-1} (+2.4%)

2. The cost of other fertilisers and the cost of spreading the N are assumed to be constant.

Objective

Nitrous oxide emissions from soils are known to be highly sensitive to the amounts of nitrogen fertilisers applied. The objective of this measure is to reduce N fertiliser application rates in order to reduce N_2O emissions without having a significant impact on yield. The expected change in GHG emissions would occur as a consequence of reduced direct and indirect N_2O loss and by reduced CO_2 emissions associated with N fertiliser manufacture.

Assumptions for farm modelling

- The measure is applicable to grass and arable cropping.
- Small changes in applications of fertiliser N can be made without significant loss of crop yield.
- Cropland soil management assumed to follow best practice. This would include full allowance for residual soil N and N content of slurries of manure prior to the application of mineral N. it would also assume that soil is maintained in good condition *i.e.* that drainage is maintained and at first soil conditions such as compaction are avoided.
- It is assumed that emissions of methane and carbon dioxide from the soil would be unaffected by this measure

Further guidance for the farm experts

- Formulation:
    - o This measure is applicable to all forms of mineral nitrogen fertiliser. The cost of ammonium nitrate purchased in May 2013 is £270/t.
- Costs:
    - o The effects on cost of directly proportional to the cost of fertiliser N.

Model variables and parameters affected

Parameter	Unit	Likely range of change	Farm type/AEZ	Reference
Crop yield		Reduced by up to 5%	All farms	
Mineral N fertiliser		Reduced by up to 20%	All farms	

Rationale and mechanism of action

Nitrous oxide emissions are strongly influenced by N fertiliser applications (Bouwman *et al.*, 2002; Rees *et al.*, 2013). This is often considered to be the single most important factor influencing emissions from agricultural soils, although its effects interact with local environmental conditions such as soil wetness and temperature. However, recent studies have shown that the relationship between N_2O emissions and end fertiliser application is often non-linear, with a slow increase in emissions at low fertiliser application rates, followed by a much more rapid increase in emissions at fertiliser rates at or above the economic optimum (Cardenas *et al.*, 2010; Pappa *et al.*, 2011). This highlights the importance of avoiding over fertilisation as a mitigation measure, since N applied at these high rates please to disproportionally large quantities of N_2O release.

Most fertiliser recommendation systems use economic optimum to set fertiliser rates. This is defined as the point at which additional inputs of fertiliser N cost more than the financial benefits gained by additional yield. Although fertiliser recommendations tend to be fixed within particular regions, in reality the economic optimum would vary from year to year as a consequence of variations in the costs of fertiliser N and crop yield. A further complication in precisely defining the economic optimum is that crop yield tends to be much less sensitive to fertiliser application at high levels of addition than it is at lower levels. Recent studies in the UK have confirmed the relatively flat response in terms of yield at N application rates close to the recommended economic optimum and have been able to demonstrate that a 10% reduction in fertiliser application rates would lead to less than 1% reduction in yield (Sylvester-Bradley *et al.*, 2009). Other studies suggest that such fertiliser reduction strategies would be applicable more widely across Europe and globally, with the opportunity to reduce global fertiliser use by 20% without significant impacts on crop yield (Good *et al.*, 2011). It is anticipated that such changes in management could lead to significant environmental benefits, and address serious concerns about the environmental impacts of excessive N use in Europe (Anon., 2011; Galloway *et al.*, 2002).

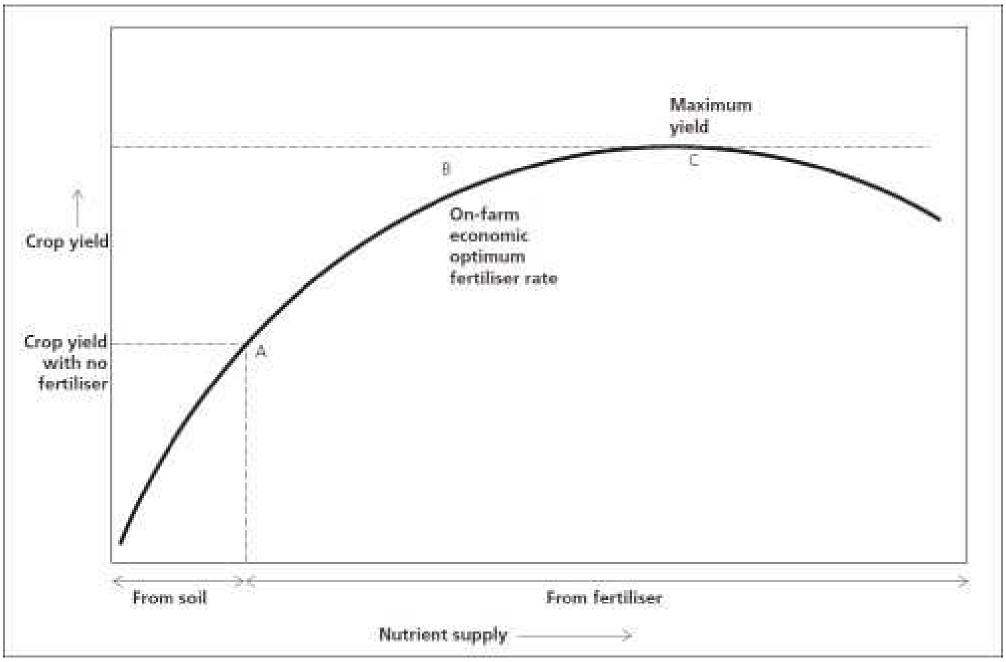

Figure 3. A typical nitrogen response curve, used to develop fertiliser N application guidelines for UK crops (Defra, 2011)

Therefore at fertiliser recommendations close to the economic optimum, there is a relatively low sensitivity in yield response, but a high sensitivity changes in nitrous oxide emission. A number of recent studies have shown that when N_2O emissions are scaled according to yield, minimum levels of emission intensity can be identified at nitrogen fertiliser rates that that may differ from the economic optimum (Figure 4). This leads to the interesting observation that in order to achieve the minimum N_2O intensity is important to avoid both low and high levels of fertiliser N application (Hoben *et al.*, 2011; Pappa *et al.*, 2011). However, such relationships are not consistent in some studies have shown fairly linear relationships between emission intensity of N_2O and fertiliser application rates (Thorman *et al.*, 2013).

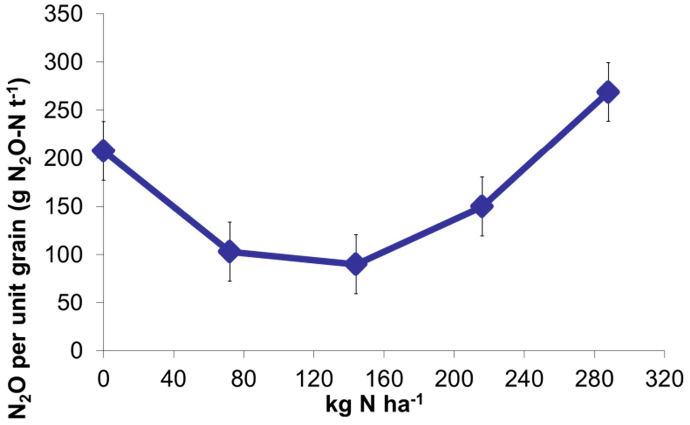

Figure 4. Relationships between fertiliser N application to spring barley and N_2O emission intensities, (Pappa *et al.*, 2011)

Proposed actions to reduce fertiliser nitrogen application rates

It is proposed that fertiliser application rates recommended by N fertiliser recommendation systems should be reduced by 10% in all circumstances. It is anticipated that this would have negligible effects on yield whilst contributing significantly to a reduction in both direct and indirect nitrous oxide emissions. The measure should then lead to a 10% or greater reduction in N_2O emissions.

Other effects of the action

Reducing fertiliser application rates will be associated with reduced direct and indirect emissions of N_2O. There will also be an associated reduction in losses by leaching and in some cases volatilisation. A further reduction in GHG emissions would be associated with reduced energy consumption from fertiliser manufacture

Effects neglected

This measure is unlikely to have any significant impacts on increasing greenhouse gas emissions elsewhere in the farming system or supply chain

Cost data

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Nitrification inhibitors: the role of DCD in reducing N_2O emissions and NO_3^- leaching

For farm modelling in the Animal Change project, Component 3
Authors: Laurence Shalloo (TEAGASC)

This review is dealing predominately with dairy cows on grazed grassland.

Nitrogen Loss

The rate of utilisation by the sward of N deposited in urine is dependent on the timing of deposition. Nitrogen deposited in the spring has a high level of utilisation due to high demand by the growing plant, while in late autumn N use efficiency is low as grass is not actively growing and the N is available for loss through one form or another. Nitrogen in urine is in the form of urea, however, once applied N is converted to NO_3^- through the nitrification process. Nitrate leaching and N_2O emissions are key environmental loss pathways from grazed grassland as a result of urine deposition by grazing livestock. There are numerous strategies to mitigate N losses in grazing systems including the use of nitrification inhibitors such as dicyandiamide (DCD).

Dicyandiamide (DCD)

Dicyandiamide is a white crystalline nitrogenous powder naturally broken down in the soil (Amberger, 1989). Nitrification inhibitors such as DCD are compounds that delay the bacterial oxidation of the ammonium ion (NH_4^+) by reducing the activity of the edaphic Nitrosommas spp. bacteria (Irigoyen *et al.*, 2003). Dicyandiamide has been shown to reduce

N losses from urine patches (Di and Cameron, 2005; Dennis *et al.*, 2012). The performance of nitrification inhibitors such as DCD is influenced by factors such as soil temperature, rainfall, and time and rate of application of the DCD.

Herbage production

Dicyandiamide has been shown to increase herbage production in a number of studies in New Zealand (Di and Cameron, 2002; Di and Cameron, 2005; Moir *et al.*, 2012), however, the application of DCD to pastures to increase herbage production has proved inconsistent in Internationally with a number of studies in Ireland showing only small agronomic benefits (Dennis *et al.*, 2012; O'Connor *et al.*, 2012, 2013a) while in some New Zealand studies a similar affect was found (Monaghan *et al.*, 2009). Di and Cameron (2005) reported that the application of DCD gave an annual average increase in herbage production of 33% when the DCD was applied directly to the urine patch. This type of application would prove extremely difficult at the paddock application level. Monaghan *et al.* (2009) observed that DCD application had no significant effect on annual or seasonal pasture production in any measurement year. Dennis *et al.* (2012) reported that there was an inconsistency in the increase in herbage production when DCD was applied following urine application to lysimeters in Irish soils; O'Connor *et al.* (2012; 2013a) found inconsistent herbage production responses and when a positive effect occurred it was very small.

Di and Cameron (2005) reported that the application of DCD increased herbage production when urine was applied to grassland in autumn by an average of 49%, while there was also an increase of 18% in spring. This gave an annual average increase in herbage production of 33%. A study completed in New Zealand by Di and Cameron, (2007) showed that an application of DCD to urine treatments can increase herbage production by an average of 25% across all treatment, an application of urine at a rate of 700 kg N ha^{-1} yr^{-1} with DCD increased herbage production from 13.90 t DM ha^{-1} yr^{-1} without DCD to 18.71 t DM ha^{-1} yr^{-1}, an increase in herbage production of 35%, an application of urine at a rate of 1000 kg N ha^{-1} yr^{-1} increased herbage production from 19.74 t DM ha^{-1} yr^{-1} without DCD to 23.24 t DM ha^{-1} yr^{-1} with DCD, an increase in herbage production of 18%. A national series of farm trials was conducted in New Zealand by Carey *et al.* (2012) to investigate the effectiveness of DCD at increasing pasture DM yield in a paddock situation. The results from the study found that DCD effectiveness in increasing herbage production varied between north and south islands, with a herbage response in the north island varying between 4-27% and in the south island by 12-31%. Monagahan *et al.* (2009) observed that application of DCD had no significant effect on annual or seasonal pasture production in any measurement year.

Therefore it can be concluded that the application of DCD to soil gives a region specific response based on climate and soil type in any particular region, however there could also be a within paddock specific affect which relates to the application of DCD to urine patches within paddocks.

Environmental benefit

In New Zealand the application of DCD at a rate of 15 kg ha^{-1} to urine patches in autumn resulted in total NO_3^--N leaching losses being reduced by 76% compared to urine only treatments (Di and Cameron, 2002). Dicyandiamide applied to Irish soils reduced NO_3^--N leaching by an average of 45% (Dennis *et al.*, 2012). Selbie *et al.* (2011) also reported that the application of DCD at a rate of 15 kg ha^{-1} to urine patches (1000 kg N ha^{-1}) reduced N_2O emissions in the winter season by 70% on Irish soils. In Ireland, Dennis *et al.* (2010) reported that the application of DCD to urine treatments reduced NO_3^--N leaching by up to 45%. In New Zealand, the application of DCD to urine patches was shown to reduce NO_3^--N leaching by 60-65% (Singh *et al.*, 2009). Qui *et al.* (2010) reported that applying 15 kg DCD ha^{-1} to dairy cow urine patches in winter and summer reduced N_2O-N emissions by 40 and 69%, respectively. A study carried out by Di *et al.* (2007) concluded that the application of DCD, reduced N_2O emissions from urine patches by 70%, from 9.2 kg N_2O-N ha^{-1} without DCD to 2.8 kg N_2O-N ha^{-1}. Inter-urine patches have had total N_2O emissions reduced by 25% from 0.48 kg N_2O-N ha^{-1} to 0.36 kg N_2O-N ha^{-1} (Di *et al.*, 2007). A study completed in the Basque region of Northern Spain has reported that the addition of DCD to cattle slurry can reduce N_2O emissions by 60% (Merino *et al.*, 2002).

Nitrate leaching

Di and Cameron (2007) reported that the application of DCD with urine (1000 kg N ha^{-1}) led to a reduction in NO_3^- leaching of 45%. Total NO_3^- leaching loss of 254.9 kg ha^{-1} yr^{-1} in the treatment that received 1000 kg N ha^{-1} was observed, with total NO_3^- leaching loss of 139.0 kg N ha^{-1} yr^{-1} with the treatment receiving DCD at a rate of 10 kg ha^{-1}. When urine was applied in autumn without DCD, total NO_3^- leaching loss was equivalent to 516 kg N ha^{-1} yr^{-1}, with the application of DCD (15 kg ha^{-1}) this was reduced to 128 kg N ha^{-}1 yr^{-1}, this is equivalent to a reduction of 76% in autumn applied urine (Di and Cameron, 2002). Dennis *et al.* (2012) reported that DCD applied to Irish soil reduced NO_3^- leaching by an average of 45%, however this may be a significant reduction, it is not as impressive as reductions observed in New Zealand (Di and Cameron, 2002). Shepherd *et al.* (2010) observed that DCD was effective in reducing NO_3^- leaching from silt (61%) and clay (36%) but not from sand soils, this suggests that soil-type is also a factor in affecting the effectiveness of DCD reducing NO_3^- leaching. Monagahan *et al.* (2009) observed that the application of DCD reduced NO_3^- losses in drainage by between 21 and 56%. Zaman *et al.* (2010) and Cookson and Cornforth (2002) reported that the application of DCD to soils with and without urine did not reduce the amount of NO_3^- being leached.

Nitrous oxide emissions

On average, the application of DCD to soils reduced total N_2O emissions from the urine by 70%, from 9.2 kg N_2O-N ha^{-1} without DCD to 2.8 kg N_2O-N ha^{-1} (Di *et al.*, 2007). Di and Cameron (2003) reported that the use of DCD can have a positive effect on reducing N_2O emissions by treating grazed pasture soil, including animal urine patch areas, the N_2O flux can be reduced by 76% for the autumn urine application and by 78% for the spring urine application.

The average amount of N_2O emitted (5.1 kg N_2O-N ha^{-1}) after DCD application was only slightly above background emissions (1.4 kg N_2O-N ha^{-1}), measured in New Zealand, where no N fertiliser or urine was applied in clover based pastures. Qui *et al.* (2010) reported that the application of DCD at a rate of 10 kg ha^{-1} to urine patch receiving 1000 kg N ha^{-1} reduced N_2O emissions in the winter season by 69% and by 40% reduction in N_2O emissions were achieved during the summer measurement period. Selbie *et al.* (2011) reported that the application of DCD at a rate of 15 kg ha^{-1} to urine patch receiving 1000 kg N ha^{-1} reduced N_2O emissions in the winter season by 70% on Irish soils. Zaman *et al.* (2009) observed that urine applied with DCD reduced N_2O emissions, DCD does not reduce nitrification indefinitely, and it is dependent on soil moisture, temperature, microbial activity and pH. These results suggest that treating urine patches with DCD in dairy pastures provides an effectiveness method of mitigating N_2O emissions in agricultural systems.

Using the animal to apply DCD

Ledgard *et al.* (2008) successfully infused DCD into the rumen of sheep and 86% of DCD was recovered in the excreted urine. O'Connor *et al.* (2013b) infused DCD into the rumen of dairy cows and found that 82.3% was recovered in urine and 2.1% in faeces. When the urine collected from the cows infused with DCD into the rumen was applied to lysimeters N_2O

emissions on were reduced by 84 and 57% on a free draining soil type and a on a poorly drained soil, respectively, compared to applying urine from non-treated cows (O'Connor, 2012). Similarly, NO_3^- leaching was reduced by 91 and 86% on a free draining soil type and a on a poorly drained soil, respectively, when the urine collected from the cows infused with DCD into the rumen was applied to lysimeters compared to applying urine from non-treated cows (O'Connor, 2012). Ledgard *et al.* (2012) examined the possibility of application of DCD in water troughs for consumption by dairy cows. The authors reported a 44% reduction in N_2O emissions and 40% reduction in nitrate leaching from grazed grassland when DCD was added to dairy cows drinking water.

Economic benefit

This product is not commercially available in Europe but with the expected varied agronomic response, the expected economic benefit of applying DCD would be limited on farm. In comparison to the purchase of chemical nitrogen at €1.05/kg of N and 15 kg of herbage DM per kg of N versus €5/kg of DCD or €75/ha, there would have to be an agronomic response of 1,125 kg DM/ha associated with the DCD to justify using it over chemical nitrogen.

Human Health

A recent food scare in relation to the widespread use of DCD in New Zealand has resulted in the banning of its use on commercial farms. Traces of DCD were found in whole milk powder in China. The median lethal dose of a substance (LD50) is used to determine the quantity of the substance that is likely to cause death to 50% of the population (Barth *et al.*, 2002). Amberger (1989) reported that DCD had an LD50 of 10g/kg liveweight and DCD is classed as a non-toxic substance.

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More legumes in grass swards

For farm modelling in the Animal Change project, Component 3
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Introduction

White clover (*Trifolium repens* L.) is the most important pasture legume in temperate regions of the world (Frame and Newbould 1986; Whitehead 1995) because of its wide climatic range, high nutritional quality and digestibility, and the significant contribution it makes to a perennial ryegrass white clover pasture through the fixation of atmospheric nitrogen (N). It grows well in association with perennial ryegrass. It is tolerant of frequent defoliation and grazing as its growing point is at or just below ground level. In recent years there has been renewed interest in white clover use on farms because of the cost/price squeeze at farm level, and increased importance of environmental sustainability at farm level.

Herbage production

White clover can play a role in the development of grass based milk systems by reducing the costs of N fertiliser and to some extent flattening the curve of annual DM herbage production (Frame and Newbould, 1986; Riberio Filho *et al.*, 2003). Productivity of white clover in mixed pastures with perennial ryegrass is influenced by a number of climatic, soil and management factors. Within management factors N fertiliser use and the control of sward height by grazing livestock are two vital factors (Ledgard *et al.*, 1995). The proportion of white clover in a sward is generally highest in the summer and lowest in the winter. White clover and perennial ryegrass have different temperature responses and different seasonal growth patterns (Davies, 1992). As for most plants, white clover growth and plant morphology are influenced by cultivar, climate, soil type, companion species, radiation, day length, temperature, soil water, farm management practices (rotational grazing or set stocking, fertiliser regimes, etc.) and grazing effects (Frame and Newbould, 1986; Harris, 1994). White clover has a lower growth rate than perennial ryegrass at temperatures below 10^0C, but its growth rate continues to increase up to 24^0C, whereas perennial ryegrass peaks at 15 – 20^0C (Davies, 1992; Frame and Newbould, 1986). Growth rates of perennial ryegrass peak in mid-summer in temperate regions and subsequently decline, while white clover growth rate reaches a maximum in late summer, coinciding with the reduction in perennial ryegrass growth (Davies, 1992). This results in a considerable increase in the proportion of clover in the harvested DM material (Davies, 1992) at this time. As a consequence of this low clover growth before mid-summer, the strategic use of N fertiliser on grass clover swards in the spring is commonly practiced to increase total herbage yields in spring, compared with swards reliant solely on N fixation (Humphreys *et al.*, 2009). However, this N fertiliser application may reduce sward clover content if correct grazing management techniques are not practiced. White clover content reduction in mixed swards is usually more severe when high herbage masses are allowed to accumulate (Laidlaw *et al.*, 1992). Harris and Clark (1996) have shown that frequent and tight grazing can enhance white clover content and yield in mixed swards.

White clover monocultures can grow up to 12 t DM/ha in temperate regions; however, clover monocultures are unable to supply the energy requirements of milk solids production in intensive dairy systems and those yields are highly unrealistic in intensive grazing systems. Greater yields are obtained from mixed perennial ryegrass and white clover swards, and even these can fail to meet the energy requirements of lactating dairy cows, especially in early spring and autumn, and so require N fertiliser application and concentrate supplementation.

Nitrogen saving versus increased stock carrying capacity

Many studies (Harris *et al.*, 1996; Clark and Harris, 1996) have found that high N fertiliser application levels can reduce sward clover content. Perennial ryegrass is more efficient at taking up N applied as fertiliser than white clover and as a result perennial ryegrass will grow at a faster rate than the clover and the competition between species particularly for light, results in shading of the clover and may also result in water and nutrient stress (Blackman and Black, 1959). Over a three year period Ledgard *et al.* (1995) found that N fertiliser application reduced the proportion of white clover in the sward by as a much as 30%. Ledgard *et al.* (1995) and Harris *et al.* (1996) found that white clover content was not affected by N fertiliser application during the spring and summer, suggesting that N fertiliser application did not have an effect on white clover content of the swards.

Environmental impact

Artificial fertiliser N requires a considerable amount of energy for its manufacture and use, which has an environmental consequence. Increased use of forage legumes offers some potential to mitigate these effects. The substitution of forage legumes for inorganic N fertiliser will reduce the quantities of non-renewable resources required to manufacture and distribute fertiliser (Rochon *et al.*, 2004).

N Leaching

Overall N leached from pasture is related to level and intensity of the defoliation activities placed on the sward and whether they are cut or grazed (Wachendorf *et al.*, 2004). Generally, in swards that are fertilised or where there is a grass clover component to the sward there are significant N surpluses. The level of leaching depends on the soil type and level of surplus organic N built up in the soil. However, the level of surplus N is only an indicator of the N leached from the sward with leaching significantly less than the surplus N. A number of studies have shown relatively low rates of nitrate leaching from beneath legume swards; however the evidence is not conclusive (Owens *et al.*, 1994; Fillery 2001). Some studies comparing clover/grass and N fertilised grass only pastures at similar levels of total N input have indicated similar levels of nitrate leaching losses (Ledgard *et al.*, 2009).

Nitrous oxide

Nitrous oxide (N_2O) emissions from grazed pastures due to N cycling from excreta are similar for clover/grass and N fertilised grass-only pastures at similar total N inputs (Ledgard *et al.*, 2009). However, when artificial N is applied to grassland N loss in the form of N_2O emissions from surplus N, and so higher N_2O losses are associated with artificial fertiliser application in grass based systems compared to systems relying on N fixation from clover. The N_2O losses reported form grazing dairy systems in New Zealand and Australia range between 6 to 11 kg N_2O -N per hectare per year (Luo *et al.*, 2008). It would be expected that at comparable levels of production it is likely that N_2O emissions resulting from N cycling from animal excreta would be similar for both clover/grass and grass pasture, however additional losses N losses associated with the fertiliser would be expected where fertiliser was being applied =. In Australia the N_2O losses increased from 6 kg/ha/year to 13 and 15kg/ha/year when approximately 200kg of chemical N was applied in differing formulations. In New Zealand the losses increased from 3.4 kgN/ha to 19.3 kg/ha when there was 400 kg of N fertiliser applied (Ruz Jerez, White and Ball, 1994). The level of loss is multiplied when the soil becomes compacted and there is a build-up of moisture in the soil. There is very poor information available on the actual N losses associated with N_2O in the form of clover N or artificial N in the literature.

Methane

Enteric CH_4 fermentation (hereafter referred to as CH_4 emissions) accounts for up to 49% of the total greenhouse gas (GHG) emissions (Casey and Holden, 2005). Previous studies have reported that net CH_4 emissions can be reduced on a per product basis if animals can be more efficient (Eckard *et al.*, 2010; Buddle *et al.*, 2011), *e.g.* achieving greater output for same feed intake. Methane emissions related to gross energy intake of animals fed with legumes are lower than animals fed with grasses (Waghorn *et al.*, 2006; Beauchemin *et al.*, 2008). However, while some work has shown that clover inclusion into pasture can reduce dairy cow CH_4 emissions (Lee *et al.*, 2004) others have found no effects (Van Dorland *et al.*, 2007). In an Irish study, it was shown that cows grazing grass clover swards produced 3.0 g CH_4/kg dry matter intake (DMI) less than the cows grazing perennial ryegrass swards (Enriquez-Hildalgo *et al.*, 2013).

Clover and the interaction with the rumen

White clover has a higher nutritive value than perennial ryegrass due to structural carbohydrate content, higher digestible protein and a faster rate of passage through the rumen. These qualities can result in higher herbage DMI and subsequently increased milk production compared to pure perennial ryegrass swards (Harris *et al*, 1997; Woodfield and Clark, 2009). White clover has a higher nutritive value per unit DM than that of perennial ryegrass (Clark and Harris, 1996). For grazing animals, white clover compares favourably with grass, being high in protein and minerals and low in structural fibre, and unlike grass it maintains a high level of digestibility as it matures (less stemy material) (Davies, 1992). The cell wall content of white clover is approximately half that of perennial ryegrass of similar digestibility, and the principle difference between perennial ryegrass and white clover is that the hemi-cellouse is a fraction of the cell wall (Thomson, 1984). Research has shown a benefit of white clover over perennial ryegrass swards for milk production, particularly in the second half of lactation (Riberio Filho *et al.*, 2003; Harris *et al.*, 1998). This increase in milk production is due to a combination of both feed quality and intake factors (Harris *et al.*, 1998; Clark and Harris, 1996). The superiority of white clover over perennial ryegrass for milk production occurs under ad libitum and restricted levels of feeding (Clark and Harris, 1996). Harris *et al.* (1997) found that cows fed diets containing 65% clover had milk yields equivalent to 98% of the milk yield produced by cows fed 100% clover. With the high nutritive value of perennial ryegrass during the spring and early summer along with high growth rates (Harris *et al.*, 1997; Brereton, 1995) the benefit from increased white clover content during spring and early summer is likely to be relatively small (Harris *et al.*, 1997). The lower structural fibre/cell wall of white clover seems to be a main reason for the higher DMI relative to grass when feeding with white clover (Davies, 1992). Thus in a grazing situation increasing clover content in the diet may result in increased DMI in the second half of lactation. Cows grazing white clover spend less time ruminating (Harris *et al.*, 1998) due to clovers lower retention time in the rumen, lower bulk density, and the relatively higher amount of herbage that enters the small intestine, and can therefore graze for a larger proportion of the day (Clark and Harris, 1996; Harris *et al.*, 1998). White clover in the sward can result in a higher rate of passage through the rumen; this faster rate of passage is explained by the lower structural fibre/cell wall and lower resistance to mechanical breakdown by chewing. Some studies (Harris *et al.*, 1998; Riberio Filho *et al.*, (2003) have shown that cows grazing white clover swards have higher voluntary DMIs than those on perennial ryegrass only swards, although the difference in intake between the two diets varies, depending on stage of lactation and the energy requirements of the animal.

Economic benefit

Chemical fertiliser N costs have increased dramatically over the past number of years driven by increases in demand and increased energy costs. Including clover has the potential to allow an increase in stock carrying capacity and/or reduced use of chemical N fertiliser. Recent research showing the potential for clover when managed in combination with chemical N at higher stocking rates indicates that there is significant potential for clover to act in combination with chemical N fertiliser to increase the profitability of grass based ruminant production systems.

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Feeding more maize and less grass

For farm modelling in the Animal Change project, Component 3
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Objective

Increase the part of area dedicated to maize production and decrease that to grass on farm and at the same time feed more maize and less grass.

(It was original suggested that DM intake from maize:grass silage should be I) 50:50 and II) 25:75 respectively).

This option can change many GHG emissions: enteric CH_4, manure CH_4, N_2O emissions, ammonia emissions, C sequestration, CO_2 fossil source.

Assumption for farm modelling

- Maintain constant the area dedicated to roughage production.
- Adapt stocking rate (and thereby milk/meat production) according to the change in the forage production and quality.

(This measure will only be about maize silage, not silage from wheat or barley). For farms where maize is not economic to grow, we don’t model this measure.

Input variables/parameters affected

- Change in land use to obtain higher DM production from maize and lower from grass silage
- Diet changed (decreased grass silage, increased maize silage and type of concentrates changes (for example cereals to soy bean/rape seed cake to maintain crude protein content in the ration)
- Mineral fertilization and manure production changes will automatically be calculated by Farm AC, when area grown with grass and maize as well as the feed ration are changed

- Milk production and composition are as a starting point assumed to be unchanged or alternatively, can be adjusted by the local expect according to what is expected due to the chances in nutrients caused by change in the feed ration
- Average selling price of milk are assumed to be unchanged
- Time spent indoor are assumed to be unchanged as the same total amount of roughage and grass grazed is used in the feed ration

Major changes in GHG emissions

Enteric CH_4

Enteric methane is produced when especially carbohydrates but also amino acids and glycerol are digested in the rumen. Amount of methane produced can be manipulated by changes in the feed composition. Starch causes a lower methane production than sugar, whereas it is difficult to show differences in methane production depending on type of starch, even though degradation and rumen digestibility differ. Starch from roughage also causes a reduced methane production, where maize silage causes a lower methane production than grass silage (Johannes *et al.*, 2011).

In a newly conducted Danish study, Brask *et al.* (2013) compares three different silages in a 6x4 incomplete Latin square also including the effect of adding supplement with or without cracked rapeseed (extra fat):

- EG: Early grass clover, harvested 26th may (329 g NDF/kg DM)
- LG: Late grass-clover, harvested 15th of June (484 g NDF/kg DM)
- MS: Maize silage (390 g NDF/kg DM).

The TMRs contain 64% forage (of DM) from one of these silages.

As can be seen in Table 1, a late cut of grass and a higher content of fiber and lower digestibility, result in a higher CH_4 production. Whereas for early cut of grass, and maize silage CH_4 production was reduced by 9 and 17% respectively compared to late cut grass silage. This indicates that highly-digestible grass silage can be as favourable as maize silage for reducing CH_4 emission.

Table 1. GHG from enteric fermentation of grass versus maize silage in TMRs contain 64% forage (of DM) from one of these silages (Johannes *et al.*, 2011).

	EG	LG	MS
DM intake, kg/d	17.6	16.0	17.6
ECM, kg/d	24.8	21,8	26.0
CH_4, L/d	539	542	495
CH_4, L/kg total DM intake	29.0	31.8	26.5
CH_4, l/kg ECM	21.7	24.9	19.0
Relative **CH_4**/kg DMI	91	100	83
Energy loss as **CH_4**, % of GE intake	6.1	6.7	5.4

However, some earlier studies (McCourt *et al.*,2007; Doreau *et al.*, 2011) found that grass hay or silage and maize silage did not differ in CH_4 production, but Staerfl *et al.* (2012) found in agreement with the Danish study a lower CH_4 production per kg DMI in fattening bulls receiving maize silage compared with grass silage (cf. Brask *et al.*, 2013)

4.2.6.2. C sequestration

Enhancing carbon (C) sequestration in soil is a way to reduce GHG emissions and increase soil fertility. C sequestration happen when we add biomass, however the carbon will not stay in the soil forever. Amount of C in the soil depend on the balance between C input and C output. C sequestration is stimulated by crop residues left in soil, use of manure, especially deep litter, perennial grass and catch crops.

However, the size of the sequestration potential is debatable. As a first estimate, GHG contribution from C sequestration was calculated according to Vleeshouwers & Verhagen (2002). Later Farm AC will be updated to account for changes in soil carbon taking into account results from Animal Change.

Vleeshouwers & Verhagen (2002) assume that growing grass works as a sink for C, whereas growing other crops is causing a release of C from soil. Carbon sequestration in grassland crops were estimated to 0.52 Mg C/ha/year (191 g CO_2/m^2/year), whereas growing other crops is assumed to cause release of C from soil corresponding to 0.84 Mg C/ha/year (308 g CO_2/m^2/year) (Vleeshouwers & Verhagen, 2002).

Table 2 shows contribution from soil C (based on Vleeshouwers & Verhagen, 2002) using crop productivity for growing grass and maize under Danish condition (Mogensen *et al.*, 2011).

Table 2. GHG from changes in soil C from grass versus maize silage production

	Grass-clover silage	Maize silage
Crop yield, kg DM/ha	8300	11300
Manure input, kg N/ha	170	170
Fertilizer input, kg N/ha	118	39
Carbon foot print from growing, g $\mathbf{CO_2}$/kg DM	389	210
Contribution from soil C [1)] g $\mathbf{CO_2}$/kg DM	**-231**	**272**
Total CF including soil C, g $\mathbf{CO_2}$/kg DM	158	482

[1)] based on Vleeshouwers & Verhagen, 2002: positive number means C sequestration whereas negative number means C release

Change in manure CH_4, N_2O emissions, ammonia emissions, CO_2 fossil source

The changes will be calculated by the Farm AC model when the above changes in input variable has been done

Combined effect on GHG emissions of grass versus maize silage in the feed ration

Under Danish condition, GHG contribution from growing 1 kg DM of maize silage is lower than from growing 1 kg DM of grass-clover silage (Mogensen *et al.* 2011, Table 1, before taking into account soil C) (this will be calculated by Farm AC). Furthermore, CH_4 from enteric fermentation of maize silage is 8% lower than from grass clover silage assuming an average digestibility of grass silage (Table 1).

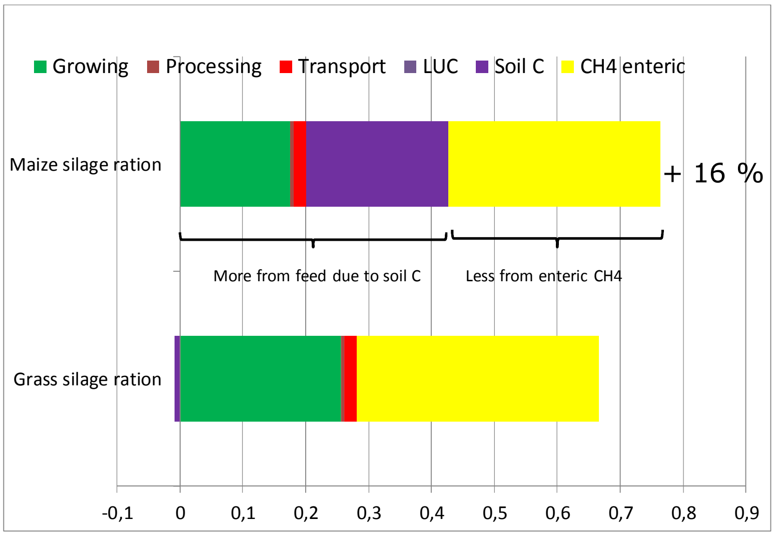

Figure 1. GHG from feed and CH_4 enteric, kg CO_2-eq/kg ECM (Mogensen *et al.* 2011)

However, if taking into account contribution from soil carbon as suggested in Table 2 this will more than set off the positive effects on GHG of growing and feeding maize silage, thereby the ration with grass-clover silage will have the lowest GHG emission. As can be seen in Figure 1, the maize silage ration ends up causing 16% higher GHG emissions per kg ECM (including GHG from growing the feed and enteric fermentation of the feed).

Finally, it has been shown that reduced enteric CH_4 production can increase the methanogenic potential of the slurry (Külling *et al.*, 2001) and a study with fecal samples from the Danish study by Brask *et al.* (2013) conducted by Møller (2012) showed that this that valid. Therefore, reducing CH_4 emission by reducing digestibility can be counteracted by increased fermentation in the slurry, which is only favourable if the slurry is used for biogas (Brask *et al.*, 2013).

Therefore, the effect of maize versus grass as a mitigation option is highly depended on the assumptions, the boundaries of the study and the method used to include contribution from soil C. But also the quality of the grass clover silage and the regional relation between crop yields in grass and maize will be very important for which effect should be assumed..

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Feeding more fat with ruminants

For farm modelling in the Animal Change project, Component 3
Authors: P. Faverdin (INRA PEGASE), M. Doreau (INRA UMRH)

Objective

Reduce CH_4 emissions due to rumen fermentation by the addition of lipids in the diet.

Assumptions for farm modelling

- The measure is only applied to ruminants.
- The animal performance are changed, which has to be considered.
- Diet formulation increases the proportion of unsaturated fat as a substitute to other sources of energy with an appropriate choice of compounds to reach a 5% lipids content in the diet.
- Consider if the distribution of these new compounds is possible for each specific farming system. Generally, distribution of concentrates should exist in the reference situation.
- Formulation is based on local circumstances and available feedstuffs.
- CH_4 emissions from manure are assumed to be constant.

Further guidance for the farm experts

- Formulation:
    - If the supplement of concentrate with the fatty acid content of the diet is less than 5% replace conventional concentrated concentrate enriched oils to a value of 5% of fatty acids in the diet.
    - With the formulation established for concentrated food, calculate the change in quantities of grain and meal.
    - Calculate the fatty acid supplement versus conventional operation, and after the mitigation of methane on the basis of 4% reduction (mean value) for 1% added fat. The lower limit and upper limit are 3.2 and 4.8% loss to 1% added fat.
- Costs:
    - Feed costs of the concentrate have to be recalculated according to the change in the formulation and the price of the different compounds. The cost of extruded compounds is generally increased. Other costs or benefits could be neglected if the formulation considers the recommendations proposed in this action.

Model variables and parameters affected

Parameter	Unit	Likely range of change	Farm type/AEZ	Reference
Proportion of feed components		to be defined by local farm experts		
Cost of feed		to be defined by local farm experts		
Enteric CH_4 emission factor		to be defined by local farm experts		
Milk production and composition		To be defined by local farm experts only if the maximum proposed of 5% lipids is exceeded.		

Rationale and mechanism of action

Carbohydrate fermentation in the rumen is achieved by a complex ecosystem of bacteria and protozoa. It produces volatile fatty acids, which are the main source of energy for ruminants, and also carbon dioxide and hydrogen. Methane is normally produced in the rumen by methanogenic archaea, microorganisms that convert hydrogen to methane. The conversion of carbohydrates into volatile fatty acids is done in two concurrent paths, the first leads to the formation of acetate and butyrate and produces hydrogen, the latter results in the formation of propionate and consumes hydrogen. There is a net production of hydrogen, because the path of acetate and butyrate is more important than the way propionate. This orientation is related to the balance of the bacterial population in the rumen (flora cellulolytic or amylolytic) and protozoa population. Diets rich in cellulose (grass-products rich in plant cell walls) preferentially produce acetate, diets rich in starch (cereals) preferentially produce propionate. In addition, protozoa are major hydrogen producers. Unsaturated fats (especially polyunsaturated) reduce cellulolytic bacterial populations and / or protozoa, and thus the production of hydrogen.

Proposed actions to increase the proportion of unsaturated lipids in the diet

Lipids, whatever they are, are digested in the intestine and are not producing methane in the rumen, unlike carbohydrates they replace in the diet. In addition, some sources of fat (unsaturated among others) affect the microbial ecosystem in a direction towards a reduction in methane emissions (Popova *et al.*, 2011).

Some sources of fat are more effective to reduce methane than others. In order from best to least effective: medium chain fatty acids, linolenic acid, linoleic acid, saturated fatty acids 16 and 18 carbons and oleic acid. But it has not been shown that the average efficiency differences are statistically significant. The magnitude of the effect is related to changes in the microbial ecosystem under the influence of lipids. These are the strongest for fatty acids and medium chain linolenic. For oleic acid, the results are highly variable. The dose-response effect is unclear. According to a test conducted with flax seed, the effect would be small when adding fat is less than 2%, but this does not appear in a quantitative analysis of the literature (Doreau *et al*, 2011.). It should be noted that the effect of fat seems to maintain over the long term (Grainger and Beauchemin, 2011). This was especially observed for linolenic acid flaxseed after a year of distribution by Martin *et al.* (2011).

It is proposed to prefer the use of a mixture of oilseeds (rapeseed and linseed half each) extruded, and secondly oils (soybean and rapeseed half each) to incorporate in the concentrates.

To simplify the problem, it is proposed to take a common reduction in the average efficiency of enteric methane emission for all sources of fat for two reasons: firstly the variability in the experimental data and the imprecision on separate for each lipid source estimates, other from greater flexibility in the use of different sources of fat according to their market availability and cost. If the estimations of Grainger and Beauchemin (2011) and Doreau *et al.* (2011) are used, this average value is lower than 4% methane per unit of added fat in the feed, expressed as% of dry matter. The maximum intake of unsaturated fat is limited in part by the risk of decreased digestibility of the ration in particular cellulosic fraction (and therefore animal performance) related to changes in the microbial ecosystem, other share the risk of excessive growth of trans mono-unsaturated fatty acids as possible deleterious effect on the nutritional value of milk and meat. If a reasonable increase of 3.5 percentage points of lipids (*e.g.* ration from 1.5 to 5% of fatty acids in the dry matter) is fixed, it is possible to exclude these negative effects of fat intake. This increase results in an average reduction of 14% methane. In practice, lipids cannot be distributed in controlled amounts in all cases. It is possible when the ruminants are in barn, or at pasture but return every day to the barn (case of dairy cows). When the small amounts of concentrate are distributed, it will be difficult or impossible to reach 3.5% more lipids in practice. Extruded mixtures contain about 25% fat. It is proposed to distribute first the mixture of extruded up to 10%, and if necessary complete with concentrates rich in oils. The final formulation does not to exceed 5% of fatty acids in the diet. However, other formulation can be considered if local reasons support other solutions.

Other effects of the action

If the use of lipids in substitution with other sources of energy in concentrates is carried out as proposed (concentrate with the same energy and protein values), no significant change in milk or meat production is expected, except an increase in the proportion of unsaturated fat, which sometimes can increase the value of products. Otherwise, if the experts prefer to add more lipids for specific reasons they have to consider with good references all the possible impacts on intake, digestion, production and composition of products.

Effects neglected

The effect of lipids on the other greenhouse gases is largely unknown. The weak effect of fat intake on the digestibility of rations linked to an apparent digestibility only slightly higher than its rations supplemented with lipids (Doreau and Ferlay, 1994) suggests that non-digestible organic matter varies little, so that the production of methane from manure is little changed. Similarly, the fat intake low interfering with the digestion of nitrogen, fecal or urinary nitrogen losses are little changed. A study on beef and dairy cattle on a study recently showed that the introduction of flaxseed in the diet had a very small impact on other greenhouse gas emissions and other environmental impacts (Nguyen *et al.*, 2012, 2013), but to our knowledge there has been no study with other oilseeds. In the current state of knowledge, it can be assumed that unsaturated fats have no significant effect found on greenhouse gas emissions other than methane.

As the calculation of the emissions in this WP does not included the emissions due to the inputs before its use on farm, the substitution between cereals and products rich in lipids will not be considered. The experts have to avoid the substitution of cereals produced on farm by extruded seeds produced outside. Part of the change of the emissions will only be change to the change in the boundaries of the system.

Cost data

The cost of this action is mainly linked to the cost of the feeds. The changes in the cost of the diet have to be adapted according to the price of feeds in each country. However, if the experts prefer to add more lipids for specific reasons that the 5% proposed, they have to estimate the other cost on production and consumption.

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Additive nitrate

For farm modelling in the Animal Change project, Component 3
Authors: P. Faverdin (INRA PEGASE), M. Doreau (INRA UMRH)

Data to be provided by local experts

Formulate new diet with 1.5% nitrate (= 2.37% Calcinit ($Ca(NO_3)_2$), equivalent of 0.369% N in the diet), replacing other N sources, prioritising urea:

- if urea ≥ 0.8%, then replace 0.8% urea
- if no urea in the diet, then reduce the protein content by 2.31% (Ask Ph F again about this)
- if 0% ≤ urea ≤ 0.8%, then replace all urea and also other protein sources (*e.g.* soybean meal, rapeseed meal) proportionally

Finances: most probably local nitrate price is not available, so there is no need for this information from the experts.

Objective

Reduce CH_4 emissions due to rumen fermentation by the addition of nitrate in the diet.

Assumptions for farm modelling

- The measure is only applied to ruminants.
- The animal performance (weight gain) is not changed.
- The diet's energy content is constant.
- Diet formulation incorporates nitrates as a substitute to other sources of highly fermentable proteins or to non protein nitrogen compounds.
- Consider if the distribution of this small amount of nitrate is possible to distribute to the animals for the particular farming system (difficult in ranching situation for example). It will be assumed that the option will be applied if the individual dose can be controlled (individual dosing or careful mixing with roughage).
- Feed formula is set to minimise price. Formulation is based on local circumstances.
- CH_4 emissions from manure are assumed to be constant.
- If some farming systems are producing animal products with some specific rules (PDO, AOP…) specifying that the use of urea (or other similar compound) is not allowed, the use of nitrate should not be considered as an option.

Further guidance for the farm experts

- Formulation:
    - o As nitrate could toxic for the animal and is not authorized in many countries today, the possible method to use it is still unkown. Nitrates will be substitute to other sources of highly fermentable proteins or to non protein nitrogen compounds at a maximum dose of 1.5% nitrate.
- Costs:
    - o Feed costs of this feed compound is largely unkown today because it is not sold for this purpose. It will be assumed that its use will generally be limited to farming systems where equiment for the supplements distribution exists (substitution to other feedstuffs). If not, this cost should be added.

Model variables and parameters affected

Parameter	Unit	Likely range of change	Farm type/AEZ	Reference
Proportion of feed components		to be defined by local farm experts		
Cost of feed		to be defined by local farm experts		
Enteric **CH_4** emission factor		to be defined by local farm experts		

Rationale and mechanism of action

Carbohydrate fermentation in the rumen is achieved by a complex ecosystem of bacteria and protozoa. It produces volatile fatty acids, which are the main source of energy for ruminants, and also carbon dioxide and hydrogen. Methane is normally produced in the rumen by methanogenic archaea, microorganisms that convert hydrogen to methane. The conversion of carbohydrates into volatile fatty acids is done in two concurrent paths, the first leads to the formation of acetate and butyrate and produces hydrogen, the latter results in the formation of propionate and consumes hydrogen. There is a net production of hydrogen, because the path of acetate and butyrate is more important than the way propionate. Nitrate is rich in oxygen, easily used in an anaerobic system like the rumen. With nitrates, oxygen is replaced by hydrogen with formation of ammonia, preferably with methane being formed. In short, it is possible to consider that nitrates prevent the formation of methane. The review of Leng (2008) presents a comprehensive background on the use of nitrates in different ruminant species.

The role of nitrate on enteric methane emissions has been demonstrated in vivo in several trials effect, including the long term (Van Zijderveld *et al.*, 2011). The level of emission reduction achieved in vivo following an intake of nitrate is also quite similar from one test to another. Until recently, all published trials came from the same team, but a recent trial involving researchers from different countries has been achieved with consistent results (Hulshof *et al.*, 2012).

Proposed actions to incorporate nitrate in the diet

The proposed action consists to replace the different sources of highly degradable proteins or nitrogen with the use of nitrate. Nitrates will be substitute to other sources of highly fermentable proteins or to non-protein nitrogen compounds at a maximum dose of 1.5% nitrate. The new diet should be balance to maintain constant the energy and metabolizable protein content of the diet, and to reach the same level of degradable nitrogen if this level is close to the recommendation or higher in the reference situation, to increase it up to the recommendation, if there is a deficit in the reference situation. The calculation should normally be made by the experts using their favourite feeding systems available for protein (PDI, DVE and OEB). In theory, it is difficult to consider with diet based on forages rich in protein (grass, grass silage). In this case, the addition of nitrate will lead to a too high content of degradable protein, which could be a problem. The maize or sorghum based diets are probably the best candidate for this option, but not only (poor roughage can also be considered). If it is allowed, it is possible to increase the proportion and protected protein (formaldehyde treated meal for example) to increase the proportion of nitrate in the diet.

No commercial form of nitrate for animal nutrition is available today. It is propose to base the calculation on the virtual use of the Calcinit (trade name Calcinit ®, including 63% of nitrates) a product derived from ammonium calcium nitrate double salt and normally used for fertilization. As the value of PDIN kg urea is 1472 g, it could be assessed that the value of Calcinit ® is 589 g / kg of dry matter, 489 g / kg crude, based on the number of nitrogen atoms which will be integrated into ammonia molecules. Distribution of 1% of nitrate in the diet corresponds to 1.58% of Calcinit ®. It corresponds to a reduction of 0.53% urea.

Different tests have shown that a dose of 2.2 to 2.6% of nitrates added to the diet (NO_3 equivalents) resulted in a decrease in methane production from 16 to 31%. Considering a linear response, the expected reduction of enteric CH_4 emission will be close to 10% for 1% of nitrates in the diet. As a maximal dose of 1.5% is proposed to avoid possible risks of nitrates on animal health, the maximal response expected should not exceed 15%.

Other effects of the action

If the use of nitrates increases the N content of the diet, it must be considered for the other effects associated to an increase of N excretion (see mitigation option on the reduction of CP content of the diet). However, if the nitrates are used in substitution to other sources of degradable nitrogen as recommended, this effect has not to be considered.

Effects neglected

The emissions of the feed components are not considered in this package. However, the CO_2 emission associated to the production of nitrate is unknown, but could probably be considered negligible compared to the CO_2 cost of the diet, which is very likely. Moreover, the nitrates in theory replace a portion of the urea ration, so another additive industrial production.

Nitrate is able to produce nitrite which is known to react with haemoglobin in an irreversible manner (methaemoglobin). At high doses, this can of course induce health problems and generate some change in animal production. However, it will be assumed than the doses given and the feeding process will limit the problem and that the production will not be affected.

Cost data

The cost of nitrates is difficult to assess because it is not yet commercially available for introduction in the diet of animals. Of course, artificial fertilizers cannot be added to the ration just like that, due to the great risks of undesirable other substances. Fertilizer producer Yara from Norway has set up a special animal feed line for the production of nitrate that is suitable as feed additive for ruminants (Newsletter KTC De Marke, No 4, May 2013), but the price is unknown. An idea of price could be extrapolated from the fertilizer with a supplement due to the preparation for animal. The product sold under the name Calcinit ® is located at prices ranging between 230 and 2050 € / t for deliveries from 20 to 25 T (www.alibaba.com website) without the possibility of have information on the quality of the product. It is proposed to use an average price similar to the cost of urea, which is about 860 € / T in France. The changes in the cost of the diet have to be adapted according to the price of feeds in each country.

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Balance amino acids and reduce CP in pigs

For farm modelling in the Animal Change project, Component 3

Authors: P. Faverdin, F. Garcia-Launay, J. Y. Dourmad (INRA PEGASE)

Objective

Reduce the crude protein (CP) content of the diet without changing the animal performance, by using phase feeding and amino acids supplementation. Diet energy content is assumed to be constant. The expected change in GHG emissions concerns mainly N_2O either directly or indirectly (NH3).

Assumptions for farm modelling

- The measure is only applied to pigs.
- The animal performance (weight gain) is not changed.
- The diet's energy content is constant.
- Two-phase feeding using synthetic essential amino acids in the formula to reduce the CP content of the diet.
- Feed formula is set to minimise price. Formulation is based on local circumstances.
- CH_4 emissions from manure are assumed to be constant.
- Adjustment of mineral N fertilization has to be considered according the farm practices (important in systems where the conservation of excreted nitrogen until spreading is high, and if the additional mineral fertilization is exactly adjusted to the nitrogen supply to the crops or grass), with the objective to maintain crop production.

Further guidance for the farm experts

- Formulation:
    - L-Lysine HCL, L-thréonine, DL-méthionine, L-tryptophane and Valine are currently available for feed formulation.
    - INRAporc (2006) is a free available to formulate pig diet.
- Costs:
    - Feed costs for Europe are proposed in Table 1 if no other data are available.

Model variables and parameters affected

Parameter	Unit	Likely range of change	Farm type/AEZ	Reference
Proportion of feed components		to be defined by local farm experts		
Cost of feed		to be defined by local farm experts		
Mineral N fertilisation of crops		to be defined by local farm experts		

Rationale and mechanism of action

Nitrous oxide (N_2O) emissions associated with manure management have a significant impact in GHG emission and are produced in the animal building, during manure storage and manure spreading. They come from food nitrogen not retained by the animal, but excreted in the faeces (in a relatively stable form), and – mainly – in the urine as urea. The amount of urinary nitrogen is high in monogastric animals, representing from 70 to 80% of the total nitrogen excreted. Urea is very unstable and is converted into N_2O and ammonia (NH_3) which itself can lead to N_2O emissions. The evolution of NH_4^+ in NH_3 or N_2O depends on the building type and method of effluent management.

These emissions can be reduced by better adjusting the amount of protein to the needs of animals, and improving the quality of these proteins and thus their use efficiency. The decreases in nitrogen intake in pigs effectively reduce excretion: a decrease in the protein content from 20% to 12% can reduce 67% NH_3 emissions during manure storage.

The aim is to implement this strategy with little or no impact to production. The action is applied to pigs, which receive large protein food that is easy to control.

Proposed actions to reduce CP content of the diet

The nitrogen excretion can be reduced without the loss of production by two ways:

1. Limiting the total CP in the diet while ensuring coverage of the essential amino acids (AA) (what the body does not produce and must be present in the feed). Many studies have shown that a diet for fattening pigs of reduced protein content decreased the nitrogen excretion and does not affect weight gain or feed efficiency if the energy content and the content essential amino acids are maintained. The industrial production of amino acids is able to deliver more and more types of essential amino acids, which gives new opportunities to reduce CP content of the diet without changing the animal performance.
2. In current practice the animals usually receive a single type of food throughout his life (single-phase feeding) or two types of food, each adapted to a development phase (two-phase feeding). Adjusting the composition of the food ten times during the life of the animal (multi-phase feeding) can reduce the overall amount of protein distributed. The two phase feeding system is the easiest to manage and does not imply new investment. The multiple phase feeding is more efficient but requires special investment to adjust the diet of pigs several times combining two main compounds.

Considering the action for animal change, the more realistic option available consists in a two phase feeding using more synthetic essential amino acids in the formula to reduce the CP content of the diet. L-Lysine HCL, L-thréonine, DL-méthionine, L-tryptophane and Valine are currently available for feed formulation. INRAporc (2006) is a free available to formulate pig diet.

Using formulation tools, it is possible to assess the change in the composition of compounds, but several approaches can be used to formulate them (Mosnier *et al.* 2012). It is possible to minimize the price, the carbon footprint or the CP content of the diet. As the option is considered at farm level, a simple approach of minimizing the price is consistent. It could be oriented by the feedstuff available on farm for pig feeding.

Other effects of the action

Reducing protein intake may affect the fertilizer value of manure: it decreases the total nitrogen in the effluent which can lead to the farmer increasing the use of mineral fertilizers. In practice, the measured nitrogen availability for plants remains high even with a reduced protein content of the diet, suggesting that this change in food has little impact on the fertilizer value of the effluent. However, the adverse effect could be more important in systems where the conservation of excreted nitrogen until spreading is high, and if the additional mineral fertilization is exactly adjusted to the nitrogen supply to the crops or grass. Adjustment of mineral fertilization has to be considered according the farm practices, with the objective to maintain crop production.

Effects neglected

CH_4 emissions could increase due to an increase in fermentation of manure, which could be facilitated by the decrease in NH3 (pH shift). This effect will be neglected because the effect of NH3 is still poorly documented.

Cost data

Table 1: Cost of ingredients (€/t)

Ingredients	Average price 2010-2011 (€/t)	Source
Wheat	191	IFIP
Maize	201	IFIP
Barley	175	IFIP
Wheat bran	130	IFIP
Peas	233	IFIP
Rapeseed meal	212	IFIP
Rapeseed oil	848	La Dépêche
Soyabean meal	326	IFIP
Extruded Soyabean	414	La Dépêche
L-lysine.HCl	1800	Ajinomoto Eurolysine
L-threonine	1950	Ajinomoto Eurolysine
L-tryptophane	9500	Ajinomoto Eurolysine
L-valine	10000	Ajinomoto Eurolysine
DL-methionine	3600	Ajinomoto Eurolysine
Lactoserum Powder	752	FranceAgrimer
Phytase	9500	Relevés mensuels IFIP
Monocalcium Phosphate	650	Relevés mensuels IFIP
Salt	100	Mosnier *et al.* 2011
CaCO3	50	Relevés mensuels IFIP

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Genetic improvement of dairy cattle

For farm modelling in the Animal Change project, Component 3
Authors: D. O'Brien and L. Shalloo (TEAGASC)

Objective

Increase genetic merit of dairy cattle by improving genetic traits for fertility, survival, milk yield and milk composition (fat and protein). The strategy will affect the number of replacement heifers, diet requirements, manure chemical composition, mineral fertiliser requirements and effect most emissions including CH_4, N_2O, NH3, CO_2.

Assumptions for farm modelling

- The measure affects dairy cows and heifers.
- The fertility, survival, milk yield, milk composition and meat performance of dairy cows will all be changed or individually.
- The diet's energy and N content is affected.
- Concentrate and forage feeding is changed according to changes in dairy cow performance and changes in replacement heifers.
- Concentrate feed formulation is set to minimise price. Formulation is based on local circumstances.
- Changes in concentrate and forage feeding will change manure chemical composition and mineral fertiliser requirements
- All emissions will be affected.
- The indirect effects of changes in meat yield from dairy systems on meat production from other sectors such as suckler or monogastric systems will not be considered

Rationale

In general, research studies (*e.g.* Schils *et al.*, 2005; Lovett *et al.*, 2006; Weiske *et al.*, 2006; Beukes *et al.*, 2010) indicate that improving the genetic merit of dairy cows for fertility, survival and milk yield reduces emissions per unit of milk. For instance, previous analysis in the Netherlands by Schils *et al.* (2005) showed that increasing milk yield per cow by 500kg to 8,600 kg reduced greenhouse gas (GHG) emissions per unit of product by 4%, because the total number of cows required to produce a fixed volume of milk was reduced. Similarly, Rotz *et al.* (2010) reported that an increase in milk yield of 16% reduced the carbon footprint per unit of milk by 8% of USA dairy systems in Pennsylvania, but the reduction was due to an increase in feed conversion efficiency (kg of milk/kg of feed) and not a reduction in animal numbers.

Nevertheless, it is important to stress that Schils *et al.* (2005) and Rotz *et al.* (2010) assumed that the increase in milk yield only affected the level of forage and concentrate feeding and did not result in a change in the number of replacements heifers required to maintain the dairy herd. In contrast, Lovett *et al.* (2006), who compared Holstein-Friesian cows with different genetic potential for milk, fed different quantities of concentrate, reported Holstein-Friesian cows with higher milk yields increased emissions per unit of product relative to Holstein-Friesian cows with lower yields. This was because Holstein-Friesian cows with higher milk yields had lower herd fertility rates, which led to a higher ratio between productive and non-milk producing animals, which increased emissions per unit of milk (Lovett *et al.*, 2006).

O'Brien *et al.* (2010) also evaluated the effect of genetic merit of dairy cows on carbon footprint per unit of milk using the phenotypic results of Horan *et al.* (2004, 2005) and McCarthy *et al.* (2007) and Moorepark Dairy System Model (Shalloo *et al.*, 2004). In short, the study assessed GHG emissions from 3 strains of Holstein-Friesian cows differing in genetic merit, blocked across 3 grazing treatments; high grass allowance (2.5 cows/ha with 325kg DM concentrate/cow); high concentrate (2.5 cows/ha with 1,445kg DM concentrate/cow) and a high stocking rate (2.74 cows/ha with 325kg DM concentrate/cow). The results showed that the carbon footprint unit of milk varied by up to 15% between cows genotypes. This was because dairy cows selected solely for milk production were not as fertile as cows selected on the basis of fertility, survival and milk performance. Consequently, higher yielding cows increased emissions from non-milk producing animals and had reduced expected herd lifetime milk performance given the greater proportion of primiparous cows in the herd.

Thus, these findings indicate that it is important to consider a combination of genetic traits to reduce GHG emissions from milk production. However, apart from Lovett *et al.* (2006) and O'Brien *et al.* (2010) few have considered the antagonistic genetic relationship for milk production and fertility traits (Pryce and Veerkamp, 2001). Weiske *et al.* (2006) and Beukes *et al.* (2010) also modelled the effect of improving genetic merit on dairy systems GHG emissions, but only considered the effect of improving fertility. The results of these studies indicated that improvements in fertility reduced the replacement heifer requirement by 10% and decreased GHG emission per unit of milk by an average of 14%. This decrease in GHG emissions occurred due to a decline in emissions from non-milk producing animals. Similarly, Vellinga *et al.* (2011) reported that this strategy reduced GHG emissions per unit of product on commercial dairy farms in the Netherlands. However, modelled reductions were lower than previous studies because the strategy is also determined by farm management (Vellinga *et al.*, 2011).

Mechanism of action

The results of current research demonstrate that a balancing breeding program that improves several economically important genetic traits has a positive effect on emissions per unit of milk. This can mainly be explained by the following factors, which are relevant to grass-based systems and in part to confinement systems:

- Improving fertility, which reduces calving intervals and replacement rates, thus reducing enteric CH_4 emissions per unit of product
- Increasing milk yield per unit of forage and improving milk composition. This increases the efficiency of production, which decreases emissions (Martin *et al.*, 2010)
- Shorter calving interval to increase the proportion of grazed grass in the diet and reduce culling and to increase lifetime herd performance.
- Improved survival and health to reduce deaths and disease, which increases efficiency and reduce emissions

Other effects of the action

Altering the genetic merit of dairy cows also affects meat production from dairy systems. The carbon footprint of meat produced from dairy systems is significantly lower than suckler systems but greater than monogastric systems (Williams *et al.*, 2006; Flysjö *et al.* 2012). Thus, a reduction in the production of meat from milk production systems can have a negative or positive affect on emissions from total milk and meat production. For instance, Zehetmeier *et al.* (2012) showed that to meet a constant demand for milk and meat, increasing milk yield per cow from 6,000 kg to 10,000 kg increased the requirement to produce beef from suckler beef systems, which caused net emissions from milk and meat production to increase.

Effects neglected

The effect a change in meat production from dairy systems has on overall meat production emissions is generally not considered. The main reasons this is not considered is the uncertainty associated with determining the meat and quality of meat that dairy systems replace and the uncertainty in projecting demand for different meat products.

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Agroforestry

For farm modelling in the Animal Change project, Component 3
Authors: Amaury Burlamaqui

System combining in the same area, intercropping associations, including trees, annual and perennials crops, forages and pastures for livestock

Using the word "agro-pastoral" or "agro-sylvo-pastoral" system focuses more on the animal component integrated to the farming system.

Using “Sylvo” makes reference to the forest as an ecosystem (natural or not), or something different than plantations (cultivation) of trees.

Objective

Increase the C rate sequestered in the whole farm system and increase the production of biomass per unit area. The carbon sequestration process occurs into the soil and in the trees biomass planted in the system.

Assumptions for farm modelling

- Address to agroforestry systems including animal component (agro-pastoral, silvopastoral or agro-sylvo-pastoral systems).
- GHGE should be reduced. May be these will increase in the first steps(1), then they will decrease more due to the C stock in the system.
- GGE will increase in the first steps related to the larger use of inputs (fertilizers, agricultural machinery, chemicals) and the higher number of animals in the system.
- The weight gain of cattle doesn’t change.
- The animal gain per unit area in the silvipastoral systems can be decreased and it can be increased in the agrosilvipastoris and agro-pastorales systems.
- The total biomass of the system increases.
- The biomass increase per unit area can contribute to GHGE reductions, due to the sequestration in the soil.

Further guidance for the farm experts

- The N fertilization has to apply to corn and rice crops. Soybean and cowpea don’t require nitrogen fertilizers, due to inoculants use.
- Costs: costs for Amazonia are proposed in Table 1 if no other data are available.

Model variables and parameters affected

Parameter	Unit	Likely range of change	Farm type/AEZ	Reference
Livestock Unit/ha	Unit/ha	450kg – 1350kg	Amazonia	
Plant protection cost	EUR/year/ha	1.09 – 165.38	“	
Machinery cost	EUR/year/ha	8.75 – 273.73	“	
Labour requirement	man-day/year/ha	0.004 – 0.034	“	
Seed buying price	EUR/ha	0 – 92.31	“	
N fertiliser cost	EUR/ha	0 – 115.40	«	
Amount of N fertiliser used	kg N/year/ha	0 – 90	“	
Number of animals	head/ha	0.66 – 3	“	
Feed composition - grazed grass	t/year	15 – 60	“	
Wood quantity	m3/ha	0 – 15	“	
grains production	Kg/ha/an	0 – 8000	“	
Liveweight gain cattle	Kg/ha/an	126 – 600	“	
Soil Carbon seq.	t/ha/an	??		

Rationale and mechanism of action

Increase carbon sequestration

The C sequestration in the system occurs firstly in the trees, secondly in the soil. That depends on the tree species, spatial arrangements and mainly by management of the system.

Increase the production of biomass

In silvopastoral system the biomass increase occurs mainly in the trees.

In agrosilvopastoral the biomass increase is the sum of the three components (trees, crops and cattle).

Proposed actions to increasing the fixation of C in the soil and the production of biomass

Use of forage more adapted to shadow.

Use of trees which interact with grass, legume trees which are good options.

Use spatial cropping designs which optimize the productivity of pasture, the production of total biomass by the system, and C sequestration in the trees and the soil.

Use of pasture management strategies that better respect the cycles of forages.

Other effects of the action

The intensification process based on the higher use of fertilizers and chemicals should increase GGE.

On another hand, the use of no-productive or degraded areas could contribute to deforest for food production.

Cost data

Table1 : Cost of ingredients (€/t)

Ingredients	Average price 2010-2011 (€/t)	Source
Rice (2009)	270	local market Roraima
Soybean (2010-2011)	308	CEPEA
Tecthona grandis (2008)	1000 €/m3	AIMEX
Liveweight cattle (2010)	1282	CEPEA

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Restoring degraded land

For farm modelling in the Animal Change project, Component 3
Authors: R. F. Veloso, R. D. Sainz Gonzalez, L. G. Barioni (EMBRAPA)

Areas of natural vegetation and anthropogenic land in the Cerrado biome (Figure 1 and Table 1) , have incorporated over 54 million hectares of planted pasture, large parts of which are in some stage of degradation (Figure 2; Barcellos *et al.*, 2001;Sano *et al.*,2008).

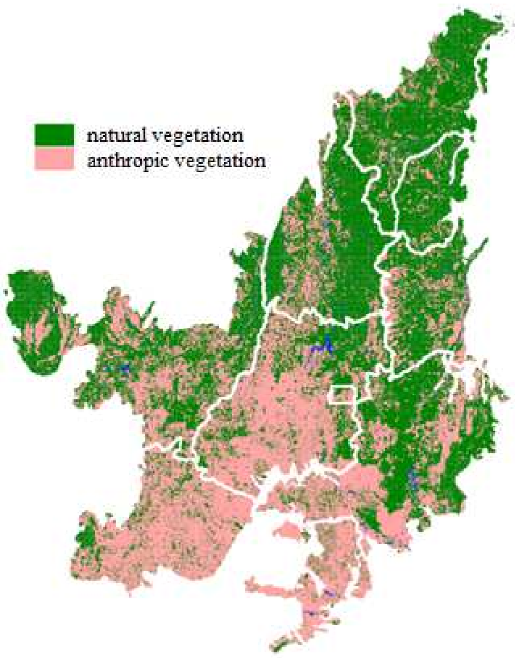

Figure 1 – Areas of natural and anthropic vegetation in the Cerrado biome in 2002. (Source: http://mapas.mma.gov.br/geodados/brasil/vegetacao/vegetacao2002/cerrado/documentos/relatorio_final.pdf

DISCRIMINAÇÃO DE ÁREAS OCUPADAS POR DIFERENTES CLASSES DE COBERTURA VEGETAL EM DIFERENTES REGIÕES HIDROGRÁFICAS DO CERRADO

Região Hidrográfica	Área Total (ha)	Cobertura Natural (Fisionomia)			Cobertura Antrópica		
		Florestal	Savânica	Campestre	Pastagem Cultivada	Cultura Agrícola	Reflorestamento
Atlântico Nordeste Oriental	12.608	12.229	0	0	0	0	0
Atlântico Sudeste	164.823	39.337	12.898	39.661	71.637	0	765
Atlântico Leste	3.324.836	258.122	1.412.885	754.958	343.246	58.354	488.169
Atlântico Nordeste Ocidental	12.477.471	9.382.857	1.762.400	59.606	1.190.119	57.629	24.947
Parnaíba	15.573.672	3.990.222	9.628.843	197.330	820.281	531.373	3.603
Amazônica	15.679.538	4.613.834	6.529.726	45.176	1.747.723	3.216.557	587
Paraguai	18.025.034	2.982.228	5.998.838	290.150	6.721.159	1.961.617	73.197
São Francisco	36.513.093	5.372.339	16.816.462	2.122.813	8.796.498	2.367.198	802.921
Paraná	43.013.213	4.361.310	4.626.543	1.687.526	19.739.907	10.022.347	1.743.860
Tocantins	59.865.603	9.308.907	28.553.023	2.822.305	14.636.989	3.277.530	27.606
TOTAL	**204.649.891**	**40.321.386**	**75.341.619**	**8.019.525**	**54.067.559**	**21.492.604**	**3.165.656**

Table 1
(Source: http://mapas.mma.gov.br/geodados/brasil/vegetacao/vegetacao2002/cerrado/documentos/relatorio_final.pdf)

Reviews on animal production systems that have incorporated pasture (planted and natural) areas have shown that traditional beef cattle production systems persist in Brazil in some regions because even with low (about 50 kg of meat/ha·year) productivity, their low cost makes them still competitive in economic terms as long as the price of land is low .

The production base is crucial for improving the technical and financial efficiency of such systems. This involves aspects such as: soil type, relief, climate, infrastructure (machinery, equipment, buildings, facilities), subdivisions of paddocks, types and conditions of fences, geographic location and logistics (road network access, proximity to consumer centers and suppliers of raw materials, and availability of service providers), and availability and quality of skilled labour. Stocking rate or grazing method and management practices are basic elements for better animal performance (Mendes Peixoto *et al.*, 2003;Silveira Pedreira, 2005;Carneiro da Silva *et al.*, 2009).

According to the agricultural subsidies analysis carried out by Nassar *et al.* (2009), in 2009 Brazil invested around 4% (US$ 56 billion) of the agricultural Gross Domestic Product as green box expenditure. At the same time the total amount available for the EU-15 was 12% (US$ 205 billion). Since then the Brazilian government has undertaken specific domestic initiatives to foster sustainable economic development while reducing GHG emissions.

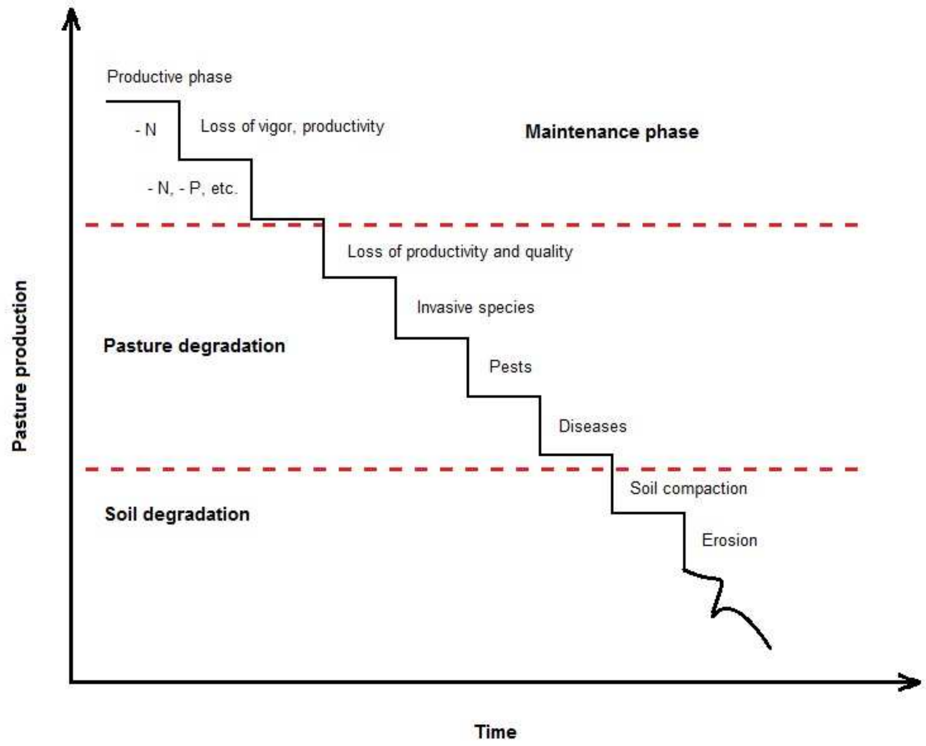

Figure 2: Dynamics of degradation of planted pasture. Adapted from Barcellos *et al.* (2001).

In 2011, the Brazilian Government established the ABC Low Carbon Agriculture Program aiming to promote technological changes in traditional beef cattle production systems and especially for restoration of degraded pastures by the incorporation of new grain crops (soybean and Phaseoulus beans) , cereals (such as: maize and sorghum) and trees (eucalyptus) into crop-pasture rotations. Basically, following environmental criteria, government-subsidized credit (R$ 4.5 billion) has been made available for investments and crop maintenance. Interest rates are very low (5% per year) when compared to the Brazilian capital market. In practice, however, the implementation of the ABC program has been limited due to complex environmental legislation and the bureaucracies that rural producers must face to obtain any agricultural credit in the local public banks.

Restoration of degraded pastures may be carried out directly (*i.e.*, removal of existing vegetation, incorporation of fertilizer and soil amendments and reseeding new pasture species) or indirectly (*i.e.*, through integration of crops and livestock, by cropping degraded lands for 1-3 years (with, *e.g.*, maize and/or soybeans) and then interseeding a new pasture with the last crop). In general, restoration of degraded pastures is best accomplished by the second method, as the direct restoration generally is not economically feasible because its high cost cannot be recovered through livestock production alone. Indirect pasture restoration, on the other hand, can be economically advantageous because income from the grain crop subsidizes the new pasture establishment. Cost-benefit analyses are complicated due to the almost infinite variations of crops, sequences and time periods that may be used. For simplicity, the values below would apply for direct restoration of degraded pasture, without the cropping component.

The restoration of degraded pastures in a traditional beef cattle production system located in the “Cerrado (savannah) biome, would require at least the following inputs to start a technically sustainable and ecologically sound beef production cycle:

Inputs

- Removal of weed species (including shrub regrowth); variable costs depending on state of pasture and technology used (*e.g.*, mechanical, chemical, fire).
- Lime (2 tons/ha, US$150/ha) – applied every 5 years.
- Phosphogypsum (CaSO4 - 500 kg /ha) – applied each 5 years.
- Fertilizer (300 kg 10-10-10/ha.year-1,+ FTE (80/1080),US$200/ha) applied in the first and the second years.However,the fertilization rate after the second year does not requireadditional FTE (Zn, Cu, B, Mn and Mo micronutrients). In the case of additional N application the urea fertilizer costs US$ 650/ton.
- Tilling ($90/ha) –every 5 years.
- Reseeding pasture species (20 kg/ha, US$120/ha + US$ 30/ha for sowing seeds) – applied every 5 years.

Outputs

- Increased stocking rate (1 AU*/ha to 3 AU/ha) (1 AU = 450 kg live weight)
- Increased individual performance (50 kg carcass eq/animal/year to 150 kg carcass eq/animal/year at US$3/kg carcass eq)

For small properties, after the first year, the reseeding and fertilization practices could be carried out by using the equipment shown in Figure 3 which requires less fuel than any tractor.

Figure 3: Low cost application equipment. Further information available at http://www.youtube.com/watch?v=I1IleF2-RPY

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