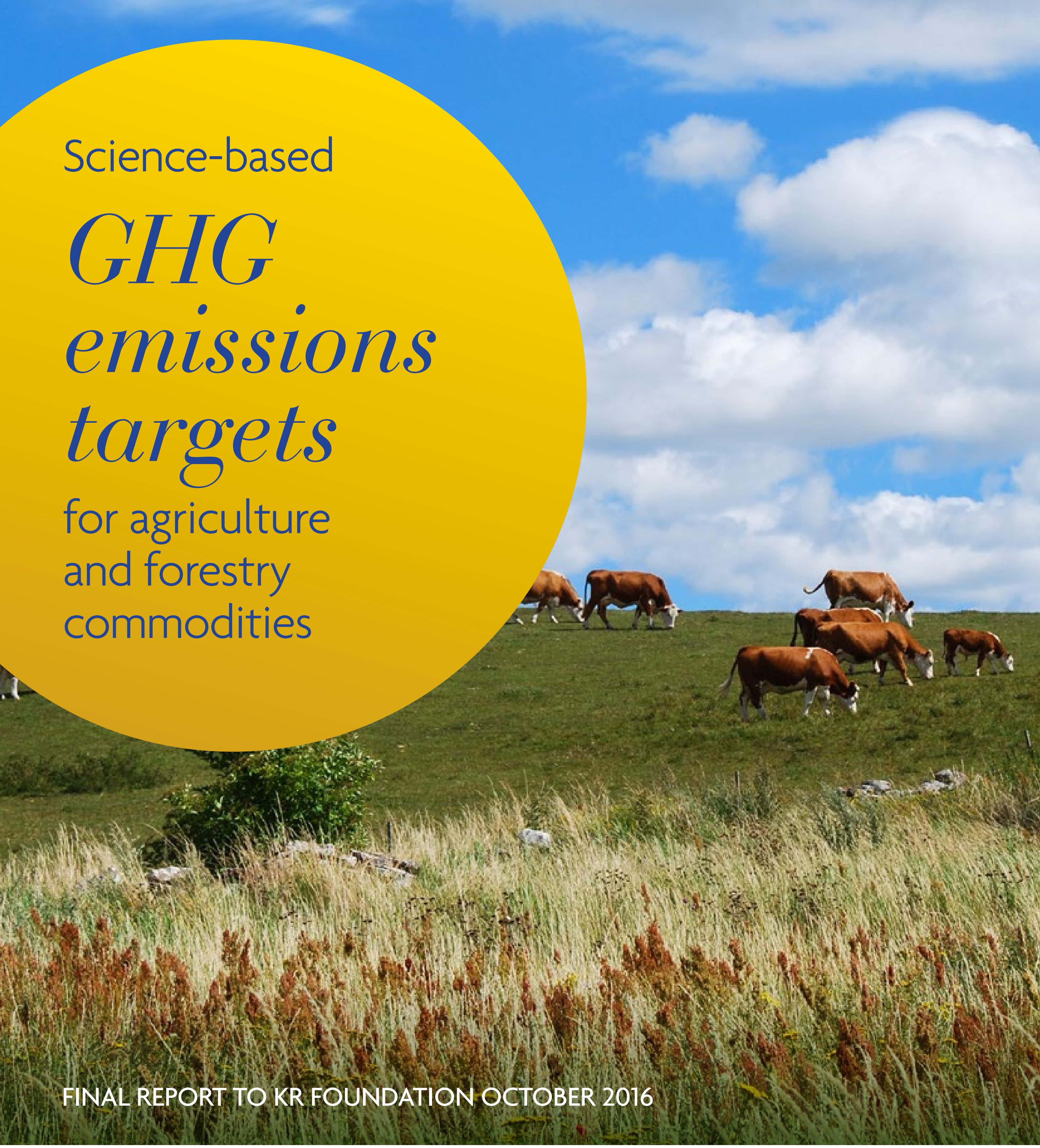

Science-based *GHG emissions targets* for agriculture and forestry commodities

FINAL REPORT TO KR FOUNDATION OCTOBER 2016

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Acknowledgements

The University of Aberdeen, PBL Netherlands Environmental Assessment Agency and Ecofys would like to gratefully acknowledge the inputs, advice and support received from various experts and organisations during the course of the project.

This report strongly builds on the science-based targets methodology (the Sectoral Decarbonization Approach) developed for the Science Based Targets initiative (www.sciencebasedtargets.org) by CDP, the World Resources Institute and WWF with the technical support of Ecofys. We would like to thank, particularly, the drivers of this initiative for their interest and support of this project.

Our methodology and its accompanying calculation tool were developed through a multi-stakeholder process. A Technical Advisory Group, including experts from companies, universities and other organisations, met four times to provide feedback and input on the scope, assumptions and use of the methodology. The Technical Advisory Group provided us with detailed inputs and advice that we carefully considered and integrated into our project. We like to thank the following members for the Technical Advisory Group for their valuable contribution and cooperation:

- Tiffanie Stephani, Fertilizers Europe
- Jan Peter Lesschen, Wageningen University (WUR)
- Mark Henson, Monsanto Company
- Kevin Rabinovitch, Mars incorporated
- Lini Wollenberg, Climate Change, Agriculture and Food Security (CCAFS), University of Vermont
- Pedro Faria, CDP
- Henry King, Unilever
- Petr Havlik, International Institute for Applied Systems Analysis (IIASA)
- Shaun Ragnauth, US Environmental Protection Agency (EPA)
- Stephen Russell, WRI

In addition to the Technical Advisory Group, we also like to thank various other stakeholders, like companies, governments, universities, NGOs and other organisations, who participated in two online workshops and provided valuable feedback to our project.
Finally, the University of Aberdeen, PBL and Ecofys would also like to express their gratitude to the KR Foundation for their funding, ongoing support and understanding throughout this project.

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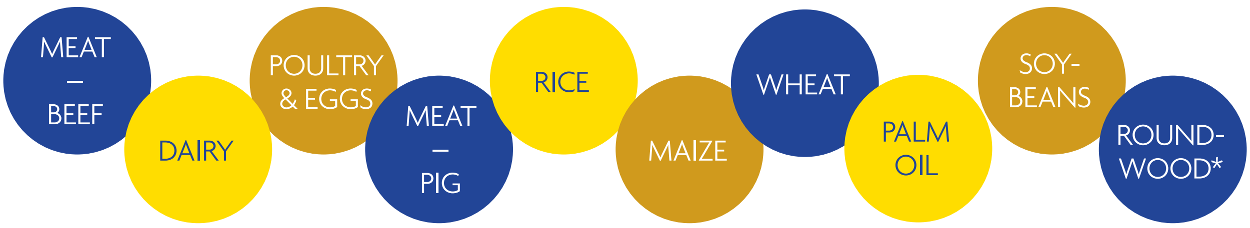
1 EXECUTIVE SUMMARY

To limit global warming well below 2° C, as agreed in the Paris Agreement, climate actions of the Agriculture, Forestry and Other Land-Use (AFOLU) sector are crucial. The Greenhouse Gas (GHG) emissions of AFOLU represent approximately a quarter of global anthropogenic GHG emissions (10 to 12 $GtCO_2eq$ per year) and need to be halved by 2050. At the same time, agricultural production is expected to double. To meet this challenge, companies need to act fast and need guidance to align their GHG emission reduction with climate science.

In mid-2015, CDP, UN Global Compact, the World Resources Institute (WRI) and WWF launched the Science Based Targets initiative to guide and support companies on aligning their GHG emissions reduction targets with climate science and creating a common business practice to set science-based targets. For this initiative, a new methodology, called the Sectoral Decarbonization Approach (SDA) was developed by CDP, WRI and WWF with technical support from Ecofys (Krabbe et al., 2015). The SDA methodology is unique, since it looks at sector-specific decarbonization pathways that are compatible with the 2° C threshold rather than applying a generic approach for all companies regardless of the nature of their operations. Since the SDA methodology builds on the 2DS of the International Energy Agency, mainly energy-related GHG emissions of carbon-intensive sectors are included in the methodology. GHG emissions of Agriculture, Forestry and Other Land-Use (AFOLU) is not modelled by IEA, and thus not included in the SDA so far.

Funded by the KR foundation, University of Aberdeen, PBL Netherlands Environmental Assessment Agency and Ecofys have carried out this project to develop an additional methodology based on the SDA, looking at key commodities of the AFOLU sector and developing emissions (CO_2 and non-CO_2) intensity pathways towards 2050 for these commodities. Stakeholder and expert reviews were used to optimize and verify the developed methodology in order to increase its adoption and integration in corporate practices.

Based on the share of GHG emissions and global volumes traded, the following commodities have been selected. In total, these commodities represent over 50% of global GHG emissions of the AFOLU sector:



*Roundwood was selected as a representative of a forestry product and added in a more qualitative way in this project.

As scope and boundary for analysing the GHG emissions of these commodities, a crade to farm gate approach was applied, with and without CO_2-emissions arising from Land-Use-Change (LUC-CO_2) related to the production of these commodities.

After a comprehensive analysis of abatement measures to mitigate the agriculture emissions (non-CO_2 and CO_2 from energy) of these commodities, various Marginal Abatement Cost Curves (MACCs) per commodity and region were updated. These updated MACCs were input into the IMAGE model, which was then used to simulate a mitigation scenario across 26 regions, consistent with keeping global warming well below 2° C. The calculations in this project are based on the so-called SSP2 scenario. (van Vuuren et al., 2014, O'Neill et al., 2014).

Based on the simulation in the IMAGE model of the SSP2 scenario, we have derived average emission intensity pathways from 2010 to 2050 per commodity per region (see Figure 1 and Figure 2). Subsequently, we translate these average emission intensity pathways of a commodity in a specific region, to a company-specific emissions intensity target by applying the convergence principle: i.e. the emission intensity of a commodity produced in a certain region converges to the same average emissions intensity in 2050.

Global commodity emission factors (total except LUC CO_2)

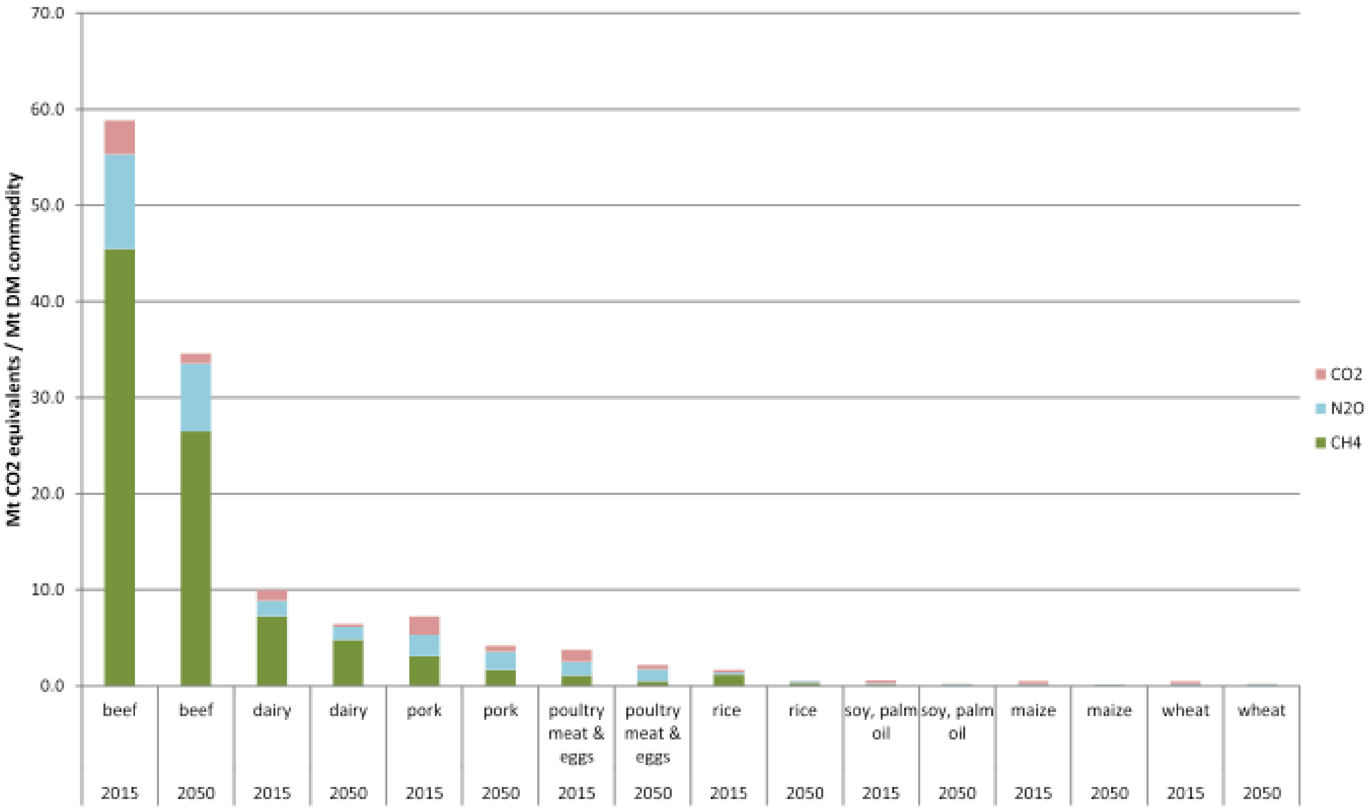


Figure 1; global emission factors for agricultural commodities under a 2° C constrain, excluding emissions from land-use change. Emission factors (in Mt CO_2eq/Mt DM commodity, DM = Dry Matter) are shown for 2015 and 2050 and grouped by CH_4, N_2O and CO_2 using a 100-year global warming potential from the fourth Assessment Report (GWP CH_4 = 25[1], GWP N_2O = 298).

Global commodity emission factors (beef not shown)

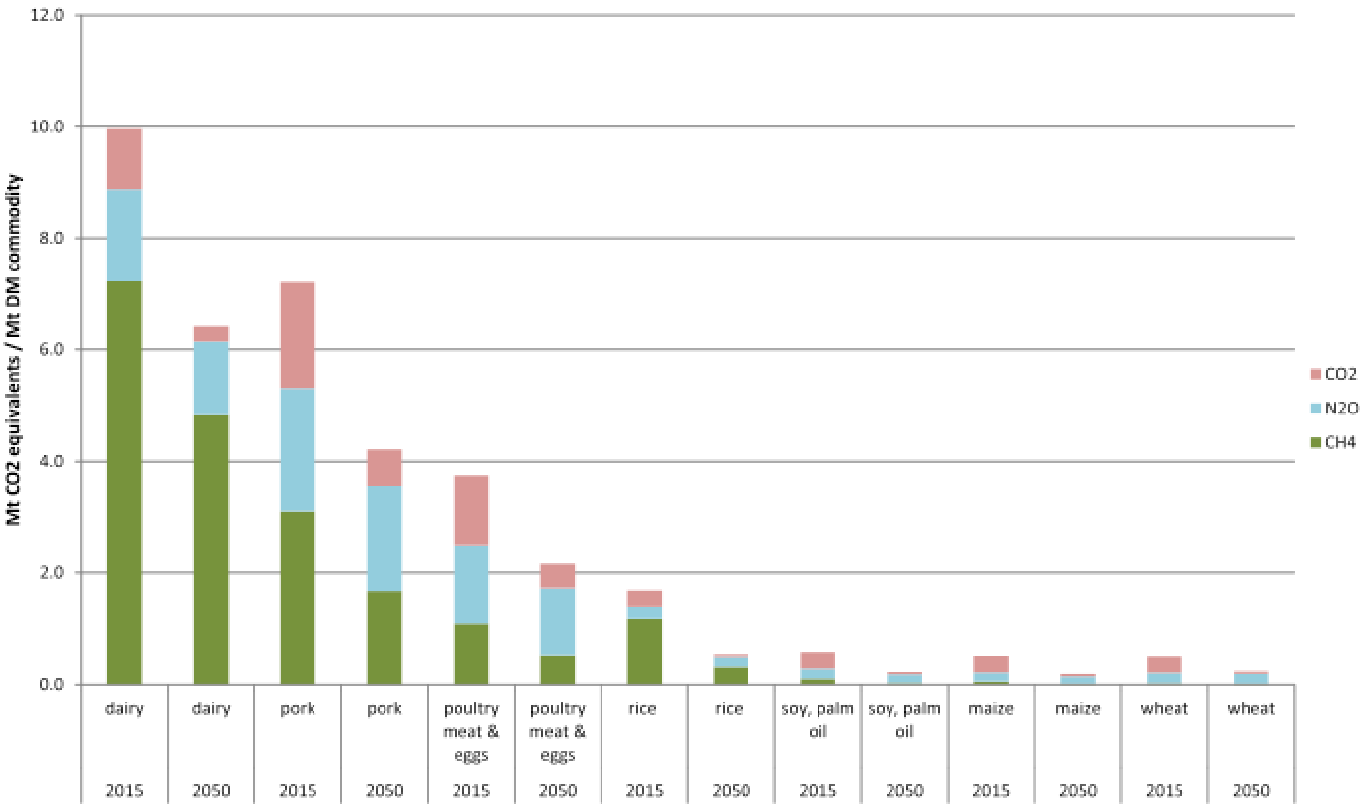


Figure 2; global emission factors for agricultural commodities under a 2° C constraint, shown for all commodities except beef excluding emissions from land-use change. Emission factors (in Mt CO_2eq/Mt DM commodity, DM = Dry Matter) are shown for 2015 and 2050 and grouped by CH_4, N_2O and CO_2 using a 100-year global warming potential from the fourth Assessment Report (GWP CH_4 = 25, GWP N_2O = 298).

In addition to mitigating agricultural GHG emissions (non-CO_2 and CO_2 from energy) of these commodities, the CO_2 emissions that result from the conversion of natural land to agricultural land (LUC-CO_2) are key drivers of global anthropogenic GHG emissions. However, these LUC-CO_2 emissions are often not accounted for in Life Cycle Assessments (LCAs) until now, partly because of the large uncertainty in the value of LUC-CO_2.

As these emissions only occur as a function of land-use area expansion, they cannot easily be attributed to a specific commodity. As there is no standard calculation method, we have explored four methodological approaches to include these important emissions in the development of this additional science-based targets methodology. These methods reflect the diversity of methods in the literatures, and consequently. cover the range of values found in the literature (see error bars in figures below).

Emission factors in kg CO_2/kg product for the 'Foregone Sequestration' method.

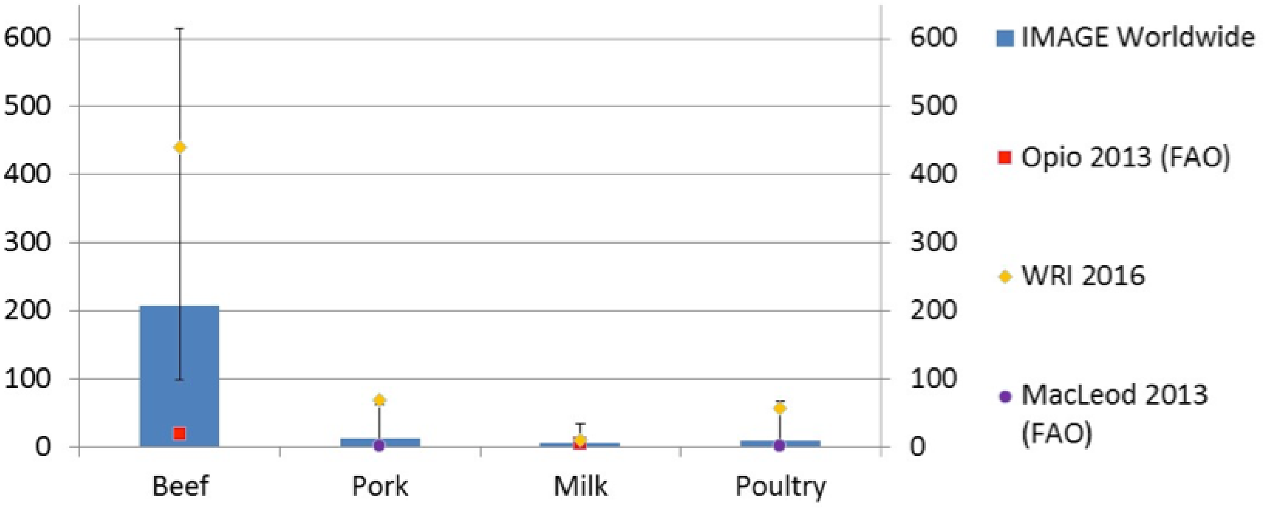


Figure 3; worldwide IMAGE emission factors (blue bars) per commodity compared to references (coloured dots) and the range in values from other methods tested in this project with IMAGE (error bars).

Emission factors in kg CO_2/kg crop for the 'Foregone Sequestration' method.

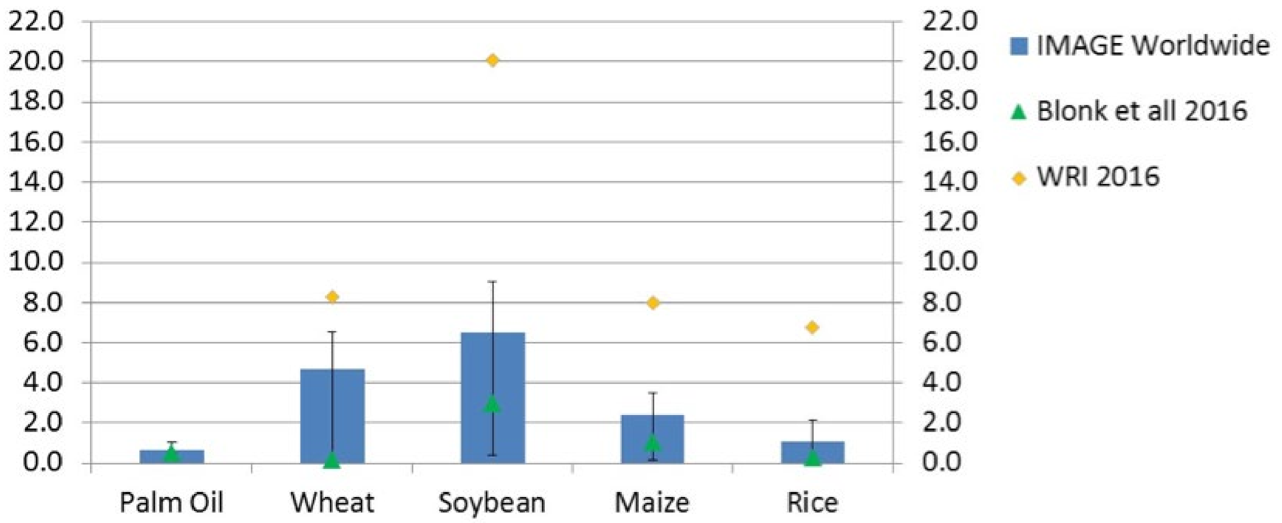


Figure 4; worldwide IMAGE emission factors (blue bars) per commodity compared to references (coloured dots) and the range in values from other methods tested in this project with IMAGE (error bars).

Although this range can be viewed as uncertainty, the main message of this project is that the choice of method determines, to a large extent, the value of the emission factor for land-use change CO_2 emissions (LUC-CO_2). References studies show a comparable (range of) results, when compared to a similar methodology used in IMAGE (coloured dots).

Factors other than choice of method, which influence LUC-CO_2 factors, include trade patterns, feed composition, role of by-products, other applications such as bio-energy and manufacturing, management type and reference period. Implicit model settings also play a role. For instance, differences exist between models in assumptions on future yield improvement, where expansion and abandonment take place and role of climate change effects and CO_2 fertilisation effects on yield. They explain differences between studies, which use a similar methodology. The most suitable method depends on the application and the preference of the user. This project recommends "Forgone Sequestration method", which shows the LUC-CO_2 factor in the case that land currently occupied by agriculture would be returned to natural vegetation. The emission factors of this method are in the middle of the range of methods, and have a valid emission factor for every region.

To guide companies in setting science-based targets and incorporating land-use change into their mitigation strategy, an online-tool has been developed. In the tool, the user can select a commodity and a region, and the accompanying average emission intensity pathway is retrieved from the IMAGE data. By inserting the base year, base year emission intensity of the company's produced/sourced commodity, and the projected company growth of production/sourcing in the selected regions towards the target year, the company can calculate its specific intensity pathway that provides the required science-based target for the specific target year. Also the LUC-CO_2 impact in the base year is included in the tool to show this impact per commodity and region and to trigger action to reduce this impact.

We invite companies that produce or source the selected agriculture and forestry commodities to use the developed methodology and set science-based targets to keep global warming well below 2° C. In addition to setting science-based targets, rapid mitigation action is required to meet these targets. In this report various actions to mitigate GHG emissions and eliminate land-use change effects are listed. Besides this, an overview is also presented on how to measure, monitor and track the progress of reducing GHG emissions of these key agricultural commodities.

By applying this new methodology and taking robust climate actions, companies can gain multiple benefits, such as:

	Increase credibility of climate targets, get recognition and exposure by NGO;
	Demonstrate leadership and build on a green reputation to increase stakeholder value and attract excellent talents;
	Outperform sector peers in benchmarks, increase rating scores and attractiveness for investors;
	Get long-term guidance to steer investments, drive innovation and transform agribusiness practices;
	Save money and increase competitiveness by gaining insight in company performance and improvement potential;
	Gain insight in the required transformation of the Agriculture, Forestry and Other Land- Use (AFOLU) sector and position yourself for upcoming policy regulations.

2
INTRODUCTION

At the COP21 in Paris, in December 2015, 195 countries made the binding agreement to limit global warming to well below 2° C and to pursue efforts to limit the temperature increase to 1.5° C. As global absolute GHG emissions continue to increase, COP21 raised the sense of urgency and called for more ambitious mitigation actions. Staying well below 2° C implies net zero CO_2 emissions by 2070 and pursuing efforts towards 1.5° C even means net zero CO_2 emissions by 2050. The Paris Agreement will lead to a robust policy framework and considerable flows of climate finance to drive the massive and fast transformation in all sectors and all parts of the world. Climate science will play a key role in achieving on the ground, evidence-based results to safeguard our communities and natural resources, and in raising ambition on a global scale.

2.1 SCIENCE BASED TARGETS INITIATIVE

The Science Based Targets initiative, founded by CDP, the UN Global Compact (UNGC), the World Resources Institute (WRI) and WWF, was launched to support and advise companies on aligning their GHG emissions reduction targets with climate science, and creating a common business practice to set science-based targets. Targets adopted by companies to reduce GHG emissions are considered 'science-based' if they are in line with the level of decarbonization required to keep global temperature increase well below 2° C compared to preindustrial temperatures'.

2.1.1 SECTORAL DECARBONISATION APPROACH (SDA)

For the Science Based Targets initiative, a new methodology, called the Sectoral Decarbonization Approach (SDA) was developed by CDP, WRI and WWF with technical support from Ecofys. The SDA builds on existing approaches that allocate a carbon budget to companies based on their relative contribution to the economy and uses a least-cost modelled 2° C scenario developed by the International Energy Agency (IEA 2DS). This model provides a cost-competitive mitigation pathway to stay below 2° C while accounting for variations in activity growth, mitigation potentials and technological options for each sector. Within each sector, companies can derive their science-based emission reduction targets by accounting for their relative contribution to the total sector activity and their carbon intensity compared to the sector intensity.

The SDA methodology combines sectoral emissions pathways with sectoral activity projections from IEA 2DS to construct sectoral intensity pathways for homogeneous[2] sectors using physical activity indicators. These sectors include power, cement, iron and steel, aluminum, pulp and paper, service buildings, and passenger transport. The SDA assumes that the carbon intensity for the companies in all homogeneous sectors tends to converge in 2050. The rate of convergence depends on the difference between the carbon intensity of the company and the 2° C carbon intensity of the sector in 2050, and the predicted change in the company's market share. For three heterogeneous[3] sectors, such as chemical and petrochemicals, other industry and other transport, physical allocation is not possible, and absolute reduction is used to allocate the remainder of the carbon budget. For these sectors, the methodology is based on the compression of absolute emissions, meaning that absolute emissions of all companies in the sector will be reduced by the same percentages as the sector in the target year. In the SDA, each activity of a company is allocated to one of the sectors to define the intensity and absolute targets.

The activities and sectors covered in the SDA represent over 60 percent of current yearly global GHG emissions and up to 87 percent of the CO_2 budget up to 2050. The Sectoral Decarbonization Approach is the most recent and most detailed method. It is transparent, well documented and reviewed through an extensive stakeholder consultation process. Moreover, it takes into account sectoral differences (for example differences in mitigation potential, mitigation costs and growth) and unlike existing approaches, looks at sector-specific decarbonization pathways that are compatible with the global 2° C threshold rather than applying a generic decarbonization pathway for all companies regardless of the nature of their operations.

[2]Sector that can be described using a physical indicator.

[3]Sector that cannot be described using a physical indicator due to the uniqueness of the characteristics of the sector or the difficulties in comparing them.

2.1.2 AN ADDITION TO THE SDA METHODOLOGY

Since the SDA methodology builds on the IEA 2DS, mainly energy-related GHG emissions of carbon-intensive sectors are included in the methodology. GHG emissions of Agriculture, Forestry and Other Land-Use (AFOLU) is not modelled by IEA and thus not included in the SDA.

As the GHG emissions of AFOLU represent approximately a quarter of global anthropogenic GHG emissions (10 to 12 $GtCO_2eq$ per year) and are supposed to half in 2050, this sector is crucial to limit global warming to well below 2°C. It is the second biggest emitter after the energy sector in terms of direct emissions or the third, if emissions from electricity and heat production are attributed to the sectors that use the final energy.

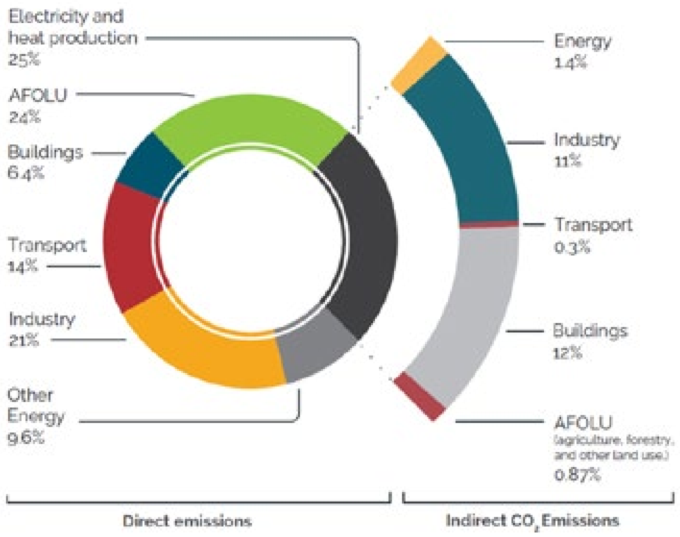


Figure 5; share of direct and indirect GHG emissions in 2010 by economic sector.

Funded by the KR foundation, University of Aberdeen, PBL Netherlands Environmental Assessment Agency and Ecofys carried out this project to develop an additional methodology looking at key commodities of the AFOLU sector and developing emissions (CO_2 and non-CO_2) intensity pathways towards 2050 for these commodities.

The final outcome of this project is presented in this report, which is structured into four sections complemented by detailed annexes. Chapter 2 defines the scope of the methodology explaining the carefully considered selection of agricultural and forestry commodities, and the system boundary. Chapter 3 focuses on the emission intensity pathways for the key commodities providing insights into methodological aspects and the allocation of emissions from land-use and land-use change. In Chapter 4, the methodology and online-tool to derive company targets are presented. Further, actions and tools are suggested so that companies can apply to reduce and track their GHG emissions of these commodities. Finally, the annexes provide detailed insights into mitigation options and GHG abatement potential as well as in the elaboration of the MAC curves.

Stakeholder and expert reviews were used to optimize and verify the developed methodology in order ensure its suitability for adoption and integration in corporate practices. The final results of the project will enable producers and buyers of agricultural and forestry commodities to determine a fair share of emission reductions and to make their own operations and supply chains truly sustainable.

2.1.3 KEY BENEFITS FOR COMPANIES OF APPLYING THIS NEW METHODOLOGY

We invite companies that produce or buy the selected agriculture and forestry commodities to use the developed methodology. By applying this new methodology, companies can gain the following benefits:

	Increase credibility of climate targets, get recognition and exposure by NGO;
	Demonstrate leadership and build on a green reputation to increase stakeholder value and attract excellent talents;
	Outperform sector peers in benchmarks, increase rating scores and attractiveness for investors;
	Get long-term guidance to steer investments, drive innovation and transform agribusiness practices;
	Save money and increase competitiveness by gaining insight in company performance and improvement potential;
	Gain insight in the required transformation of the Agriculture, Forestry and Other Land- Use (AFOLU) sector and position yourself for upcoming policy regulations.

3

SCOPE OF THIS METHODOLOGY

3.1 INTRODUCTION

In this chapter we present the scope of our methodology, the selection of the key commodities for this project and the system boundaries for the calculation of the emissions intensities. We also describe the IMAGE model and the so-called Shared Socio-economic Pathways (SSPs) that we use for the simulations in this project. The SSP scenarios have been proposed as a new set of scenarios to be used as a basis of future climate research (van Vuuren et al., 2014, O'Neill et al., 2014). On the basis of the so-called SSP2 scenario (middle of the road) a mitigation scenario was used consistent with the 2° C target.

3.2 SELECTION OF COMMODITIES

In 2014, California Environmental Associates published a global analysis on GHG emissions by agriculture commodities (Figure 6; Dickie et al., 2014). The top agricultural / land-based commodities i.e. meat-beef, dairy, chicken, meat-pig, rice, maize, wheat, palm oil and soybean with high carbon footprint were selected for this project. Roundwood was selected as a representative of a forestry product.

GHG emissions by agriculture commodity and region (Mt CO_2e / year)

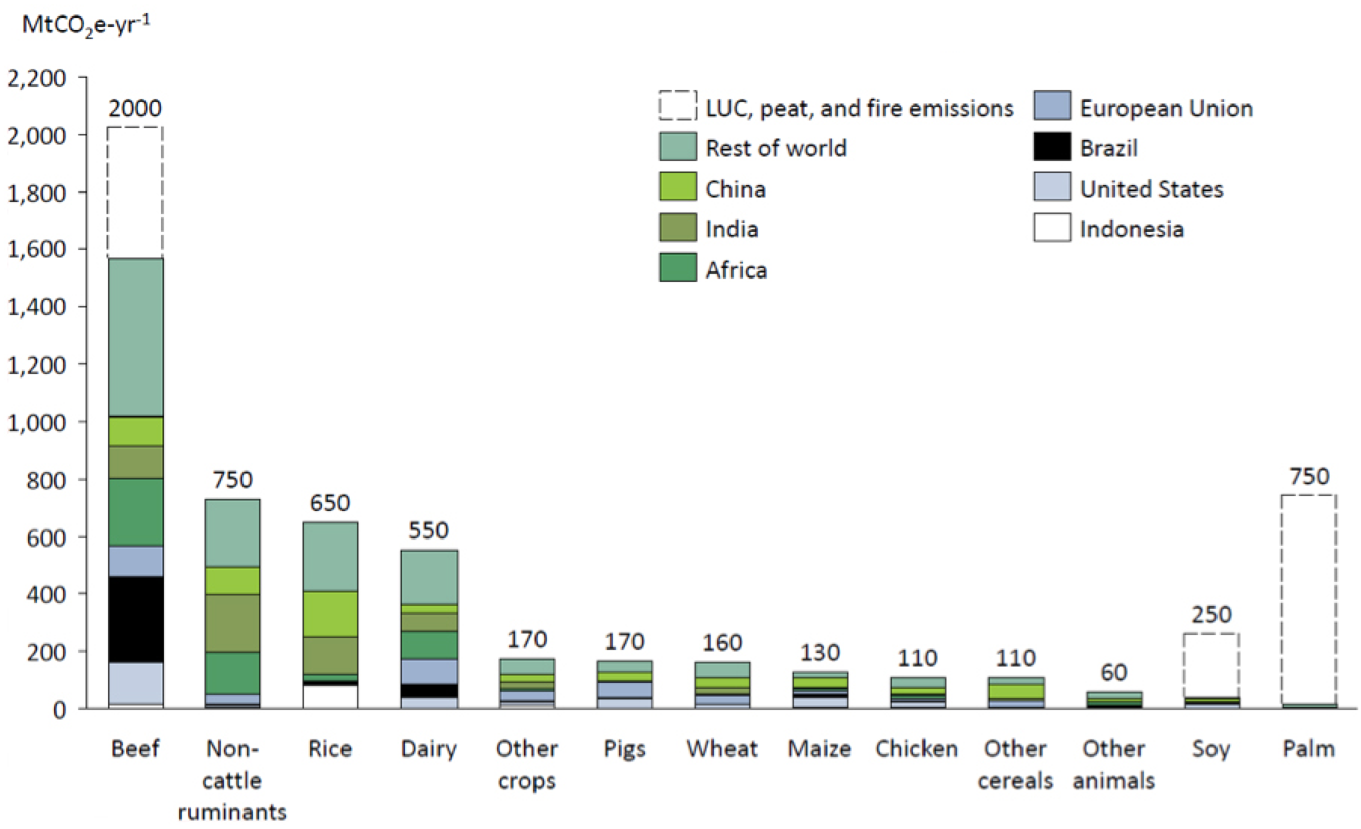


Figure 6; GHG emissions by agricultural commodity and region. Source: Dickie et al. (2014).

3.3 DEFINITION AND SYSTEM BOUNDARY FOR SELECTED COMMODITIES

COMMODITIES	DEFINITION	REFERENCES	SYSTEM BOUNDARY OF ANALYSIS	METHOD OF IMPLEMENTATION IN IMAGE AND LIMITATION
MEAT – BEEF	Meat of bovine animals, fresh, chilled or frozen, with bone in.	FAO	Cradle to farm gate (with and without LUC emission).	1. Grassland based (Extensive) 2. Mixed systems (Intensive)
DAIRY	Milk and milk products from cow, buffalo, sheep, goat.		Cradle to farm gate (with and without LUC emission).	1. Grassland based (Extensive) 2. Mixed systems (Intensive)
POULTRY – CHICKEN (MEAT) INCLUDING EGGS	Fresh, chilled or frozen.	FAO	Cradle to farm gate (with and without LUC emission).	Production system not differentiated in IMAGE.
MEAT – PIG	Meat, with the bone in, of domestic or wild pigs (e.g. wild boars), whether fresh, chilled or frozen.	FAO	Cradle to farm gate (with and without LUC emission).	All production system included
RICE	Rice grain after threshing and winnowing. Also known as rice in the husk and rough rice.	FAO	Cradle to farm gate (with and without LUC emission).	
WHEAT	Common and durum wheat are the main types. Among common wheat, the main varieties are spring and winter, hard and soft, and red and white.	FAO	Cradle to farm gate (with and without LUC emission).	
MAIZE	A grain with high germ content.	FAO	Cradle to farm gate (with and without LUC emission).	
PALM OIL (FRESH FRUIT BUNCH)	The oil palm produces bunches containing a large number of fruits with the fleshy mesocarp enclosing a kernel that is covered by a very hard shell. FAO considers palm oil (coming from the pulp) and palm kernels to be primary products. The oil extraction rate from a bunch varies from 17 to 27% for palm oil, and from 4 to 10% for palm kernels.	FAO	Cradle to farm gate (with and without LUC emission).	Oil palm on peat not differentiated.
SOYBEAN	The most important oil crop. Also widely consumed as a bean and in the form of various derived products because of its high protein content, e.g. soya milk, meat, etc.	FAO	Cradle to farm gate (with and without LUC emission).	
ROUNDWOOD	All roundwood felled or otherwise harvested and removed. It comprises all wood obtained from removals, i.e. the quantities removed from forests and from trees outside the forest, including wood recovered from natural, felling and logging losses during the period, calendar year or forest year. It includes all wood removed with or without bark, including wood removed in its round form, or split, roughly squared or in other form (e.g. branches, roots, stumps and burls (where these are harvested) and wood that is roughly shaped or pointed. It is an aggregate comprising wood fuel, including wood for charcoal and industrial roundwood (wood in the rough). It is reported in cubic metres solid volume underbark (i.e. excluding bark).	FAO	Emission intensity from literature (only qualitative analysis).	

3.4 SYSTEM BOUNDARY FOR ANALYSIS OF LIVESTOCK PRODUCTS AND CROPS

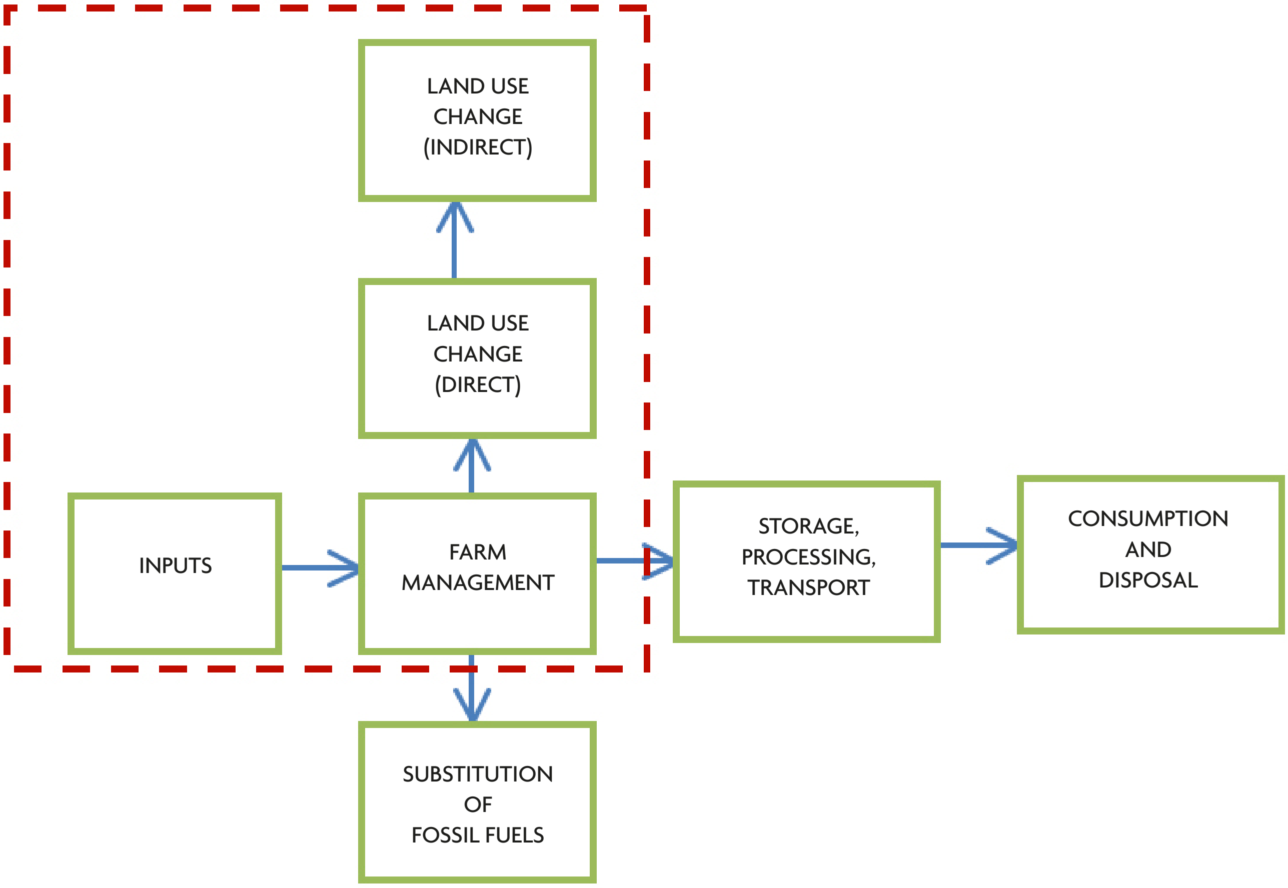


Figure 7; Schematic presentation of stages in agriculture production processes. The red dashed line indicates the GHG emission sources that are accounted for in the project. Source: Schulte-Uebbing (2013)

3.4.1 EMISSION SOURCES INCLUDED FOR LIVESTOCK PRODUCT

The system boundary for GHG emission from livestock products (Meat-Beef, Dairy, Poultry-meat, Meat-Pig) is Cradle to farm gate that includes:

1. CO_2 emissions from land-use change associated with livestock and feed for livestock
2. Emissions from feed production i.e. direct and indirect N_2O emission from application of fertilizer, crop residues and deposition of manure on pastures; CH_4 emission from manure and flooded rice.
3. CO_2 emissions from machinery used on farm and for feed production.
4. CO_2 and N_2O emissions from fertilizer production needed for feed production
5. Enteric CH_4 emissions (Meat-Beef , Dairy)
6. CH_4 emissions from manure management
7. Direct and indirect N_2O emissions from manure management

3.4.2 EMISSION SOURCES INCLUDED FOR RICE, WHEAT, MAIZE, PALM OIL, SOYBEAN

The system boundary for GHG emission from crop products (rice, wheat, maize, palm oil, and soybean) is Cradle to farm gate that includes:

1. CO_2 emissions from land-use change
2. CO_2 emissions from drained peat soils (for palm oil in Indonesia and Malaysia only)
3. CH_4 emissions from flooded soil (for Lowland rice only)
4. CO_2 and N_2O emissions due to fertilizer production
5. Fertilizer-direct N_2O emissions from soil due to fertilizer application
6. Fertilizer-indirect N_2O emissions from leaching, runoff and volatilization
7. N_2O emissions from crop residue
8. CH_4 and N_2O emissions from agricultural waste burning
9. CO_2 emissions from machinery on farm

3.4.3 SYSTEM BOUNDARY FOR ANALYSIS OF ROUNDWOOD

Emission intensity for Roundwood was based on literature review and in this report Roundwood is treated in a more qualitative way. The system boundary for most of the Roundwood literature was cradle to harvest or gate.

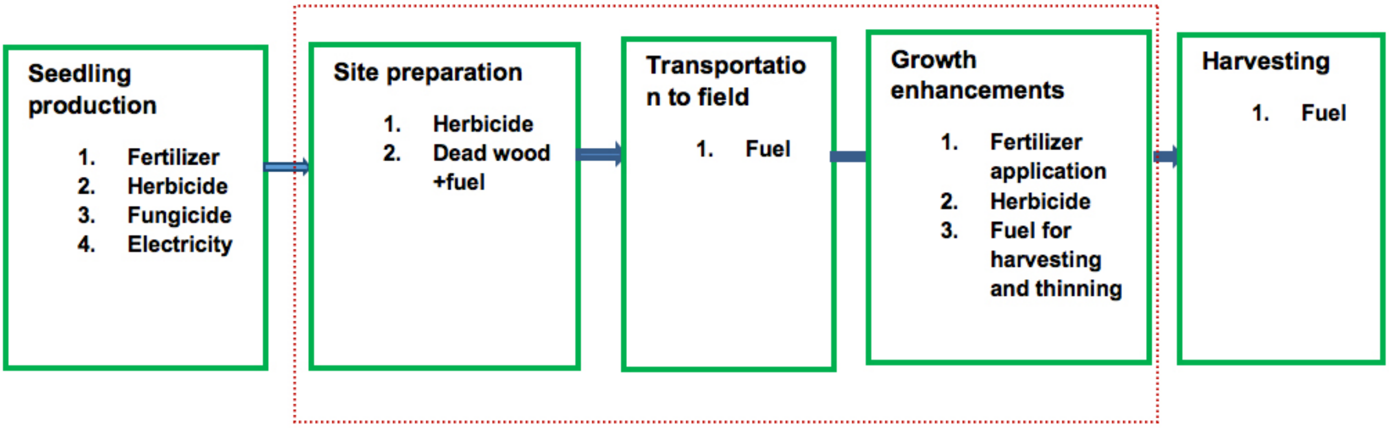


Figure 8; System boundary for forestry operations. Based on Sonne, 2006.

3.5 IMAGE MODEL AND SCENARIOS USED

3.5.1 DESCRIPTION OF IMAGE MODEL

We used the IMAGE model to simulate the GHG emissions of the selected commodities in line with keeping global warming well below 2°C. IMAGE is an integrated assessment model framework that simulates global and regional environmental consequences of changes in human activities (Stehfest et al., 2014). The model includes a detailed description of the energy and land-use system and simulates most of the socio-economic parameters for 26 regions and most of the environmental parameters, depending on the variable, on the basis of a geographical grid of 30 by 30 minutes or 5 by 5 minutes (respectively 50 km and around 10 km at the equator).

IMAGE 3.0 FRAMEWORK

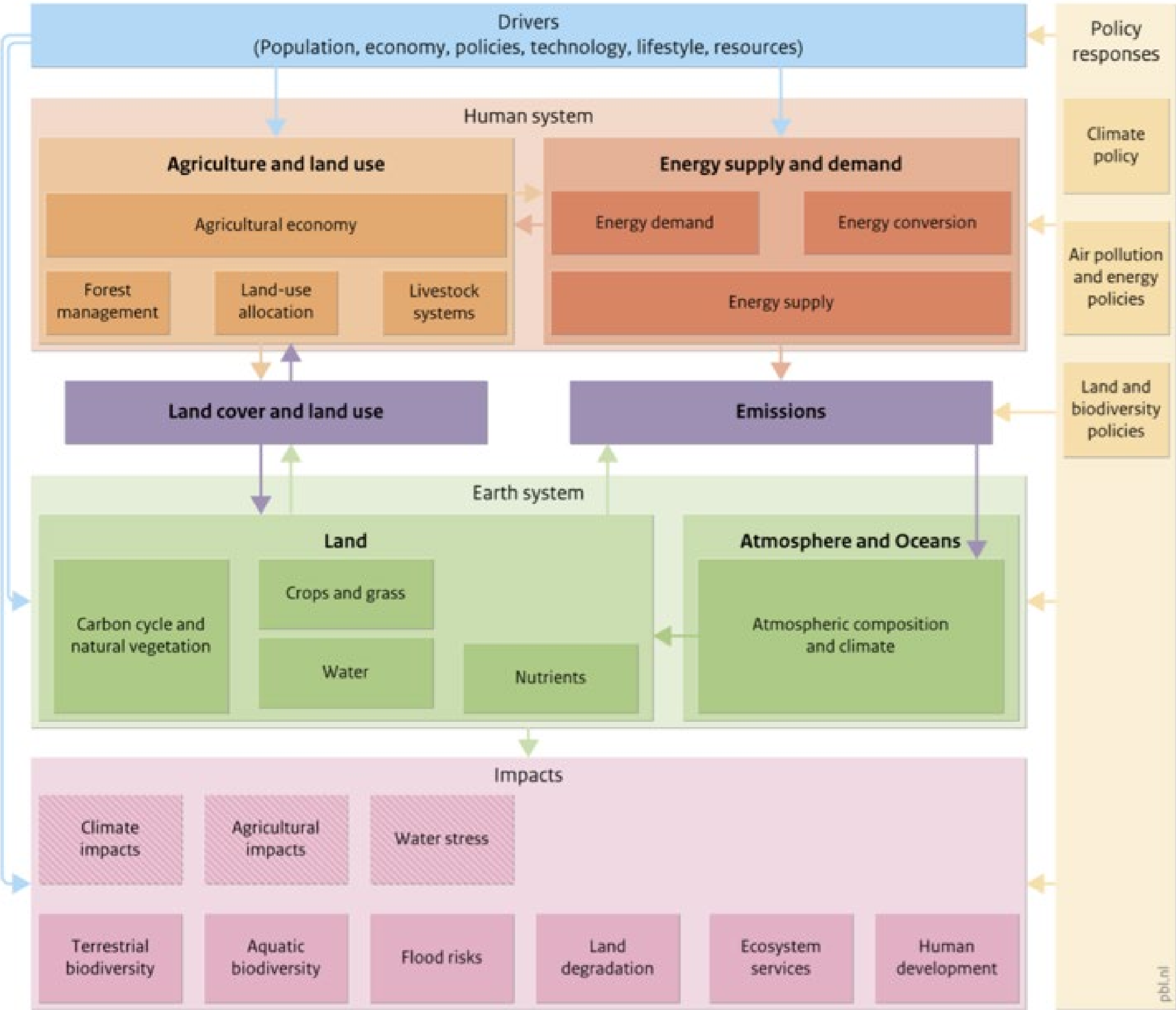


Figure 9; Overview of the IMAGE model. Source PBL (2014).

THE 26 WORLD REGIONS IN IMAGE 3.0

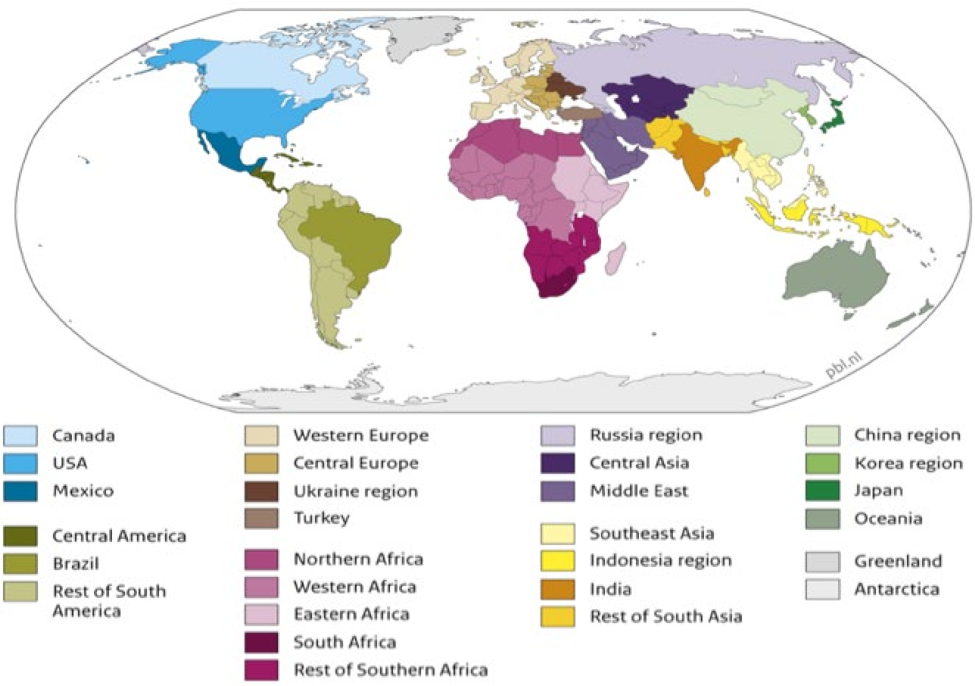


Figure 10; The 26 regions of the IMAGE model. Source: PBL (2014).

The model has been designed to analyse large-scale and long-term interactions between human development and the natural environment in the absence of new policies, but also to identify response strategies. This means that the model projects the implications for energy, land, water and other natural resources, subject to resource availability and quality, but can also look into related issues like emissions to air, water and soil, climatic change, and depletion and degradation of remaining stocks (fossil fuels, forests).

The IMAGE framework is structured around the causal chain of key global sustainability issues and comprises two main systems: 1) the human or socio-economic system that describes the long-term development of human activities relevant for sustainable development; and 2) the earth system that describes changes in natural systems, such as the carbon and hydrological cycle and climate. The two systems are linked through emissions, land-use, climate feedbacks and potential human policy responses.

Important inputs to the model are descriptions of the future development of so-called direct and indirect drivers of global environmental change: Exogenous assumptions on population, economic development, lifestyle, policies and technology change form a key input into the energy system model TIMER and the food and agriculture system model MAGNET (Woltjer et al., 2014). The results from MAGNET on production and endogenous yield (management factor) are used in IMAGE to calculate spatially explicit land-use change, and the environmental impacts on carbon, nutrient and water cycles, biodiversity, and climate. A key component of the earth system is the LPJmL model (Bondeau et al., 2007) that covers the terrestrial carbon cycle and vegetation dynamics. The calculated emissions of greenhouse gases and air pollutants are used in IMAGE to derive changes in concentrations of greenhouse gases, ozone precursors and species involved in aerosol formation on a global scale. The model accounts for several feedback mechanisms between climate change and dynamics in the energy, land and vegetation systems.

3.5.1.1 DETAILED DESCRIPTION OF THE LAND SYSTEM

In IMAGE, elements of land cover and land use are calculated in several components, namely in land use allocation, forest management, livestock systems, carbon cycle and natural vegetation. The output from these components forms a description of gridded global land cover and land use that is used in these and other components of IMAGE. In addition, this description of gridded land cover and land use per time step can be provided as IMAGE scenario information to partners and other models for their specific assessments.

Land cover and land use described in an IMAGE scenario is a compilation of outputs from various IMAGE components. This compilation provides insight into key processes in land-use change described in the model and an overview of all gridded land cover and land use information available in IMAGE. Land cover and land use is also the basis for the land availability assessment, which provides information on regional land supply to the agro-economic model, based on potential crop yields, protected areas, and external datasets such as slope, soil properties, and wetlands.

A key component of the earth system is the LPJmL model that is included in IMAGE 3.0, and that covers the terrestrial carbon cycle and vegetation dynamics. This model is used to determine productivity at grid cell level for natural and cultivated ecosystems on the basis of plant and crop functional types, while a set of allocation rules determine the actual land cover. It is referred to as a Dynamic Global Vegetation Model (DGVM) that was developed initially to assess the role of the terrestrial biosphere in the global carbon cycle (Prentice et al., 2007). DGVMs simulate vegetation distribution and dynamics, using the concept of multiple plant functional types (PFTs) differentiated according to their bioclimatic (e.g. temperature requirement), physiological, morphological, and phenological (e.g. growing season) attributes, and competition for resources (light and water).

SPATIAL SCALE	The Human system and the Earth system in IMAGE 3.0 are specified according to their key dynamics. The geographical resolution for socio-economic processes is 26 regions selected because of their relevance for global environmental and/or development issues, and the relatively high degree of coherence within these regions. In the Earth system, land use and land-use changes are presented on a grid of 5x5 minutes, while the processes for plant growth, carbon and water cycles are modelled on a 30x30 minutes resolution.
TEMPORAL SCALE	The Human system and the Earth system each run at annual or five-year time steps focusing on long-term trends to capture inertia aspects of global environmental issues. In some IMAGE model components, shorter time steps are also used, for example, in water, crop and vegetation modelling, and in electricity supply. The model is run up to 2050 or 2100 depending on the issues under consideration. For instance, a longer time horizon is often used for climate change (see Applications). IMAGE also runs over the historical period 1971-2005 in order to test model dynamics against key historical trends.

3.5.2 SCENARIOS USED

3.5.2.1 GENERAL CHARACTERISTICS

The calculations in this project are based on the so-called SSP2 scenario and the derived mitigation scenario consistent with the 2° C target. The Shared Socio-economic Pathways (SSPs) have been proposed as a new set of scenarios to be used as a basis of future climate research (van Vuuren et al., 2014, O'Neill et al., 2014). The SSPs describes five possible future development trajectories that result in fundamentally different positions of human societies with respect to the ability to mitigate and/or adapt to climate change. The scenarios can be used in combination with additional, climate specific, policy assumptions to explore the costs and benefits of climate policies in different situations or to assess the effects of climate change.

The SSP2 scenario represents a medium scenario in terms of the assumptions for the main drivers and outcomes. The population and economic growth projections (made by IIASA and OECD) form median projections in the literature and are shown in Figure 11. Population stabilizes at around 9 billion by 2050. In the SSP2 scenario, technology is assumed to further improve but no major breakthroughs are expected. Agricultural systems evolve largely following the FAO projections by Alexandratos and Bruinsma (2012).

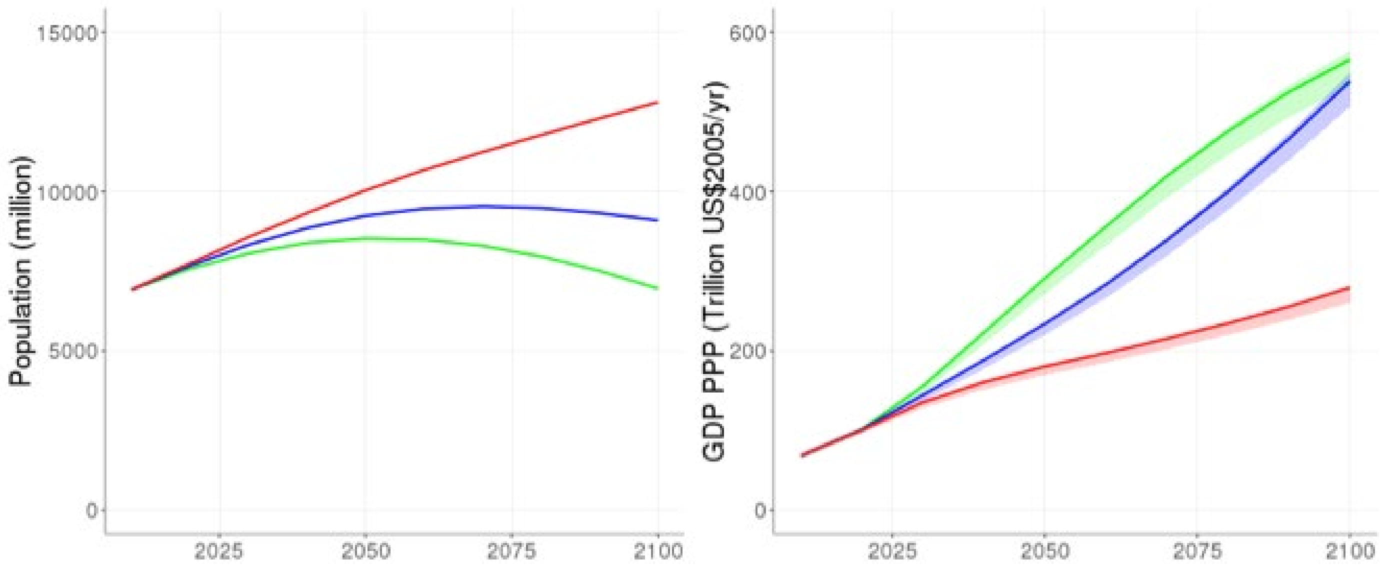


Figure 11; the population and economic development in the SSP2 scenario (for comparison also the SSP1 and SSP3 results are shown). (Van Vuuren et al., 2016)

3.5.2.2 TRENDS IN GLOBAL AGRICULTURE

Food demand forms a primary driver of land-use trends. Trends in global population and increasing welfare are expected to lead to an increasing global food demand. At the same time, increasing income also leads to a larger share of animal products as part of the overall diet. SSP1 and SSP3 lead to a lower and higher food demand, as a result of environmentally friendly lifestyle and high population growth, respectively.

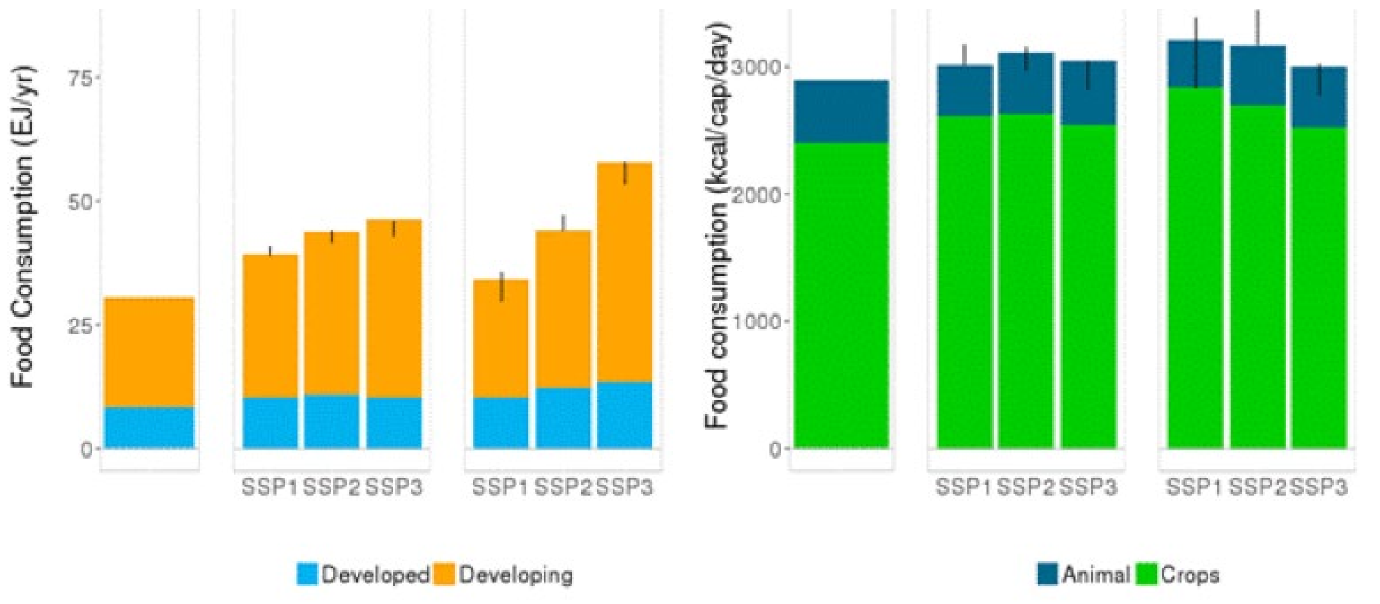


Figure 12; total food consumption (left) and per capita food consumption (animal and non-animal intake). The vertical lines indicate the range of results of the full set of IAM scenarios for the specific SSP (for comparison also the SSP1 and SSP3 results are shown). (Van Vuuren et al., 2016)

Clearly, the increasing food demand in all three SSPs implies that more food needs to be produced. In SSP2, yield improvements are in line with the projections of FAO. These yield improvements are a result of autonomous improvement in technology, but also a result of increasing land scarcity. In both SSP2 and SSP3, there is a substantial increase in the demand for feed crops for feeding both monogastric and ruminant systems.

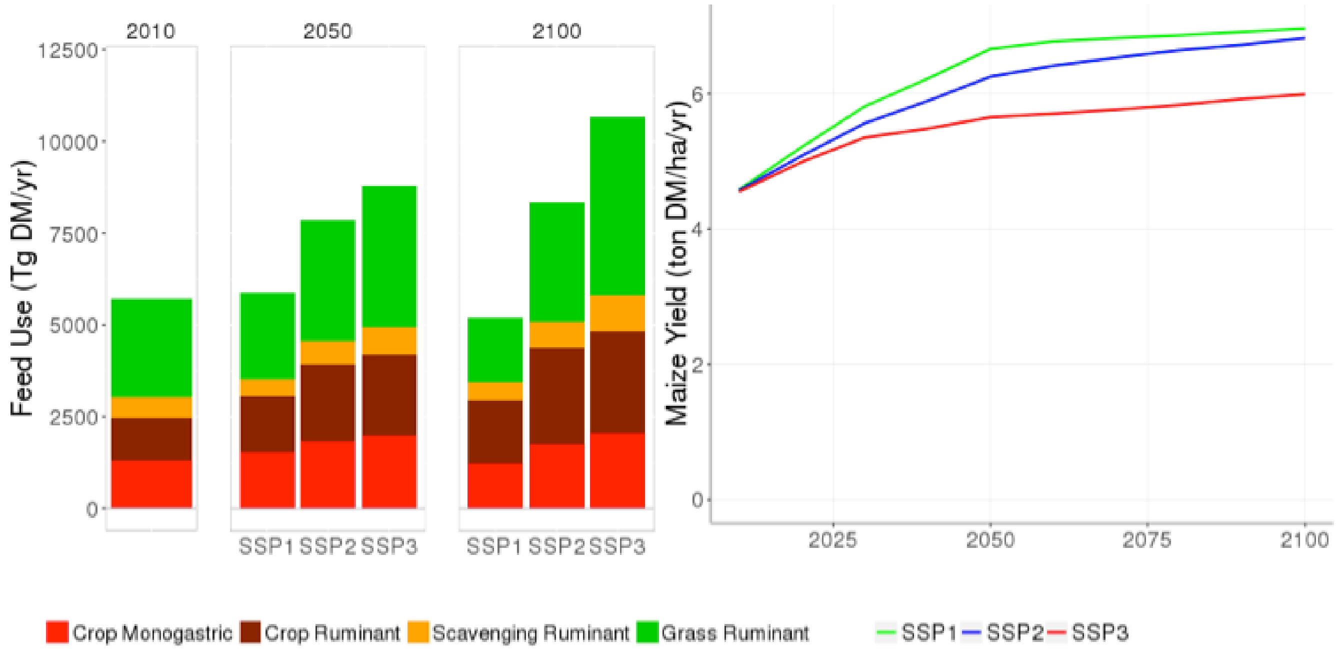


Figure 13; global feed requirement for monogastrics and ruminants (left) and global average yield for maize (for comparison also the SSP1 and SSP3 results are shown). (Van Vuuren et al., 2016)

For total agricultural land there is a slow increase over time in the SSP2 scenario – again similar to FAO projections. Most of the expansion occurs in crop land – consistent with the increase in food demand and intensive animal production systems (feed requirements).

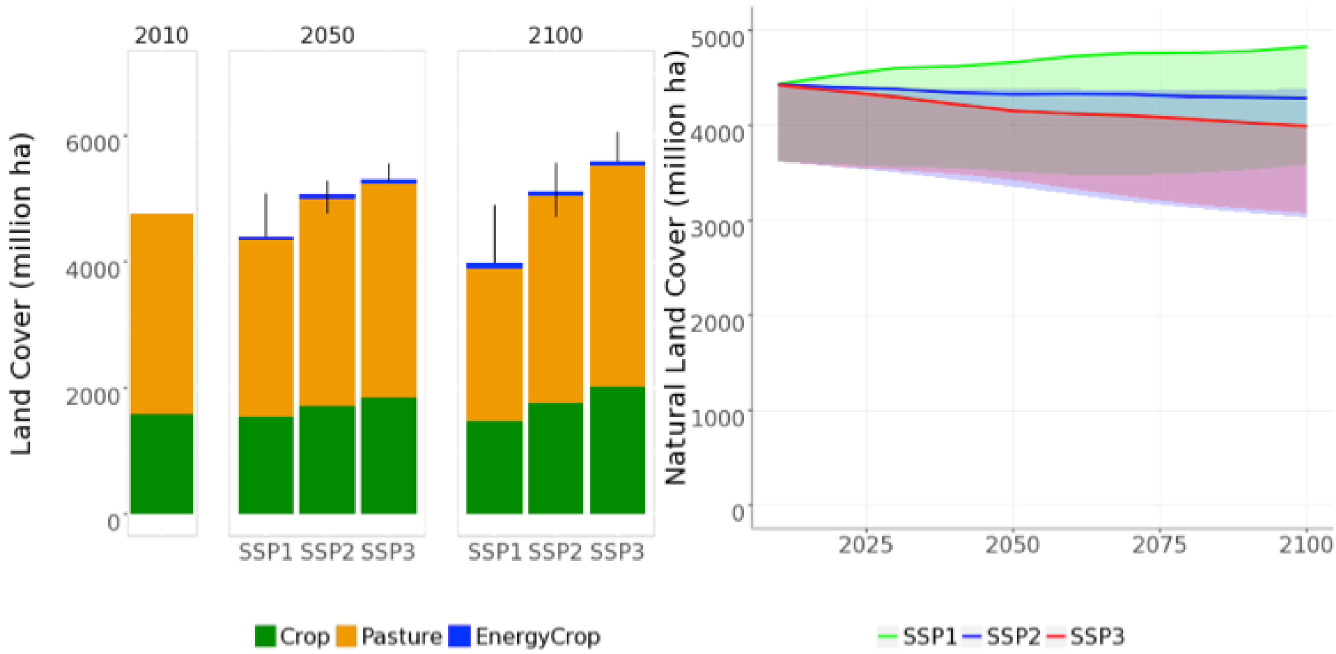


Figure 14; development of land use (crop land/pasture land/energy crop) (left) and natural area (right). The vertical lines and shaded area indicate the range of results of the full set of IAM scenarios for the specific SSP (for comparison also the SSP1 and SSP3 results are shown). (Van Vuuren et al., 2016)

As a result of the trends discussed above – land use related emissions increase somewhat in the 2010-2050 period, but decrease in the 2050-2100 period. This overall trend is a compounded result of a decrease in CO_2 emissions from land-use change and an increase in emissions associated directly with agriculture (methane and N_2O). Here, emissions mostly originate from animal husbandry, rice production and fertilizer use.

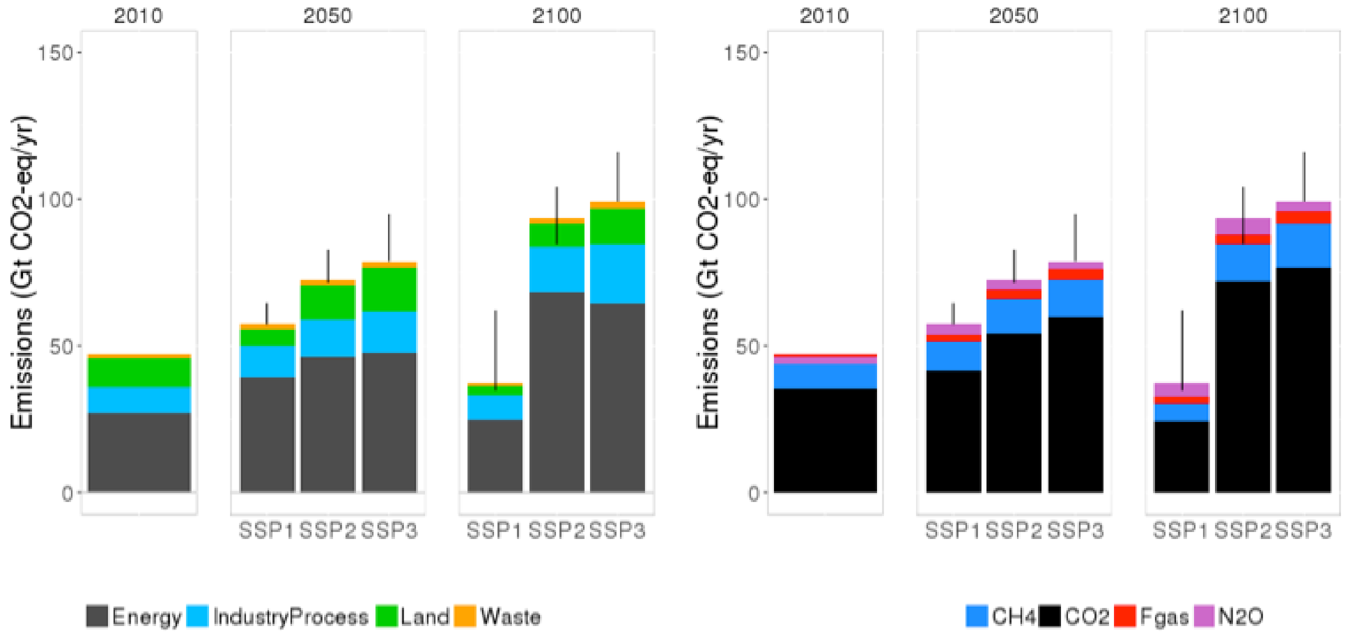


Figure 15; global feed requirement for monogastrics and ruminants (left) and global average yield for maize (for comparison also the SSP1 and SSP3 results are shown). (Van Vuuren et al., 2016)

3.5.2.3 CLIMATE POLICY

In IMAGE, climate policy is usually implemented by introducing a carbon price that induces a transition towards low-greenhouse gas emitting technologies. The application of a universal carbon price allows least-cost scenarios for different climate goals to be derived. The measures implemented include change in energy use, reduction of deforestation rates, reforestation and reduction of non-CO_2 emissions. In this project, the 2° C decarbonisation pathways for the agriculture commodities is modelled in a similar way by applying a carbon price to the marginal abatement cost curves, see Annex 1 and 2.

4 EMISSION INTENSITY PATHWAYS FOR KEY COMMODITIES

4.1 INTRODUCTION

In this chapter, we describe how the IMAGE model is used to derive commodity specific emission intensity pathways. We make a distinction between:

1) CO_2 emissions resulting from the conversion of natural land to agricultural land (LUC-CO_2) and
2) All other emissions in the agriculture sector (mainly CH_4 and N_2O).

LUC-CO_2 emissions results from the expansion of agricultural production and can come from all agricultural commodities. For LUC-CO_2, CO_2 emission factors are derived for rice, maize, wheat, soybeans, palm oil and several livestock products (beef, milk, pork and poultry). Since livestock feed consists partly of grass, also an emission factor for grass was derived. Finally CO_2 emission from drained peat soils were added to the LUC-CO_2 factor for palm oil in Indonesia and Malaysia. There are several methods to attribute the LUC-CO_2 emissions to the relevant commodities. This is explained in section 4.2.

For all other agricultural emissions, the allocation to the relevant commodities is more straight-forward. This is explained in detail in section 4.2 and can be summarized in short as follows:

In the IMAGE module, agricultural CH_4 and N_2O emissions in all IMAGE regions (from fertilizer use, crop residues, agricultural waste burning (AWB), rice production and deforestation) are allocated to the following food and feed crop groups:

- Rice, maize, temperate cereals (specifically wheat), roots & tubers, oil crops (specifically palm oil and soy), tropical cereals, pulses and other crops.

Secondly, direct and indirect CH_4 and N_2O emissions are allocated to the following animal products:

- Beef, milk, pork, mutton & goat, poultry & eggs. Direct emissions result from the sources animal waste and enteric fermentation, while indirect emissions result from feed production, either within a region or in another region.

In addition, CO_2 emissions from on-farm machinery, transportation and irrigation and CO_2 and N_2O emissions from upstream fertilizer production are also accounted to the commodities.

The result is 1) Total emissions per commodity group (specified by year, region, GHG, and underlying processes) 2) emission factors per commodity group (specified by year, region, GHG, and underlying processes). See Table 1 for the emission sources that are accounted for in the calculation, for each of the agricultural commodities.

COMMODITY	EMISSIONS*		
	CH_4	N_2O	CO_2
CROPS			
RICE	AWB, wetland rice production, deforestation	Fertilizer use, indirect fertilizer use (including correction for increased emissions due to CH_4 reduction measures), residues, AWB, deforestation, fertilizer production	Land-use change, fertilizer production, irrigation, machinery
MAIZE	AWB, deforestation	Fertilizer use, indirect fertilizer use, residues, AWB, deforestation, fertilizer production	Land-use change, fertilizer production, irrigation, machinery
TEMPERATE CEREALS (WHEAT)	AWB, deforestation	Fertilizer use, indirect fertilizer use, residues, AWB, deforestation, fertilizer production	Land-use change, fertilizer production, irrigation, machinery
OIL CROPS (PALM OIL/SOY)	AWB, deforestation	Fertilizer use, indirect fertilizer use, residues, AWB, biological N-fixation, deforestation, fertilizer production	Land-use change, fertilizer production, irrigation, machinery
TROPICAL CEREALS	AWB, deforestation	Fertilizer use, indirect fertilizer use, residues, AWB, deforestation, fertilizer production	Land-use change, fertilizer production, irrigation, machinery
PULSES	AWB, deforestation	Fertilizer use, indirect fertilizer use, residues, AWB, biological N-fixation, deforestation	Land-use change, fertilizer production, irrigation, machinery
ANIMAL PRODUCTS			
BEEF	Enteric fermentation, manure, feed crops	Manure, feed crops	Land-use change, machinery, feed crops
MILK	Enteric fermentation, manure, feed crops	Manure, feed crops	Land-use change, machinery, feed crops
PORK	Manure, feed crops	Manure, feed crops	Land-use change, machinery, feed crops
POULTRY & EGGS	Manure, feed crops	Manure, feed crops	Land-use change, machinery, feed crops

Table 1; emission sources accounted for in the IMAGE module, specified per agricultural product

** 1) AWB = agricultural waste burning . 2) Biomass burning for deforestation causes CH_4 and N_2O emissions as part of the burning process. 3) Animal feedstock emissions from the production of grass are currently assumed to be zero*

4.2 EMISSION INTENSITY PATHWAYS EXCLUDING LAND-USE CHANGE

4.2.1 METHOD

In order to derive the total emissions and emission factors for a commodity group (specified by year, region, GHG and commodity group), the following equations are used:

Equation 1:

$$EM(GHG, r, y) = \sum(GHG\ source)\ EM(GHG\ source\ GHG, r, y)$$

Equation 2:

$$EF(GHG, r, y) = (EM(GHG, r, y)) / (Prod(r,y))$$

Where:

EM = commodity specific emissions (Mt GHG)

EF = commodity specific emission factor (Mt GHG / Mt dry matter commodity)

Prod = commodity specific production (Mt dry matter commodity)

GHG = greenhouse gas

r = region

y = year

GHG source = GHG source

IMAGE defines commodity production both in terms of dry matter (DM) commodity produced as well as in fresh (or market) weight commodity produced. The former is often necessary, since the moisture content of commodities can often vary, and because commodities expressed in DM can provide a more unambiguous input for calculations, e.g. when determining the feed requirement for cattle. This is based on the proportion of digestible energy in the total energy intake, and the energy content of biomass, which is defined on a DM basis.

The commodity emission factors can also be expressed in both DM and fresh weight terms. Table 2 shows the conversion factors that IMAGE applies for all commodities considered in the project.

	DRY MATTER CONTENT	MOISTURE CONTENT
CATTLE MEAT	50%	50%
CATTLE MILK	13%	87%
PORK MEAT	50%	50%
SHEEP & GOAT MEAT	50%	50%
POULTRY MEAT & EGGS	50%	50%
TEMPERATE CEREALS (WHEAT)	88%	12%
RICE	87%	13%
MAIZE	88%	12%
OIL CROPS (SOY AND PALM OIL)	92%	8%

Table 2; conversion factor for dry matter and moisture content as applied in IMAGE for various crops.

The commodity specific production is standard output of the IMAGE model, which implies that the emission factors can easily be calculated where the commodity specific emissions are known (following the second equation). For some GHG sources (i.e. Crop residues, agricultural waste burning and wetland rice, enteric fermentation and animal waste) the IMAGE model does indeed generate commodity specific emissions. However, for other sources the emissions are aggregated and need to be allocated to the specific crops. Below, this is described for all of the relevant emission sources.

4.2.2 EMISSIONS FROM CROPS

4.2.2.1 FERTILIZER (N_2O)

Fertilizer emissions are not generated on a crop specific basis. Therefore, the following calculation steps are taken to allocate the fertilizer emissions to the crop groups:

1) Determination of fertilizer use per crop. This is based on the historical fertilizer use per region divided by the produced crops in a region. The assumption is that the crops need an equal amount of fertilizer per amount of dry matter (DM) commodity produced.[4]
2) The fertilizer distribution from 1 is used to allocate fertilizer N_2O emissions to the crops (assumption: no fertilizer is used for the production of grass used as animal feed).
3) The emission factors (region, year) can be determined using the equations above.

4.2.2.2 CROP RESIDUES AND AGRICULTURAL WASTE BURNING (CH_4, N_2O)

Crop specific residue emissions and crop specific agricultural waste burning emissions (CH_4 and N_2O) are generated as standard IMAGE output (this takes into account that part of the residues is used as animal feed and bio-energy feedstock, which lowers the net residue emissions). The emission factors (region, year) can be determined using equations 1 and 2.

4.2.2.3 WETLAND RICE (CH_4)

CH_4 emissions from wetland rice production can be fully accounted to rice, and the emission factors (region, year) can be determined using the equations above.

An additional correction is needed to account for an increase of N_2O emissions resulting from wetland rice CH_4 emission reduction. Abatement of wetland rice CH_4 leads to increase of N_2O emissions for crop residue, waste burning and fertilizer. For each reduced Mt CH_4, it is estimated there is an increase of 0.0067 Mt N_2O (median value of Li et al., 2009, Towprayoon et al., 2005, Zou et al., 2005, Wassman et al., 2000). These additional N_2O emissions are added to N_2O from indirect fertilizer use, and thus included in the overall emission and emission factor calculations.

4.2.2.4 INDIRECT FERTILIZER USE (N_20)

Note that indirect fertilizer emissions in IMAGE are actually nitrogen runoff from several primary sources: fertilizer (the main source), residues and manure application. For each of the sources, a fraction of the nitrogen content is assumed to leach away as runoff and result in N_2O emissions. The calculated total emissions from the IMAGE model are not crop-specific, so an additional step is needed to allocate these to the crop groups. Similarly, to the calculation for fertilizer emissions, the assumption is here that the crops generate an equal amount of indirect fertilizer emissions per amount of dry matter (DM) commodity produced.

The emission factors (region, year) can be determined using equations 1 and 2.

4.2.2.5 BIOLOGICAL N-FIXATION (N_20)

The calculated total emissions from the IMAGE model are not crop-specific, so an additional step is needed to allocate these to the crop groups. N-fixation is assumed to only take place for pulses and oil crops. The precise distribution between the two categories is not known, so it is assumed to be 50% / 50% (on a dry matter (DM) basis).

The emission factors (region, year) can be determined using equations 1 and 2.

[4]In a later stage this can be improved in case there is reliable data on any unequal distribution of fertilizer over the crops.

4.2.2.6 BIOMASS BURNING / DEFORESTATION (CH_4, N_2O)

This category represents the non-CO_2 land-use change emissions. These emissions are the result of biomass (mainly forest) burning, often intended to expand agricultural land area[5]. The IMAGE results are not crop-specific, so the emissions need to be divided over the relevant crops.

The biomass burning emissions (CH_4 and N_2O) are therefore accounted to the crop groups on a crop area basis[6], by assuming the following relation.:

Equation 3:

$$EM_{defor}\ (c, GHG\ source, GHG, r, y) = EM_{defor}\ (GHG\ source, GHG, r, y)\ /\ (AR_{all\ crops}\ (r, y)/AR_{crop}\ (r, y))$$

Where:

EM_{defor} = Deforestation (biomass burning) emissions

$AR_{all\ crops}$ = Land area used for all crops (including bioenergy crops)

AR_{crop} = Land area used for one specific crop

c = commodity

GHG source = GHG source

GHG = greenhouse gas

r = region

y = year

The emission factors (region, year) can be determined using the equations 1 and 2.

4.2.3 EMISSIONS FROM FERTILIZER PRODUCTION, IRRIGATION AND MACHINERY

This section describes calculation of the upstream GHG emissions associated with energy use and fertilizer production.

This relates to the following emission sources:

- Upstream N_2O and CO_2 emissions from fertilizer production. N_2O is formed as a by-product of nitric acid production, which is the main resource in the production process of fertilizer. CO_2 is formed as a by-product from the energy used in the production process.
- CO_2 emissions from energy use for on-farm machinery, transportation and irrigation.

The CO_2 emissions are expected to reduce considerably under a 2° C constraint due to decarbonisation in energy use. See Table 3 for the key energy and emission variables in the 2° C scenario used in this project.

CATEGORY		UNIT	2010	2020	2030	2040	2050
ENERGY USE	Fertilizer production	EJ	5.03	4.01	3.05	2.77	3.80
	Irrigation	EJ	2.34	1.86	1.42	1.29	1.76
	Machinery, incl. transport	EJ	5.25	4.18	3.19	2.89	3.96
CO_2 EMISSIONS	Fertilizer production	Mt CO_2	488	383	230	125	110
	Irrigation	Mt CO_2	227	178	107	58	51
	Machinery, incl. transport	Mt CO_2	509	400	240	131	115
EMISSION FACTOR	Fertilizer production	Mt CO_2/Mt DMproduct	0.147	0.096	0.048	0.020	0.017
	Irrigation	Mt CO_2/Mt DMproduct	0.068	0.045	0.022	0.009	0.008
	Machinery, incl. transport	Mt CO2/Mt DMproduct	0.143	0.093	0.046	0.020	0.017

Table 3; global agriculture energy use, CO_2 emissions and CO_2 emission factors under a 2° C constraint in 2100.

[5]Land clearing for crop production can also generate N_2O emissions and is therefore also included in this module. However, these emissions are currently assumed to be zero in IMAGE.

[6]In a later stage, the non-CO_2 LUC emissions calculation should eventually make use of the same methods to calculate LUC-CO_2 emissions per commodity and region. The current crop area based approach is one of these methods

4.2.3.1 FERTILIZER PRODUCTION (N_2O, CO_2)

In the IMAGE model, nitric acid emissions are considerably mitigated in a 2° C scenario (up to 90% in 2050), due to the availability of relatively economical abatement measures.

In the module, the fertilizer production emissions are assumed to be proportional to the fertilizer use emissions, since there is no reliable information about the origin of the fertilizer, particularly in future years. The nitric acid N_2O emissions and energy CO_2 emissions (from Table 3) are allocated to the crops using that distribution in fertilizer use emissions. The emission factors (region, year) can be determined using equations 1 and 2.

4.2.3.2 IRRIGATION AND MACHINERY (CO_2)

Due to lack of data regarding regional differences in energy use for irrigation and machinery, we make use of the average global emission factors for Table 3. This is applied equally to all commodities on a DM basis (irrigation only to crops, machinery to all commodities). The emission factors (region, year) can be determined using equations 1 and 2.

4.2.4 EMISSIONS FROM ANIMAL PRODUCTS

4.2.4.1 ENTERIC FERMENTATION (CH_4)

Enteric fermentation emissions are generated as standard IMAGE output subdivided in emissions from dairy cattle and from non-dairy cattle. Emissions from the first category are fully allocated to dairy / milk products, whereas emission from the second are allocated to beef.

The emission factors (region, year) can be determined using equations 1 and 2.

4.2.4.2 ANIMAL WASTE (CH_4, N_20)

Animal waste emissions (CH_4 and N_2O) from the IMAGE model are specified for the different animal groups, so no additional steps are needed.

The emission factors (region, year) can be determined using equations 1 and 2.

4.2.4.3 FEEDSTOCK EMISSIONS (FOR ANIMAL PRODUCTS) (CH_4, N_2O)

Animal feed emissions are indirect emissions caused during the production of the feed crops. In order to determine the total indirect emissions per animal group, several steps are needed:

1) For each of the animal groups in each of the regions, the share of feed (TFeed_factor) in the total food production is determined:

Equation 4:

TFeed_factor (ag, r,y) = Total DM feed (ag, r, y) / Total BM food(r, y)

Where:

TFeed_factor = share feed in the total food production

Total DM feed = total DM of feed production

Total DM food = total DM of food production

ag = animal group

r = region

y = year

2) TFeed_factor is made crop specific by applying assumed fractions of crops in the feed mix (frFeedCrop):

Equation 5:

*TFeedcrop_factor (ag, cg, r,y) = TFeed_factor (ag, r, y) *frFeedcrop (cg)*

Where:

TFeedcrop_factor = share feedcrop in the total food production

TFeed_factor = share feed in the total food production

frFeedCrop = fraction of total feed

ag = animal group

cg = crop group

r = region

y = year

3) Feed trade between regions has to be taken into account, due to different crop related emissions in different regions. In order to do this, a trade matrix is used (based on 2005 FAO trade data, the most recent complete source), from which the distribution of traded dry matter crops between the IMAGE regions is derived. The matrix is normalized, which means that for a specific crop type and importing region, the values of all exporting regions amount to 1.

Equation 6:

$$\mathit{TFeedcrop\_factor\_PerOrigin}(ir, er, ag, cg, r, y) = \mathit{TFeedcrop\_factor}\,(ag, cg, r, y) * \mathit{Tradematrix}\,(ir, er, cg)$$

Where:

TFeedcrop_factor_PerOrigin	= imported feed per region
TFeedcrop_factor	= share feed crop in the total food production
Tradematrix	= tradeflows of food crops between importing and exporting regions
ir	= importing region
er	= exporting region
ag	= animal group
cg	= crop group
r	= region
y	= year

4) The feed emission factors are derived by multiplying the normalized feed flows with the emission factors of the crops in the exporting regions.

Equation 7:

$$\mathit{EF\ feed}\,(ag, ir, cg, p, GHG, y) = \mathit{TFeedcrop\_factor\_PerOrigin}\,(ir, er, ag, cg, r, y) * \mathit{EF}\,(cg, er, p, GHG, y)$$

Where:

EF feed	= feed emission factor
TFeedcrop_factor_PerOrigin	= imported feed per region
EM	= emission factor
ir	= importing region
er	= exporting region
ag	= animal group
cg	= crop group
r	= region
y	= year

The emission factors of the crop groups and processes can be summed to derive a more aggregated feed emission factor:

Equation 8:

$$\mathit{EF\ feed}\,(ag, ir, GHG, year) = \sum (cg, p) \quad \mathit{EF\ feed}\,(ag, ir, GHG, year)$$

With:

ir	= importing region
er	= exporting region
ar	= animal group
cg	= crop group
r	= region
y	= year

The total feed emissions can be calculated by multiplying EF feed with the regional production of the animal group (in dry matter).

4.2.5 RESULTS

Based on above equations, we have simulated in the IMAGE model the GHG emissions of the selected commodities in 26 regions according to the SSP2 2° C scenario. Below we present some results. We refer companies and other stakeholders to use to online-tool (see chapter 4) to see and use the full set of emissions factors for the selected commodities.

Global commodity emission factors (total except LUC-CO_2)

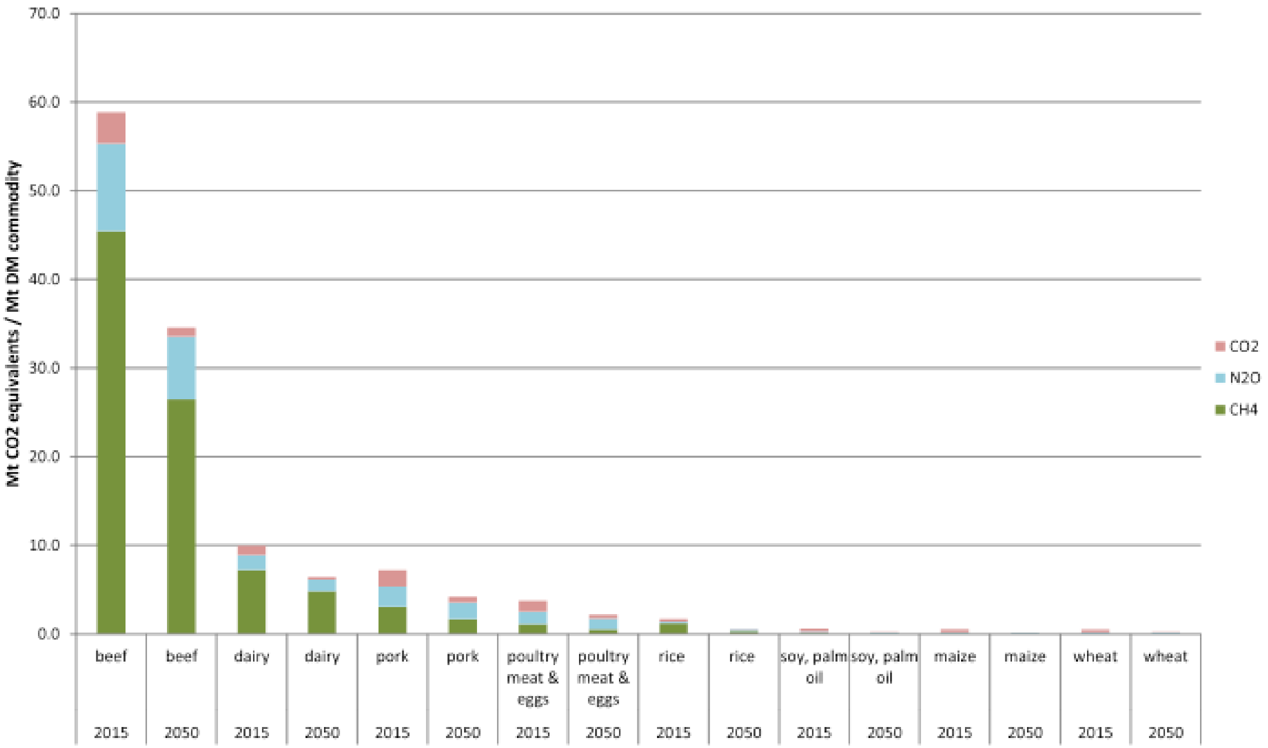


Figure 16; global emission factors for agricultural commodities under a 2° C constraint. CO_2 emissions from land-use change are excluded. Emission factors are shown for 2015 and 2050 and grouped by CH_4, N_2O and CO_2 using a 100 year global warming potential from the fourth Assessment Report[7].

Global commodity emission factors (beef not shown)

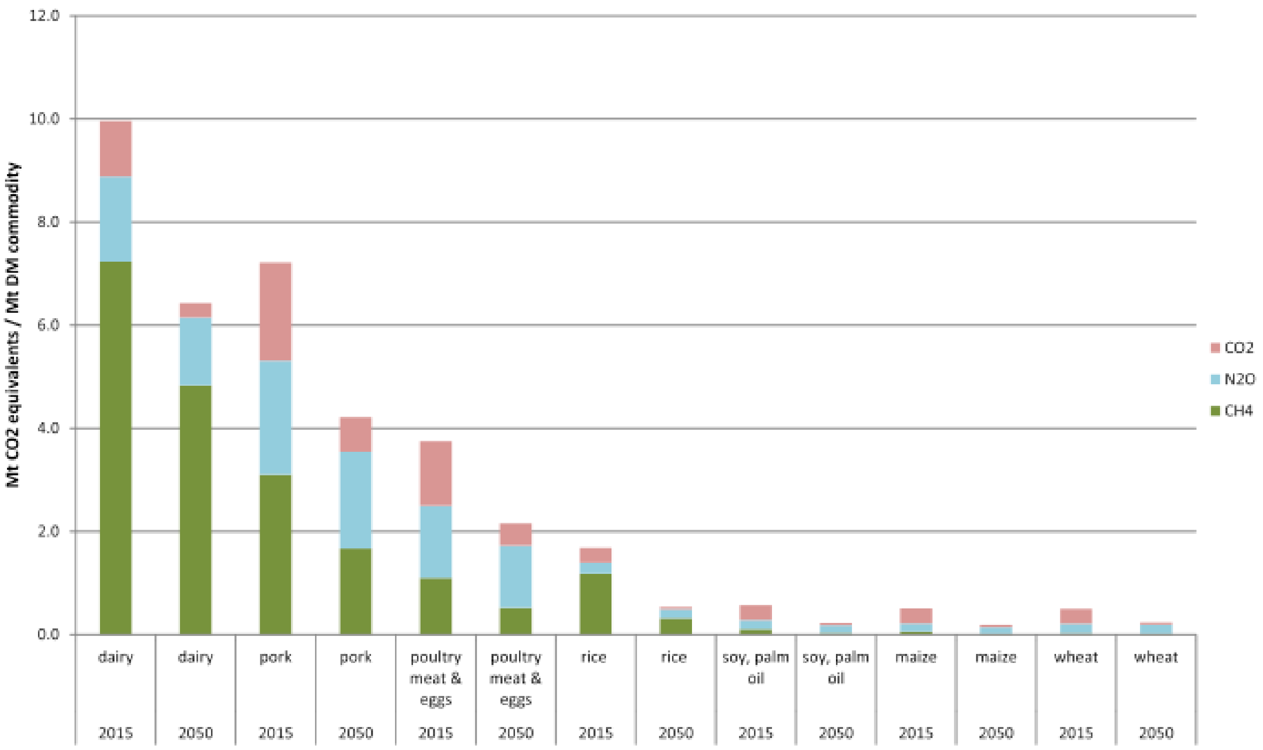


Figure 17; global emission factors for agricultural commodities under a 2° C constraint, shown for all commodities except beef to enable to show the lower values. CO_2 emissions and emission factors calculated as explained under the previous figure.

[7] GWP CH_4 = 25, GWP N_2O = 298. We have decided to use the GWP value for CH_4 of 25 instead of 28 as is done in the fifth Assessment Report in order to compare our results with literature.

Global GHG emissions per commodity (excluding feed)

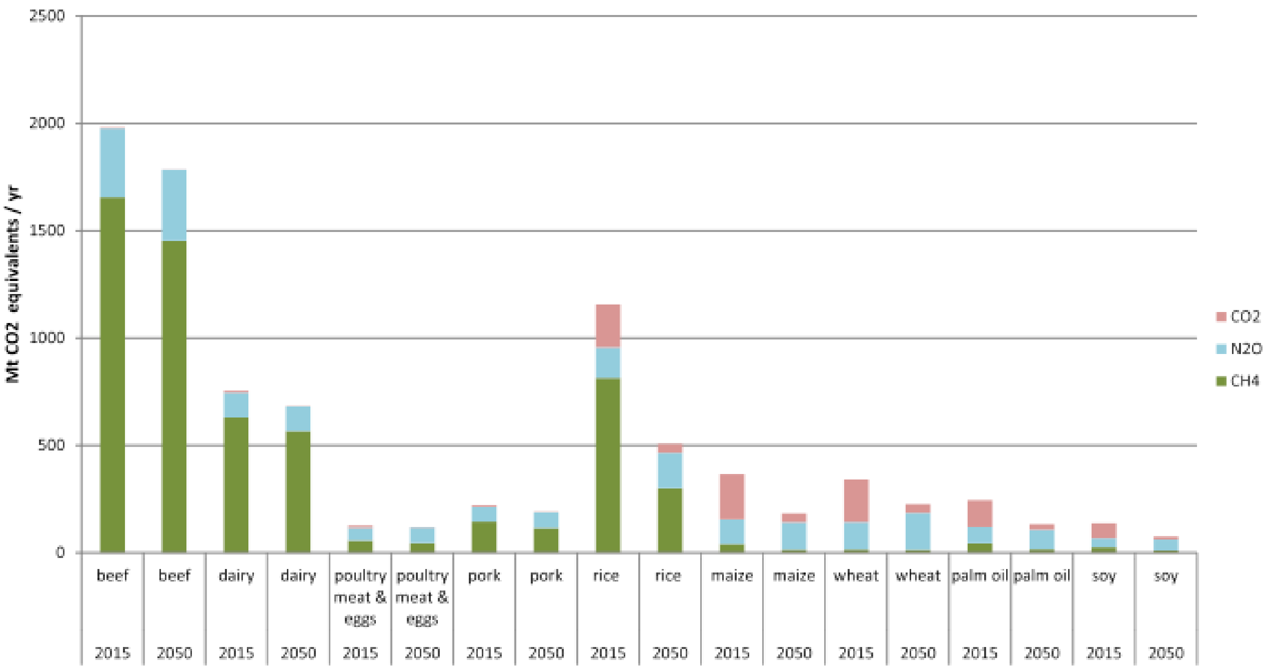


Figure 18; global emissions for agricultural commodities under a 2° C constraint. Animal feedstock emissions are excluded. CO_2 emissions from land-use change are excluded. Emission factors are shown and calculated as explained under the figures above.

Two regional examples: Rice (South East Asia) and Beef (OECD Europe)

EF Rice – South East Asia

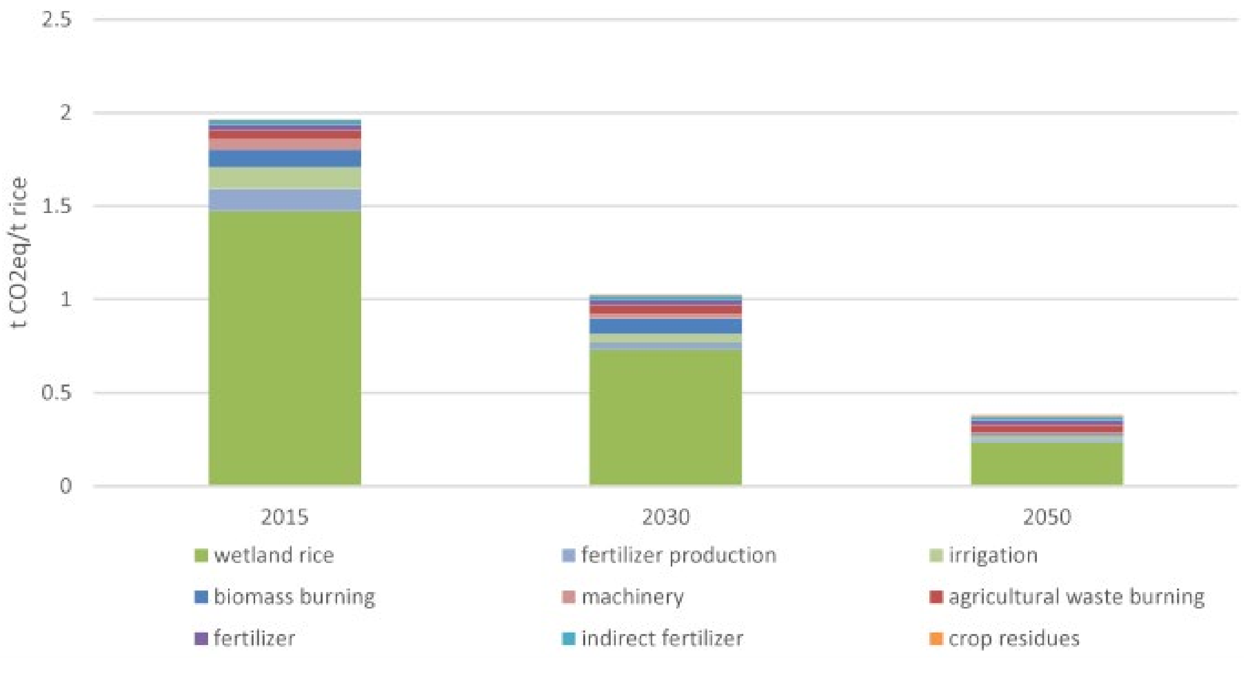


Figure 19; emission factor for rice in South East Asia under 2° C constraint in 2015, 2030 and 2050 (in tonnes CO_2 equivalents per tonnes rice). The built-up of the emission factor is shown and includes all relevant emission sources, ranging from the source with the highest contribution (wetland rice CH_4) in 2015 to that with the lowest contribution in 2015.

EF Beef OECD Europe

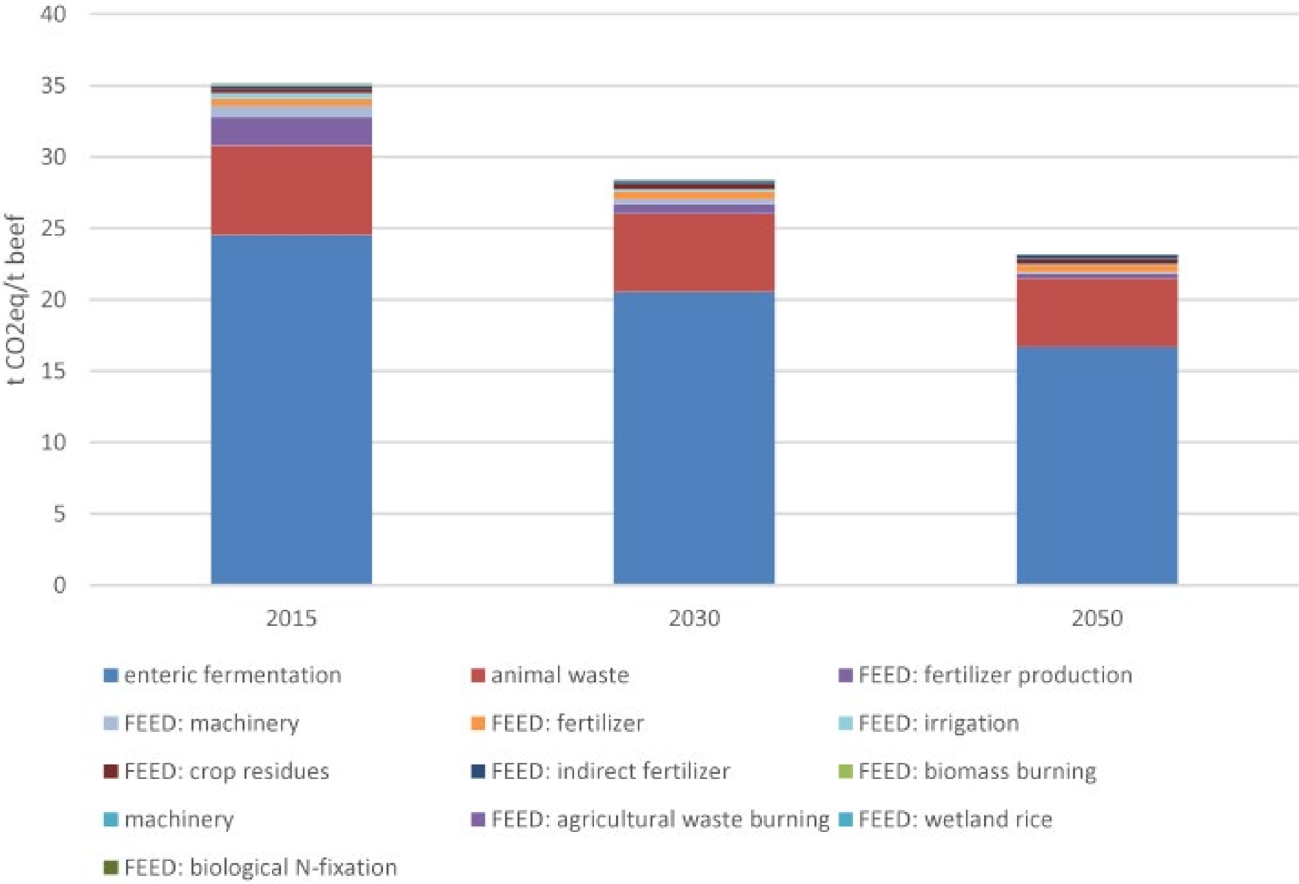


Figure 20; emission factor for beef in OECD Europe under 2° C constraint in 2015, 2030 and 2050 (in tonnes CO_2 equivalents per tonnes beef). The built-up of the emission factor is shown and includes all relevant emission sources, ranging from the source with the highest contribution (enteric fermentation) in 2015 to that with the lowest contribution in 2015.

4.3 EMISSIONS OF LAND-USE CHANGE

4.3.1 METHOD

As shown in section 2.1.2, CO_2 emissions from land-use change have a substantial contribution to the total GHG emission intensity of many agricultural commodities, in addition to direct emission along the production chain (described above in section 4.2). These latter emissions are regularly accounted for in the context of Life Cycle Assessment (LCA), there is a consensus about calculation methods, and these calculations are even standardized internationally. For CO_2 emissions, however, which result from the conversion of natural land to agricultural land (LUC-CO_2), emissions are often not accounted for in LCA's until now. As these emissions only occur if agricultural production expands, they cannot easily be attributed to a certain product or production chain. As there is no standard calculation method, we have explored various methodological approaches to include these important emissions in the development of the science-based targets methodology.

4.3.1.1 APPROACHES TO ESTIMATE LUC-CO_2 PER REGION AND COMMODITY

There are multiple possibilities in deriving LUC-CO_2 emissions for activities and commodities. Below, we describe four methods that are currently described in the literature and applied in the LCA-like approaches.

In italics we highlight the most important implications of the respective method. We have calculated emission factors according to all four methods, to highlight the uncertainty, and as a contribution to the scientific discussion and literature. In the next section, we describe the criteria that are relevant in selecting the most appropriate method for the "Science based targets" (SBT) tool.

A. "LUC marginal". As done e.g. for bioenergy, the emissions related to the additional production of one unit of product are calculated by comparing this scenario to a counterfactual world where this additional production would not have occurred. Can be calculated either by a static model, or by an economic model (applied in iLUC modelling studies), accounting for feedbacks and adjustments in the entire agricultural system. It was decided within the SBT-AFOLU project that we will not apply a macro-economic model to derive LUC emission factors including economic feedbacks. In calculating the emission factor, we introduce a 20% production in crease per commodity, in separate experiments.

If calculated as separate demand shocks for all regions and commodities, this method would include all LUC effects (i.e. direct and indirect). Applying this "marginal" emission factor to the entire production would lead to a large overestimation of total emissions.

B. "Hist. area". Allocating LUC-CO_2, which occured over a certain period (historic period, or future period) to all commodities on a per ha cropland basis, i.e. average LUC-CO_2 per ha cropland in one specific region / country (see global example calculation below).

This method would result in the same per ha emission factor within a region, independent of the crop, i.e. rice production on old agricultural land would see the same emission factor as palm-oil production which just started 20 years ago.

C. "Hist. expansion". Allocating LUC-CO_2 which occurred over a certain period (historic period, or future period) to the commodities which have increased in production and area, on a per ha basis (i.e. averaging the LUC-CO_2 across all palm oil production in that region / country, if only palm oil has expanded). This method has been applied by FAO in allocating LUC-CO_2 to livestock.

This method would give higher emission factors to commodities which have recently expanded (e.g. higher emission factor to palm oil in Indonesia than to Indonesian rice).

D. "Forgone sequestration". Derive a LUC-CO_2 factor for land occupation from the forgone CO_2 uptake which would have occured if the production would have stopped. This method has been applied implicitly by Nguyen et al. (2010), and a slightly modified variant has been proposed by Müller-Wenk and Brandão (2010).
This method would reward high yields (as less area is used), and would give a disincentive to regions with high carbon stocks in soils and vegetation.

General implications: All methods A-D work on a per ha basis, and do therefore reward higher yields, as emission per tonne decreases with increasing yields. Method A explicitly calculates all land-use change effects (direct and indirect within a region), method B and C address indirect land-use change within a region, though with a time lag, but ignore indirect land-use change / leakage across regions. Method D mirrors method A, as it evaluates the situation if the production of a unit of a certain product would have stopped. It evaluates thus the implication of continued land occupation, and the resulting foregone CO_2 sink.

4.3.1.2 DETAILS ON THE METHODS, LIMITATIONS AND CHALLENGES

Here, we provide an overview on calculation methods, limitations and challenges.

- **Reference period for LUC emissions:** In many studies, LUC emissions are calculated as average yearly values over periods of 20 (EU Directive for direct emissions) to 50 years (Ros et al., 2010). In this project we compare periods of 10 and 20 years, and use as a default the reference period 1985-2005 for method B and C, and 2006-2026 for method A.
- **Climate change effects** and CO_2 fertilisation have been set off, considering the reference periods for emission factors range from 1985 to 2026. During this time period effects of climate change are less pronounced. For longer accounting periods this is open for discussion, but may also be the appropriate choice then.
- **Grass:** pasture is part of the model calculations and dynamics, due to all its feedbacks, but in allocating land-use change emissions to various land-cover types, grazing on natural grasslands is excluded for method B and C. (grass is in some regions occupies half of the total crop area).
- **Land abandonment** is not rewarded in the current results (i.e. we do not allow for negative emission factors if decreasing agricultural land leads to net carbon uptake). However, this may be changed to reward good land management.
- **Coverage:** Not every methodology results in valid or representative emission factor for every crop in every region. This is in many cases “by design” as e.g. the crop is not growing in that region, or is not expanding, or as emission factors would be negative. Results were also replaced in case the change in land area used for cultivation of a specific crop over time is smaller than the accuracy of IMAGE grid cells. In these cases we could provide the global average, results of a simpler model run or zero, to have full coverage.
- **Palm oil and Soybean:** Since IMAGE combines all oil crops into one crop type, post processing was needed to derive separate emissions factors for soybean and palm oil and include peat soil emissions into Indonesian and Malaysian palm oil. Both crops are part of the same IMAGE crop type called oil crops, although their distribution across regions, their yields and their lifetime are very different. Each IMAGE region has its own unique share of different oil crop types. Therefore, the regional oil crop yields from IMAGE were calibrated to match regional FAO yields for palm oil and soybean over the years 2000 2014 (15 years).
- **Peatlands** are a large contributor are a large contributor to land use change emissions for specific crops such as palm oil. Peat soil emissions were applied only to palm oil grown in Indonesia and Malaysia (South-East Asia region). An average peat soil emission factor of 55 tCO_2/ha/year for drained tropical peatland (Wilson, 2016) was multiplied with the past, present and future share of palm oil grown on peat (Miettinen, 2012).
- The choice of the **reference period** has a large effect on the results, and for future analysis and updates longer reference periods might be considered.
- **Spatial detail:** in using the aggregation of 26 regions in this project, local/national trends in land expansion/abandonment are averaged out. In subsequent updates, more detail may be added.
- **Evaluation/validation:** the amount and location of agricultural land-use change is of crucial importance for the emission factors, and therefore we propose to compare IMAGE land-use dynamics to recent observational data.
- **Certification schemes** are not addressed are not addressed in this project as means to reduce emission factors, and we have not calculate specific emission factors for certified products. This may be part of a follow-up project.
- **Comparison to literature:** Literature data on LUC-CO_2 for agricultural commodities is scarce or absent, therefore we compare here our emission factors to the biofuel

4.3.1.3 THE 2° C PATHWAY FOR LUC-CO_2

In principle, all methods can be applied to derive an emission factor within the 2 degree scenario in IMAGE. However, method A and D will result in almost the same emission factor as in the current state. The emission factor of method B and C strongly relate to the following factors: cropland expansion in the baseline and in the mitigation case, and the contribution of land-based mitigation actions such as afforestation and bio-energy. The latter results – in many mitigation scenarios – in a decrease in agricutlural area used for food and feed, and thus would result in a negative emission factor on global average. Between regions, this emission factor may differ a lot, not based on agricutlural management practices, but due to baseline trends, trade patterns, and regionally differntiated ambitions for afforestation. All of these factors are outside the influence sphere of the users of the SBT tool. We therefore propose to use a zero emission factor for LUC-CO_2 for all regions and commodities in 2030. This is also consistent with the goal of halting biodiversity loss, and to achieve zero deforestation.

4.3.1.4 SELECTING AN APPROPRIATE METHOD TO CALCULATE LUC-CO_2 EMISSION INTENSITIES

We handle these criteria for selecting an appropriate method to calculate LUC-CO_2 emission factors for the SBT tool.

- The method should give an incentive for increasing yields. Excess fertilizer application to achieve that would be prevented as N_2O emissions from fertilizer are also accounted for under the emission accounting.
- The method should give higher emission factors for production on recently converted land than on existing agricultural land (as for emissions from bio-energy, 2008 would be the reference year to determine previous land use). At the same time, sustainable expansion (low iLUC-risk expansion would be stimulated, as its emission factors would be comparably low.
- The method should reward regions with low or negative land expansion and thus low or negative CO_2 emissions from land-use change. Thus, indirect land-use change within a region would be captured, but not indirect land-use change across regions.
- In case no information exists on whether an existing agricultural area or newly converted area is used for production, a default emission factor is applied. However, if it is known that production takes place on newly converted land, obviously, the use of new agricultural land would be linked to the conversion emission, and thus method A needs to be applied.

4.3.2 RESULTS

For each method presented, emission factors were calculated for crops (wheat, rice, maize, palm oil and soybeans) and livestock products (beef, diary, pork and poultry & eggs) in IMAGE. The results are compared across IMAGE regions, crops and methods.

Emission factors in kg CO_2/kg crop

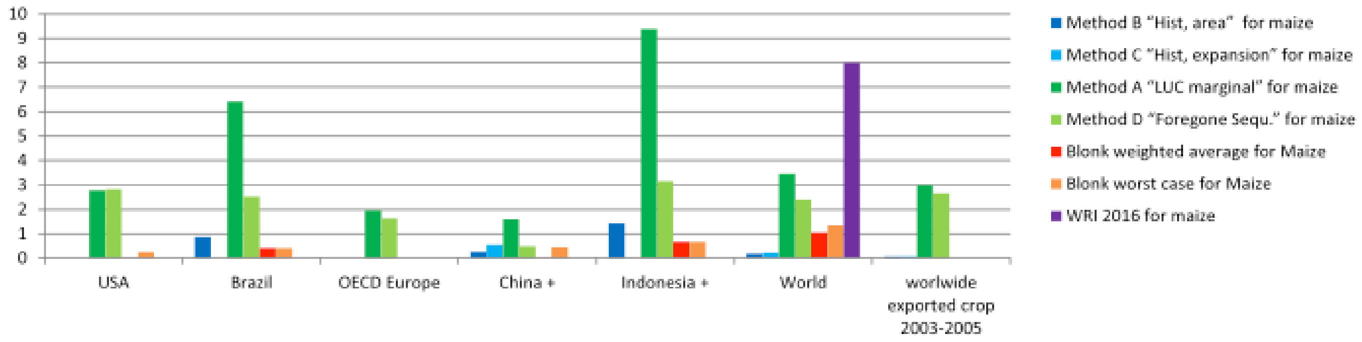


Figure 21; emission factors for maize as calculated by IMAGE.

Emission factors in kg ^{CO2}/kg crop

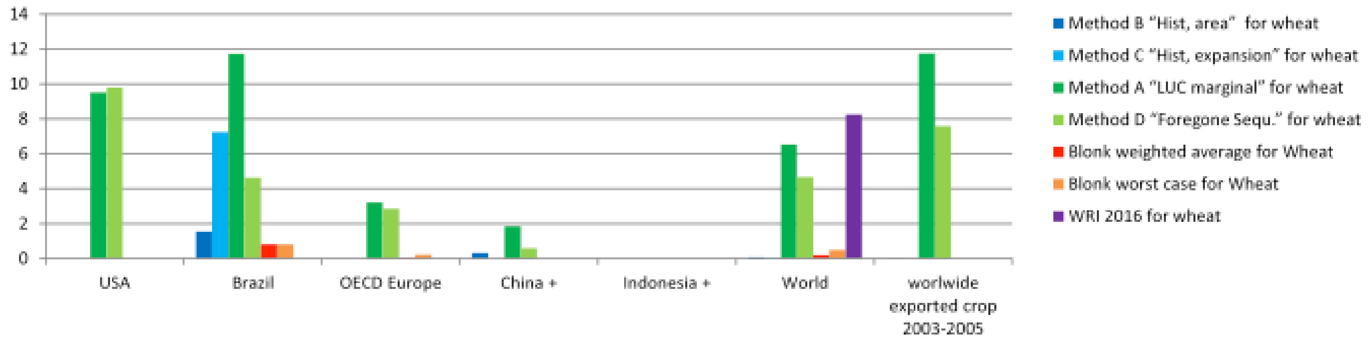


Figure 22; emission factors for wheat as calculated by IMAGE.

Emission factors in kg CO_2/kg crop

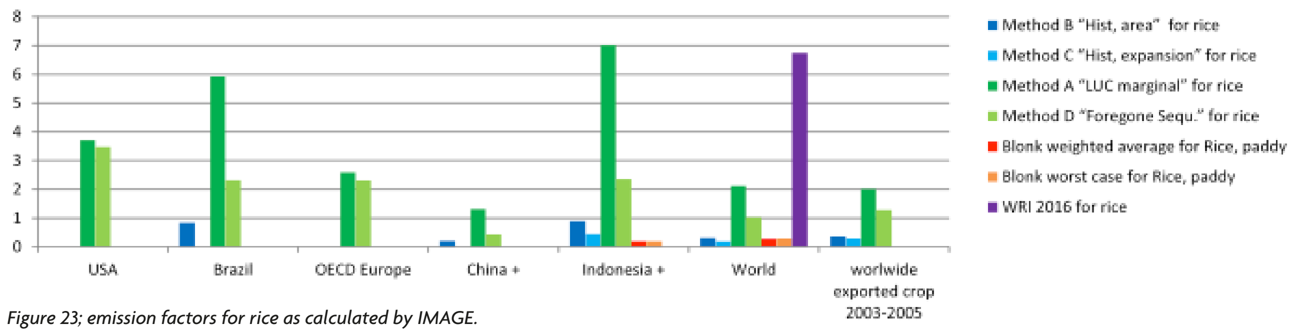


Figure 23; emission factors for rice as calculated by IMAGE.

Results show higher emission factors in the tropical regions of Brazil and Indonesia than in temperate regions. Emission factors for the USA are comparable with those from Brazil, since IMAGE assigns most agricultural expansion to pastureland, whereas in the USA forests are cleared for expanding agriculture in method A. Worldwide means of method B and C match the emissions factors of Blonk (2016), while worldwide emission factors of method A and D are in line with WRI. Some regions lack emission factors. The USA and Western Europe have no emission factors for method B and method C, since general land abandonment takes place in these regions. Indonesia does not grow wheat.

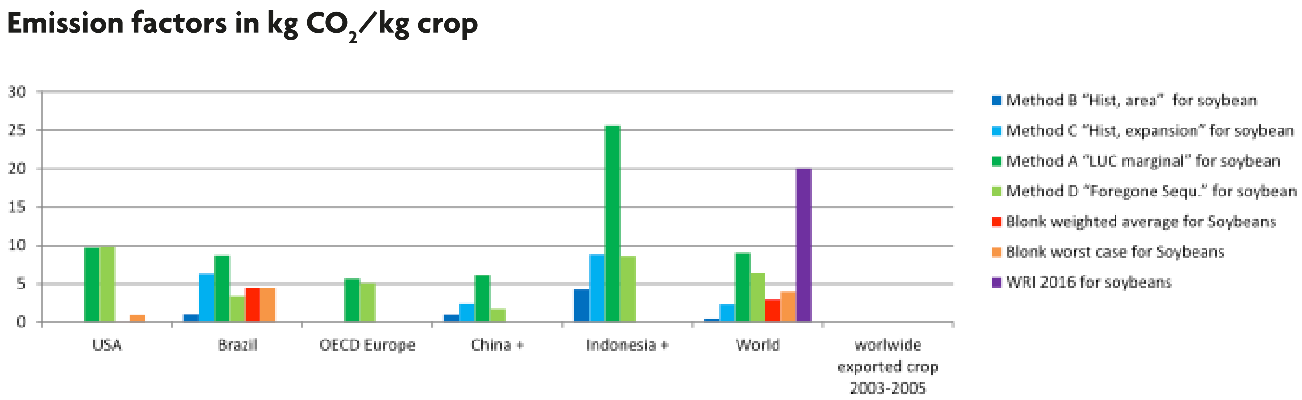


Figure 24; emission factors for soybeans as calculated by IMAGE.

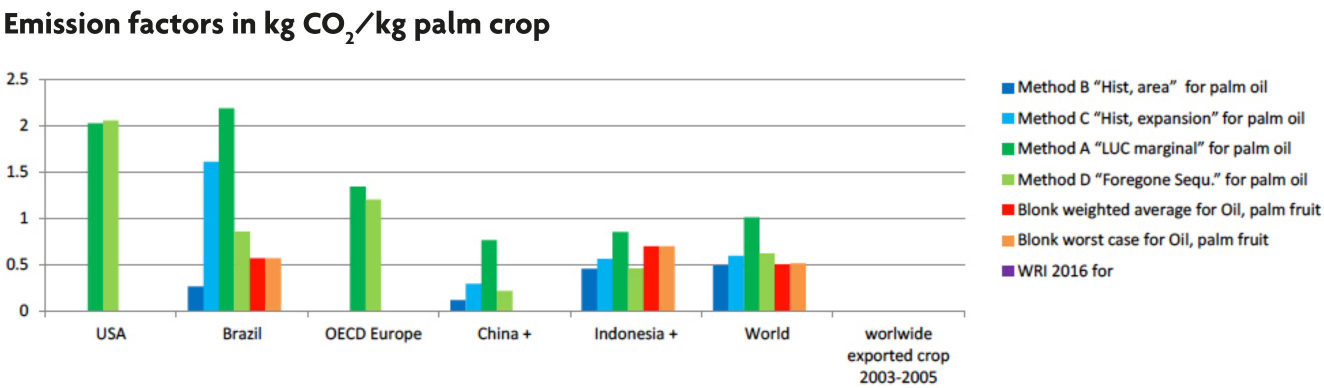


Figure 25; emission factors for palm oil or palm fruit as calculated by IMAGE.

Generally, soybean emission factors fit well into the range of reference emission factors of Blonk and WRI. Since the yield of palm oil is much higher than the yield of soybean, soybean has higher emission factors per kg crop than palm oil. This is even valid for Indonesia, despite of additional peatland emissions of palm oil. Brazil has high emission factor for soybean in method C, since soybean is often grown on newly cleared land. Therefore, method A and method C have comparable values for soybean in Brazil.

The emission factors for crops and grass were subsequently used as input for emission factors for livestock products.

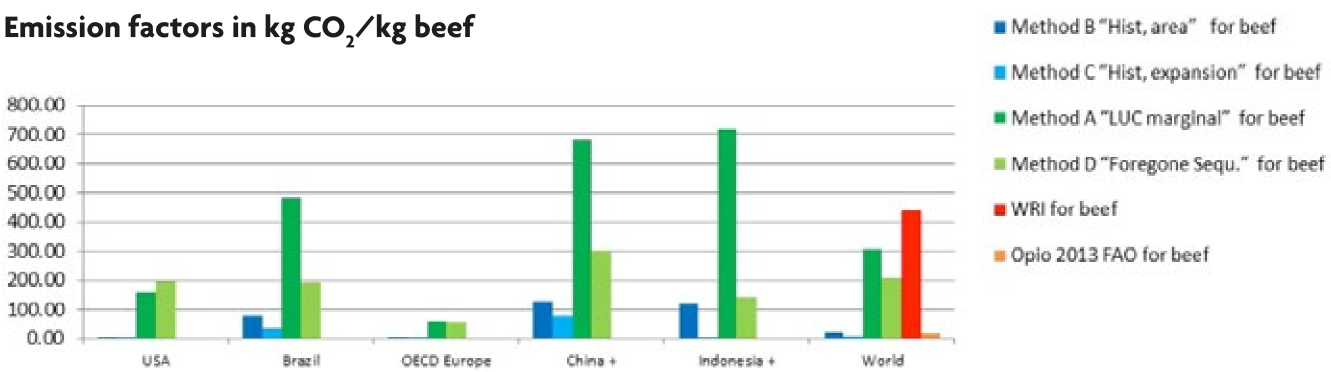


Figure 26; emission factors for beef as calculated by IMAGE.

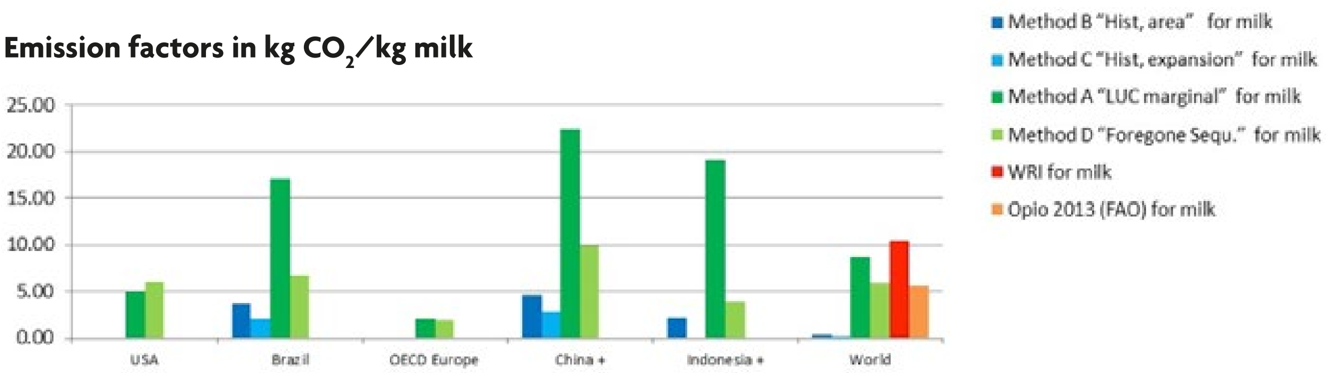


Figure 27; emission factors for milk as calculated by IMAGE.

Emission factors in kg CO_2/kg pork

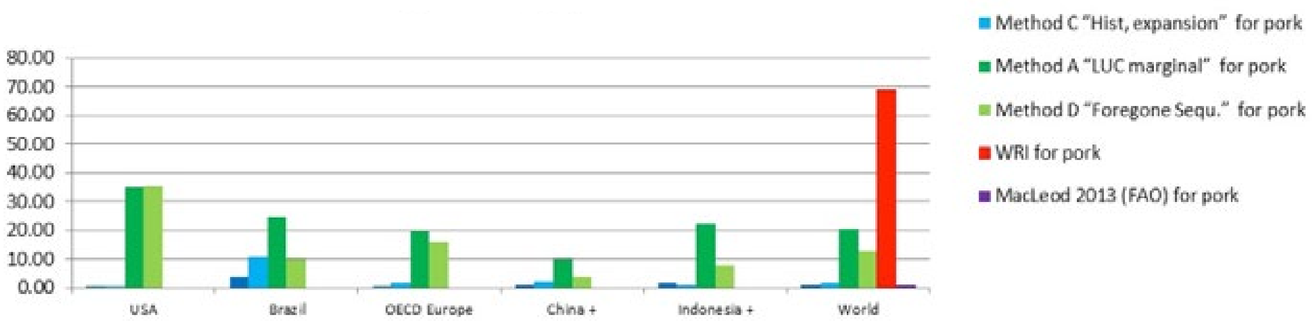


Figure 28; emission factors for pork as calculated by IMAGE.

Emission factors in kg CO_2/kg poultry & eggs

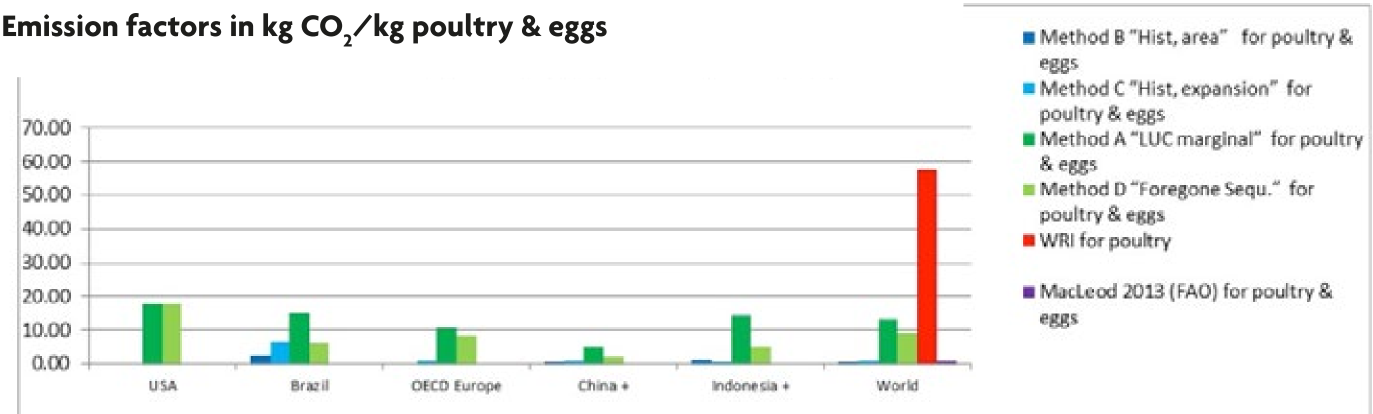


Figure 29; emission factors for poultry and eggs as calculated by IMAGE.

Below, global results are shown for livestock emission factors of milk, beef, pork and poultry & eggs.

Emission factors in kg CO_2/kg crop for "Forgone Sequential" method

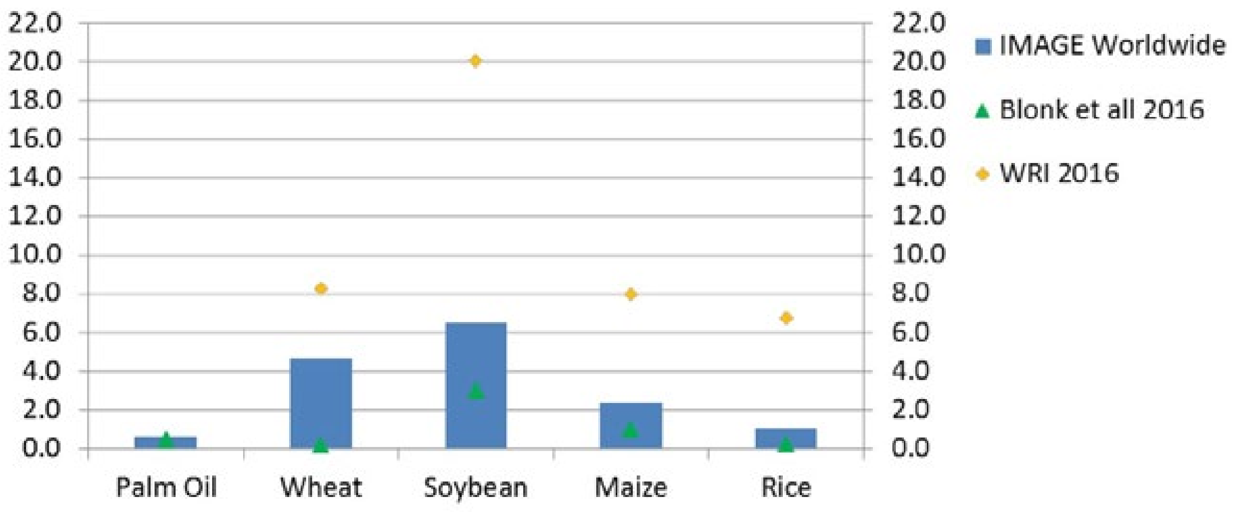


Figure 30; emission factors as calculated using method D for several crops.

Emission factors in kg CO_2/kg product for "Forgone Sequential" method

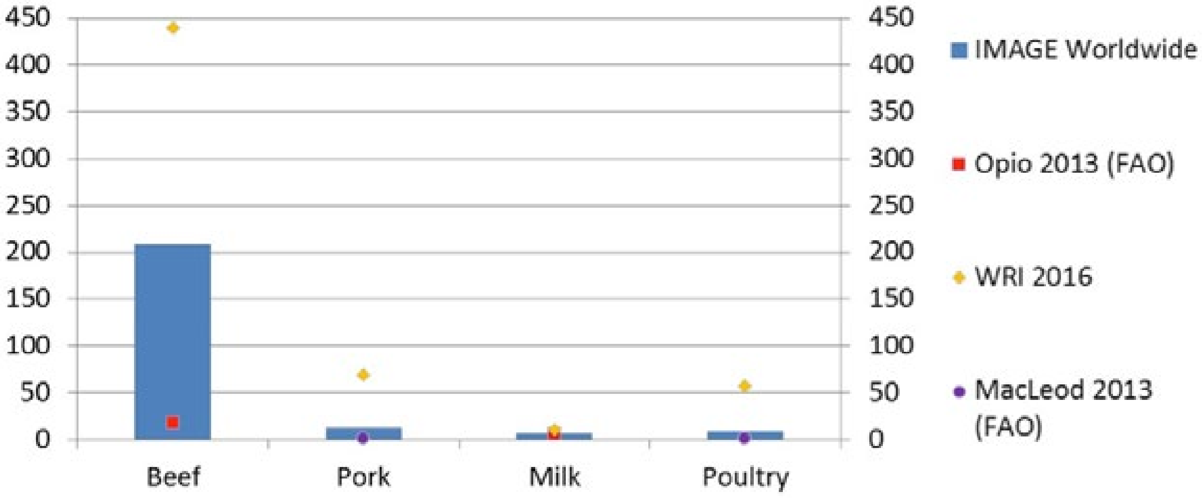


Figure 31; emission factors as calculated using method D for several crops

Beef has by far the largest emission factor, whereas pork and poultry tend to be comparable in range and values. The emission factor for milk is in line with emission factors for soybeans. Soybeans have the highest emission factor of all crops studies, followed by wheat, maize and rice. Palm oil has the lowest emission factor per kg crop, largely because of its high yield.

Worldwide means for crops and livestock for method D are generally in between results from WRI (2016), which are higher, and other references (MacLeod (2013, FAO); Opio (2013, FAO) and Blonk (2016) who tend to be lower. The range in references reflects the variation across methods A-D in this project. Blonk (2016) compares best to method C, while the WRI methodology is most in line with method A. The FAO reports of MacLeod and Opio follow the methodology of method B.

4.3.3 DISCUSSION

Below the main factors are named that influence the values for emissions factors found in this project. We also compare our results in more detail to references shown in graphs with results.

4.3.3.1 FACTORS THAT INFLUENCE FINAL OUTCOMES AND UNCERTAINTY

Trade is an important element in worldwide emission factors. Some regions cultivate large quantities of a crop in subsistence agriculture for local consumption only, while other regions grow smaller quantities intended almost exclusively for export. Emissions of subsistence farming tend to be higher, due to lower yields, occasional slash-and-burn agriculture and outdated agricultural practices, whereas some large-scale commercial farms, e.g. in Brazil, are responsible for a large part of the deforestation. Therefore, we differentiated global means between all crops cultivated and all crops traded on the global market. Worldwide, exported rice and maize tend to have slightly lower emission factors, whereas traded wheat has higher emission factors.

Not only are global means of crops affected by trade, but also livestock emission factors depend on the region from which feed is sourced. Trade patterns for feed in this project are established between the aggregated 8 food crop types of IMAGE only, not for individual crops. This means that soy and soybean cake are aggregated into the larger oil crop category. However, the trade patterns for all oil crops can differ from the trade in individual feed crops. Whereas Western Europe imports only 20% of its oil crops from Brazil and 16% from Rest Southern America, a FAO study mentions that in 2015, Western Europe imported 61% of soybeans from Brazil, 38% of its soybean cake from Argentina and 34% from Brazil (MacLeod, 2013 pp. 132). This difference demonstrates that the values for all oil crops traded differ from the trade figures for FEED oil crops only.

Moreover, in livestock, the management type is important. Intensive industrial farms have generally a lower emissions factor than extensive, traditional farming systems. In each region, a different mixture of farming systems can be found, which changes over time. IMAGE includes all agricultural systems in its emission factors as present over time.

Finally, the feeding mixture can play a role in the final emissions factor found.

- For instance, the definition of what feed is considered residues or by-products is important, since IMAGE assumes that all land-use change emissions are assigned to crops and byproducts, but not to residues.
- Also, the share of oil crops in total feed crops has increased over time in the diet of pigs, chicken and cattle. With larger emissions factor for soybean and palm oil, it is important to include a representative share of oil crops in the livestock model. Therefore, the share of oil crops in IMAGE was calibrated to match feed statistics from FAO.
- Furthermore, feeding mixtures differ between different livestock animals and between management systems.
- Finally, a lot of variation in feeding mixture can be found across countries within an IMAGE region, for instance in countries of the EU (Hou, 2016).

4.3.3.2 COMPARISON TO REFERENCES

Both FAO reports (MacLeod, 2013 and Opio, 2013) tend to be on the low side, since they only include a limited number of land-use transformations, crops and regions. Opio (2013) on beef and milk includes only 2 land-use transformations:

- the transformation of forest to cropland associated with soybean production in Brazil and Argentina.
- deforestation associated with pasture expansion in Latin America.

The results of MacLeod for pork and poultry incorporates only land-use change emissions of soybean (cake) produced in Brazil and Argentina. Therefore, these emissions factors of FAO studies will underestimate actual land-use change CO_2-emissions. In both FAO studies, soybean emission factors of 7.69 $kgCO_2/kg$ soybean and 0.93-0.94 kg CO_2/kg soybean were found for Brazil and Argentina respectively by allocating emissions of actual land-use expansion during 1990-2006 to all soybean grown in the country. This is comparable to the results found with IMAGE.

On the other hand, WRI has usually higher emissions factors than other sources. WRI (2016) is based on the GlobAgri model. In GlobAgri, all increases in demand come from cropland area expansion. Also crop yields, livestock efficiencies, and patterns of trade in the model are kept constant and additional emissions are assigned to additional land. All these settings are in line with method A in this project.

Also, land use and greenhouse gas emissions estimates for beef production are based on dedicated beef production, not beef that is a coproduct of dairy, which is in line with IMAGE. Therefore emission factors for beef in IMAGE and WRI might overestimate the emission factor for beef.

Emission factor for milk of WRI is much closer to values of IMAGE method A or Opio (2013) than for other livestock products, because GlobAgri assumes that beef produced by dairy systems displaces beef produced by dedicated beef-production systems. In other words: dairy cattle has not only milk but also beef as output, which means that total dairy emissions are split over a larger amount of products than in most other models. IMAGE does not include beef from dairy cows into its total milk emission factor.

Generally, results for method C are in line with results of Blonk (2016). The methodology of Blonk is based on based on the PAS2050 and specifically the PAS2050-1 frameworks. Any expansion of crop area is considered to be at the expense of forest in the calculation rules, with forest carbon content derived from Global Forest Resource Assessment 2015 (FRA). The current results are based on the average FAOSTAT data (harvested area) of 2011-2013 and 1991-1993. Blonk might be sensitive to missing data in FAOSTAT.

4.4 COMBINED EMISSION INTENSITY PATHWAYS FOR KEY COMMODITIES

In this section, total emission factors are shown (LUC-CO_2 and other emission sources combined). First we combine global emission factors per commodity. Next, two examples are shown of regionally specific combined emission factor per commodity for beef and dairy in Brasil.

4.4.1 GLOBAL TOTAL EMISSION FACTORS PER COMMODITY

Below global emission factors for LUC-CO_2 and all other emission sources are combined into total emission factors per commodity. Since the results of LUC-CO_2 are in fresh market weight, while all other emission factors are in dry matter, LUC-CO_2 of method D was converted to dry matter based on IMAGE standard conversion factors. This conversion to DM changes the order of commodities (from large to small), with dairy having a substantially larger value in terms of DM than in terms of fresh market weight. In a separate graph, emission factors are shown excluding beef, since beef has a much larger emission factor than other crops and livestock products. The combined graphs below show that beef is the dominant source.

Global commodity emission factors in kg CO_2 eq/kg DM

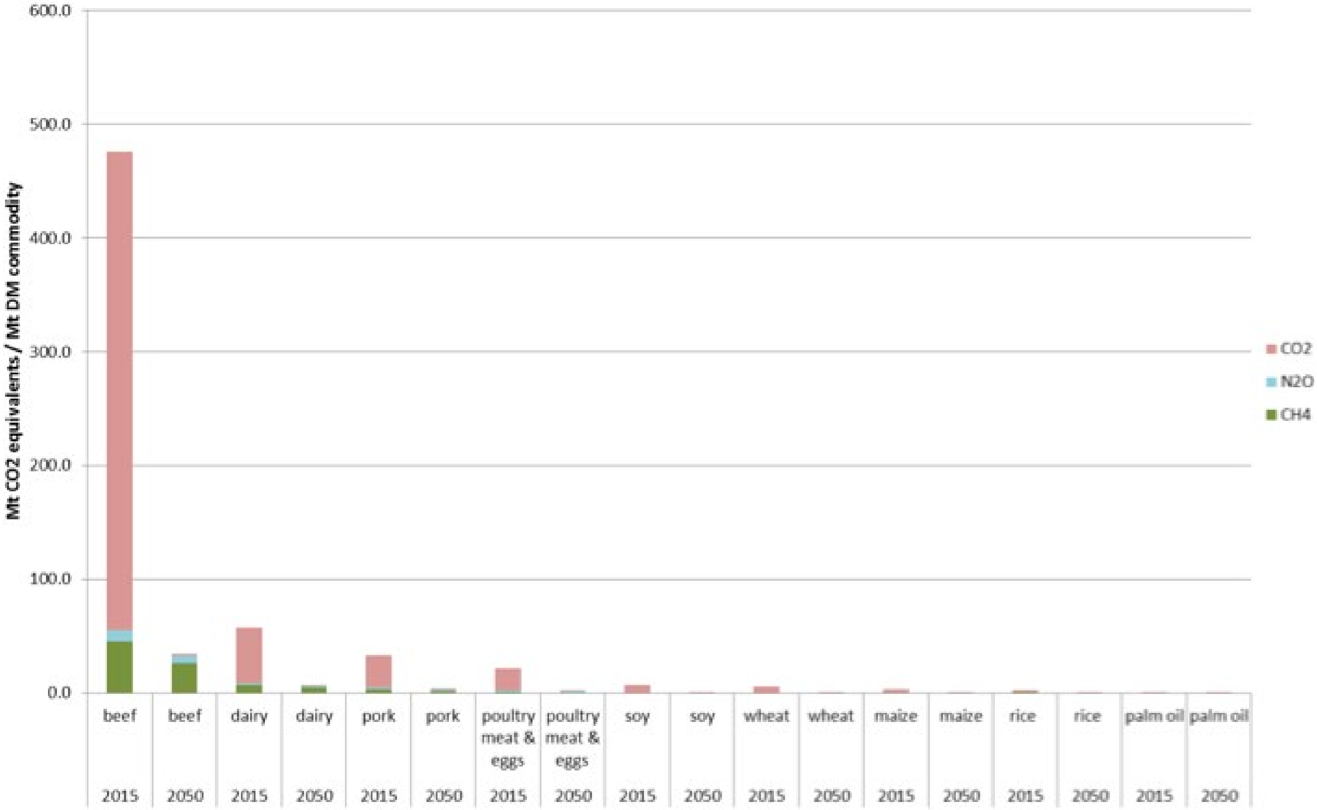


Figure 32; global emission factors for agricultural commodities under a 2° C constraint including CO_2 emissions from land-use change. CO_2 emissions from land-use change are excluded. Emission factors (in Mt CO_2eq/Mt DM commodity, DM = Dry Matter) are shown for 2015 and 2050 and grouped by CH_4, N_2O and CO_2 using a 100-year global warming potential from the fourth Assessment Report (GWP CH_4 = 25[8], GWP N_2O = 298).

[8]We have decided to use the GWP value for CH_4 of 25 instead of 28 as in the fifth Assessment Report in order to compare our results with literature.

Global commodity emission factors in kg CO_2 eq/kg DM

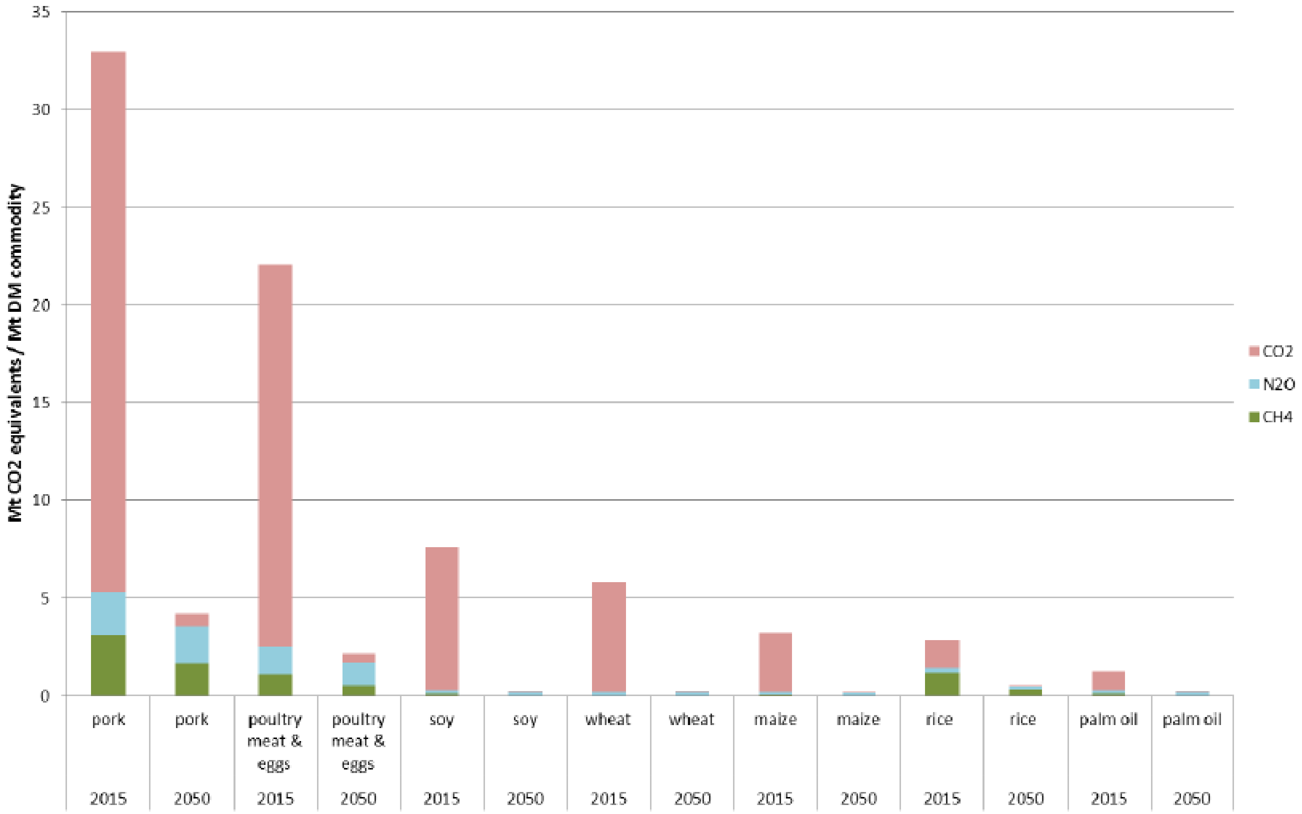


Figure 33; global emission factors for agricultural commodities under a 2° C constraint, shown for all commodities except beef, including CO_2 emissions from land-use change. Emission factors (in Mt CO_2eq/Mt DM commodity, DM = Dry Matter) are shown for 2015 and 2050 and grouped by CH_4, N_2O and CO_2 using a 100-year global warming potential from the fourth Assessment Report (GWP CH_4 = 25, GWP N_2O = 298).

4.4.2 REGIONAL TOTAL EMISSION FACTORS PER COMMODITY

We have combined all agricultural GHG emissions with LUC-CO_2 emissions to derive an overall emissions factor per commodity. Below we show as an example the combined emission factor for the production of soy and beef in Brazil.

EF – beef Brazil (base year)

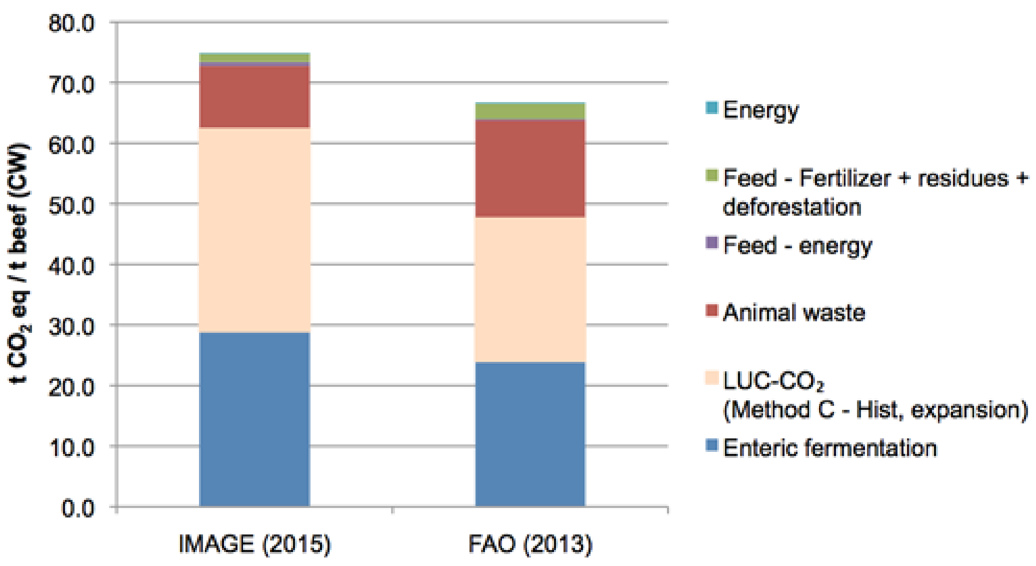


Figure 34; the combined emission factor for the production of beef in Brazil.

Compared to FAO (2013), emissions from LUC-CO_2 and enteric fermentation are higher in IMAGE than in FAO (2013). Also emissions for soy from Brazil are higher in IMAGE than in Castanheira et al. 2013. Especially, land-use change and fertiliser use + residues are higher in IMAGE, while emissions from energy are lower in IMAGE.

EF – Soy Brazil (base year)

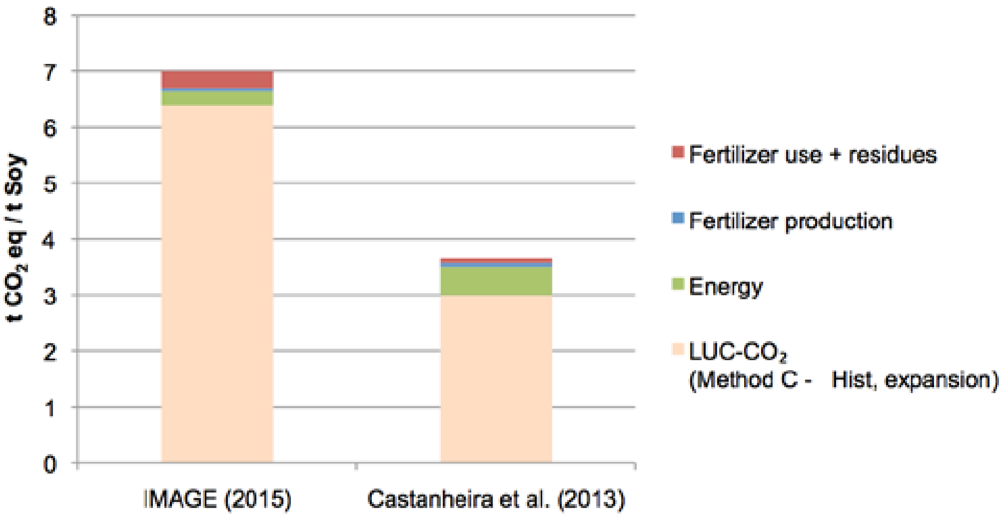


Figure 35; the combined emission factor for the production of soy in Brazil.

Compared to FAO (2013), emissions from LUC-CO_2 and enteric fermentation are higher in IMAGE than in FAO (2013). Also emissions for soy from Brazil are higher in IMAGE than in Castanheira et al. 2013. Especially, land-use change and fertiliser use + residues are higher in IMAGE, while emissions from energy are lower in IMAGE.

4.4.3 ROUNDWOOD

4.4.3.1 GLOBAL PRODUCTION OF ROUNDWOOD

In 2014, approximately 3.7 billion cubic metres of roundwood was removed from the world's forests, of which 1.83 billion cubic metres was industrial roundwood and the rest woodfuel (FAO, 2007). 53% of harvested Roundwood is used as woodfuel mostly in Africa and Asia; industrial roundwood is harvested mostly in North America and Europe (FAO, 2014). Global production of woodfuel, industrial roundwood and total roundwood has increased by 24, 80 and 47% in 2014 compared to 1961.

Global production of roundwood

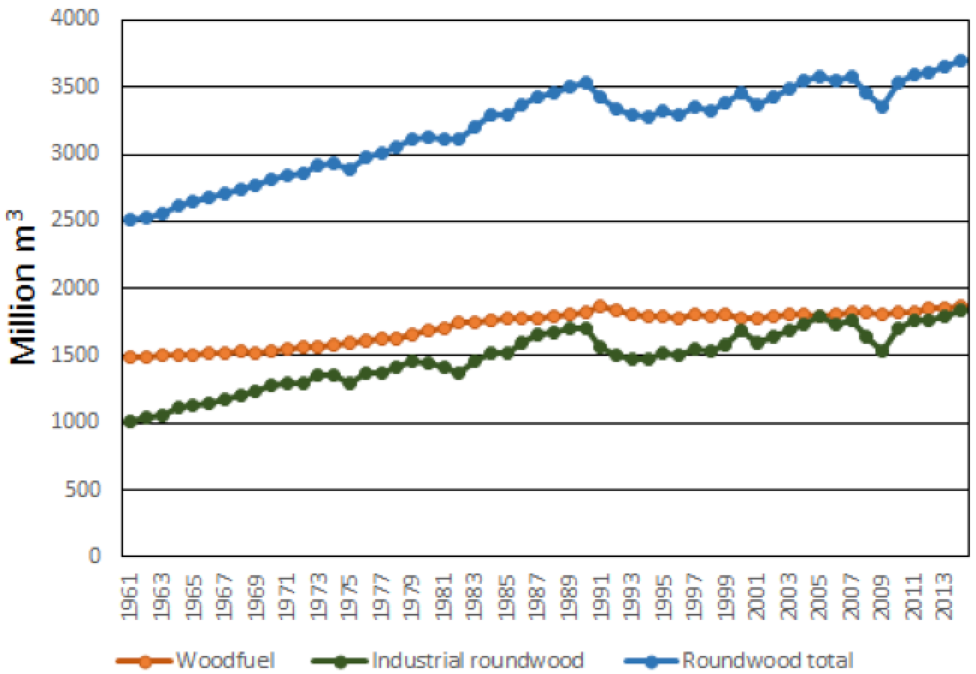


Figure 36; global production of roundwood from 1961 to 2013 based on FAO data.

4.4.3.2 EMISSION INTENSITY IN BASE YEAR (IPCC)

Roundwood/timber production is part of the AFOLU category Forestry and Other Land-Use (FOLU). In IPCC fifth assessment report, GHG emission intensity for roundwood is calculated as a ratio of carbon loss from harvest to roundwood produced and the value is around 0.5kg CO_2 eq m^{-3} of roundwood (Figure 37).

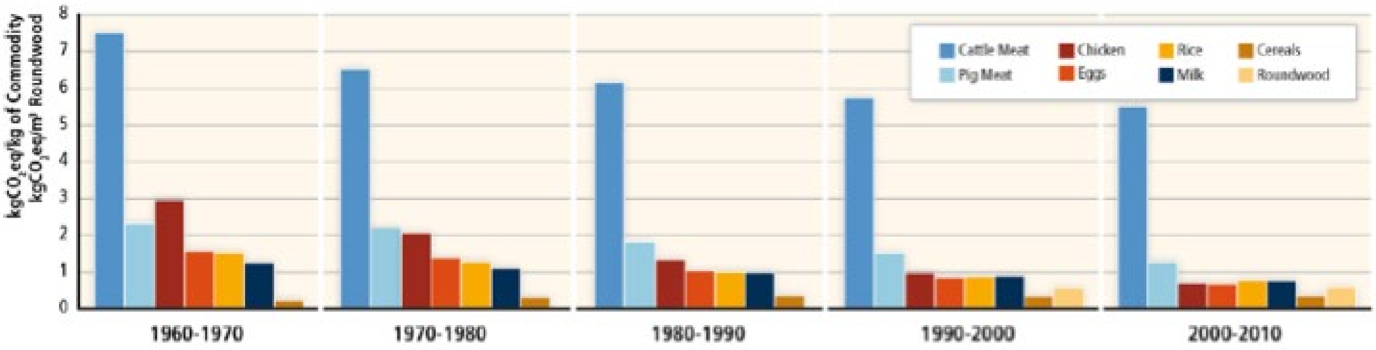


Figure 37; GHG emissions intensities of AFOLU commodities between 1960 and 2010 (note: roundwood is defined as GHG (carbon loss from harvest/roundwood produced) (source: IPCC 2014).

4.4.3.3 EMISSION INTENSITY (LCA APPROACH)

GHG emission from forestry operation and roundwood production varies according to the different kind of forestry management associated with seedling production, site preparation, stand establishment and tending, logging operation such as harvesting, thinning and loading onto trucks. Using LCA approach, Sonne (2006) reported GHG emission from Douglas-fir forestry operation in North America with different management regimes and identified three major contributors to GHG emission i.e. harvesting, site preparation (Pile and burn) and fertilization. González-García et al., 2014 studied cradle-to-gate LCA of Douglas-fir Roundwood production in Germany and concluded stand establishment and tending is the stage with largest contribution (53%) to GHG emission followed by logging or harvesting stage (33%). Table 4 shows different emission intensity value associated with roundwood production as reported in literature.

TREE SPECIES	SYSTEM BOUNDARY	FUNCTIONAL UNIT	EMISSION INTENSITY (KG CO_2 EQ/M^3/YR)	REFERENCE
WILLOW (SWEDEN)	Cradle to gate i.e. from the extraction of raw materials through the management operations up to the loading of the wood biomass onto trucks at road site. 1. Site preparation 2. Stand establishment and tending 3. Logging operations	1 m^3 of felled fresh roundwood per year (m^3yr-1)	0.59 – 2.69	González-García et al., 2014
POPLAR (ITALY)	Cradle to gate i.e. from the extraction of raw materials through the management operations up to the loading of the wood biomass onto trucks at road site. 1. Site preparation 2. Stand establishment and tending 3. Logging operations	1 m^3 of felled fresh roundwood per year ($m^3 yr^{-1}$)	0.95 – 1.10	González-García et al., 2014
MARITIME PINE (FRANCE)	Cradle to gate i.e. from the extraction of raw materials through the management operations up to the loading of the wood biomass onto trucks at road site. 1. Site preparation 2. Stand establishment and tending 3. Logging operations	1 m^3 of felled fresh roundwood per year (m^3yr-1)	0.33 – 0.53	González-García et al., 2014

Table 4; emission intensity value associated with roundwood production as reported in literature. (Continued of following page).

Table 4; emission intensity value associated with roundwood production as reported in literature. (Continued from previous page).

TREE SPECIES	SYSTEM BOUNDARY	FUNCTIONAL UNIT	EMISSION INTENSITY (KG CO_2 EQ/M³/YR)	REFERENCE
MARITIME PINE (PORTUGAL)	Cradle to gate i.e. from the extraction of raw materials through the management operations up to the loading of the wood biomass onto trucks at road site. 1. Site preparation 2. Stand establishment and tending 3. Logging operations	1 m³ of felled fresh roundwood per year (m³.yr-1)	0.13 – 0.43	González-García et al., 2014
DOUGLAS-FIR (FRANCE)	Cradle to gate i.e. from the extraction of raw materials through the management operations up to the loading of the wood biomass onto trucks at road site. 1. Site preparation 2. Stand establishment and tending 3. Logging operations	1 m³ of felled fresh roundwood per year ($m^3.yr^{-1}$)	0.15 – 0.48	González-García et al., 2014
DOUGLAS-FIR (GERMANY)	Cradle to gate i.e. from the extraction of raw materials through the management operations up to the loading of the wood biomass onto trucks at road site. 1. Site preparation 2. Stand establishment and tending 3. Logging operations	1 m³ of felled fresh roundwood per year (m³.yr-1)	0.05	González-García et al., 2014
SPRUCE (SWEDEN)	Cradle to gate i.e. from the extraction of raw materials through the management operations up to the loading of the wood biomass onto trucks at road site. 1. Site preparation 2. Stand establishment and tending 3. Logging operations	1 m³ of felled fresh roundwood per year ($m^3.yr^{-1}$)	0.18	González-García et al., 2014
DOUGLAS-FIR (NORTH AMERICA)	Cradle to harvest 1. Seeding production and transportation 2. Site preparation 3. Growth enhancement 4. Harvesting	1 ha of forestland managed for 50 yr Or Per unit timber production	0.25	Sonne, 2006

4.4.3.4 MITIGATION POTENTIAL OF GLOBAL FORESTRY ACTIVITIES

Forestry mitigation activities may be grouped into three categories (Brown et al. 1996). The first category includes activities that avoid the release of emissions from C stock, such as forest conservation and protection. The second includes activities that store C, for example afforestation, reforestation and agroforestry, and the third category involves substituting the use of C-intensive products and fuels with sustainably harvested wood products and wood fuel, for example wood substituting for concrete or steel and bioelectricity substituting for fossil fuel electricity. Total global estimates of GHG mitigation potential through forestry operations i.e. avoided deforestation,

afforestation and forest management (Figure 38) is quantified at 5.78, 3.85, 13.7 Gt CO_2 yr^{-1} for the time period 2030-2050 at a cost of 1–20, 20 –50 and 100 US\$ tCO_2 $^{-1}$ (IPCC WGIII AR4).

1. Reduced or avoided deforestation

Reduced or avoided deforestation and degradation is the forest mitigation option with the largest and most immediate carbon stock impact in the short term per ha and per year globally (IPCC WGIII AR4). The mitigation costs of reduced deforestation depend on the cause of deforestation (timber or fuelwood extraction, conversion to agriculture, settlement, or infrastructure), the associated returns from the non-forest land use, the returns from potential alternative forest uses, and on any compensation paid to the individual or institutional landowner to change land-use practices. It also varies from region to region. Based on region-specific data and GCOMAP analysis, Sathaye et al. (2006) estimated a global carbon price of \$10/t CO_2 in Africa, \$34/t CO_2 in Central America, \$40/t CO_2 in South America, and \$76/t CO_2 in the Rest of the Asia region would be sufficient to theoretically halt deforestation.

Global estimates of carbon sequestration potential through reduced or avoided deforestation (Table 5) is quantified at 1.6 – 4.3, 1.1 – 5.1, 3.1 – 4.7Gt CO_2 yr^{-1} for the time period 2030-2050 at a cost of 1–20, 20 –50 and 100 US\$ tCO_2 yr^{-1} (IPCC WGIII AR4; McKinsey, 2009; Sohngen, 2009).

2. Afforestation and reforestation

Afforestation refers to conversion of non-forested agricultural land to forest land through planting. This can include either monocultures or mixed species planting. Because agricultural land stores very little carbon in aboveground biomass, converting the land to trees, and allowing those trees to grow, will remove carbon from the atmosphere. Afforestation requires implementation and management costs, as well opportunity costs and the costs vary by land type and region. A major economic constraint to afforestation is the high initial investment to establish new stands coupled with the several-decade delay until afforested areas generate revenue.

Global estimates of carbon sequestration potential through afforestation (Table 5) is quantified at 1.6, 1.8 – 2.4, 4.04 Gt CO_2 yr^{-1} for the time period 2030-2050 at a cost of 1–20, 20 –50 and 100 US$ $tCO_2 yr^{-1}$ (IPCC WGIII AR4; McKinsey, 2009; Sohngen, 2009).

3. Forest management

Management of forests for sustainable timber production including extending rotation cycles, reducing damage to remaining trees, reducing logging waste, implementing soil conservation practices, fertilization, more efficient wood use and sustainable extortion of wood energy can increase stand-level forest carbon stocks. Planting after harvest or natural disturbances accelerates tree growth and reduces carbon losses relative to natural regeneration (IPCC 2007).

Global estimates of carbon sequestration potential through forest management (Table 5) is quantified at 1.96, 0.30 – 2.07, 5.78 Gt CO_2 yr^{-1} for the time period 2030-2050 at a cost of 1– 20, 20 –50 and 100 US$ tCO_2 yr^{-1} (IPCC WGIII AR4; McKinsey, 2009; Sohngen, 2009).

Economic potential of future GHG mitigation by forests

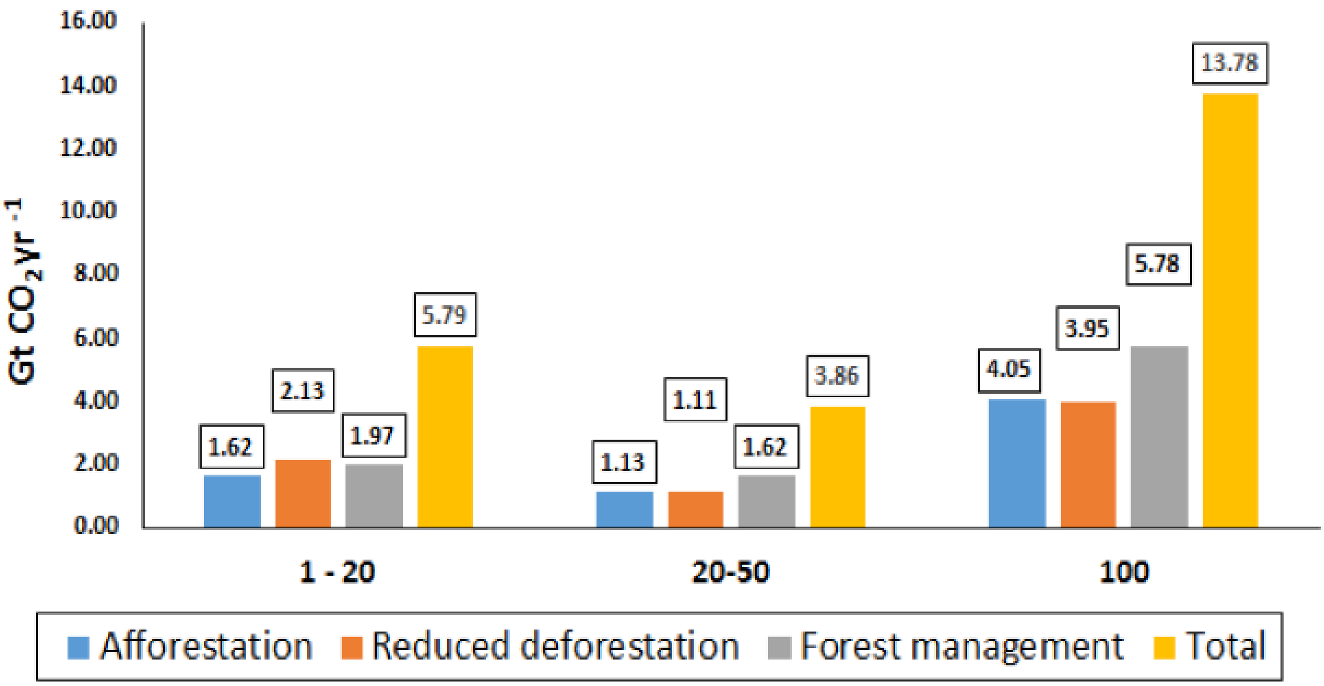


Figure 38; economic mitigation potential by global forestry activities in 2030 for various carbon prices (IPCC, 2007)

REFERENCE	MITIGATION MEASURES	TECHNICAL POTENTIAL ($MTCO_2$/YR)	YEAR	ECONOMIC POTENTIAL AT VARIOUS CARBON PRICE ($MTCO_2$/YR)		
				1-20 (US $/$tCO_2$)	20-50 (US $/ tCO_2)	100 (US $/$tCO_2$)
IPCC WGIII AR4	Afforestation		2030	1618	1132	4045
IPCC WGIII AR4	Reduced deforestation		2030	2133	1106	3950
IPCC WGIII AR4	Forest management		2030	1965	1618	5780
IPCC WGIII AR4	Total		2030	5785	3857	13775
MCKINSEY (2009)	Avoided deforestation	5100	2030		2400	
MCKINSEY (2009)	Afforestation and reforestation	2400	2030		2400	
MCKINSEY (2009)	Forest management	300	2030		300	
MCKINSEY (2009)	Total	8000	2030		8000	
IPCC WGIII AR5	Total			10 - 1450	110 - 9500	200 – 13800
KINDERMANN ET AL. (2008)	Avoided deforestation		2030	1600 - 4300		3100 - 4700
SOHNGEN (2009)	Afforestation		2020-2050		1848	
SOHNGEN (2009)	Reduced deforestation		2020-2050		2827	
SOHNGEN (2009)	Forest management		2020-2050		2076	
SOHNGEN (2009)	Total		2020-2050		6751	

Table 5; mitigation potential by global forestry activities as reported in literature.

Demand side mitigation potential

- Demand-side mitigation potential is related to changes in wood consumption: the consumption of wood, whether it is an increase or decrease, depending on the context lead to a change in GHG emissions.
  1. The replacement of wood from illegal logging by wood from sustainable certified forests can decrease GHG emissions;
  2. Reducing wood consumption through more efficient use and the use of recycled materials (i.e. paper recycling) can reduce GHG emissions;
  3. Substitution of wood for non-renewable materials (e.g. cement, aluminium, steel) in the construction sector often leads to GHG savings.
- Certification schemes can also support sustainable roundwood timber production activities. In total 8% of the global forests are certified, these are especially temperate forests, roughly one quarter of the global industrial roundwood comes from certified forests.

4.4.3.5 EMISSION INTENSITY TOWARDS 2050

With implementation of the above mentioned mitigation measures, future GHG emission intensity of roundwood might change. Sathaye et al. (2006) estimated the global potential for carbon sequestration through forest plantation and the reduction of carbon emissions from deforestation. They analysed 3 mitigation options:

1. Short rotation forestry, i.e. new or replanted tree crops or forests managed on a rotation of growth and harvest between 6-60 years; varying by region and forest type;

2. Long-rotation forestry, i.e. planting and management for rotations between 20-100 years; and

3. Avoided deforestation, i.e., land use management that extends rotations and prevent deforestation. Because the rate and spatial distribution of deforestation is uncertain, for the emission intensity calculation here only C sequestration through afforestation and reforestation is accounted, as reported in IPCC 5th assessment report (Figure 39).

Figure 39; potential changes in future emission intensities for major AFOLU commodities including Roundwood with implementation of Roundwood specific measures as reported in IPCC (2014).

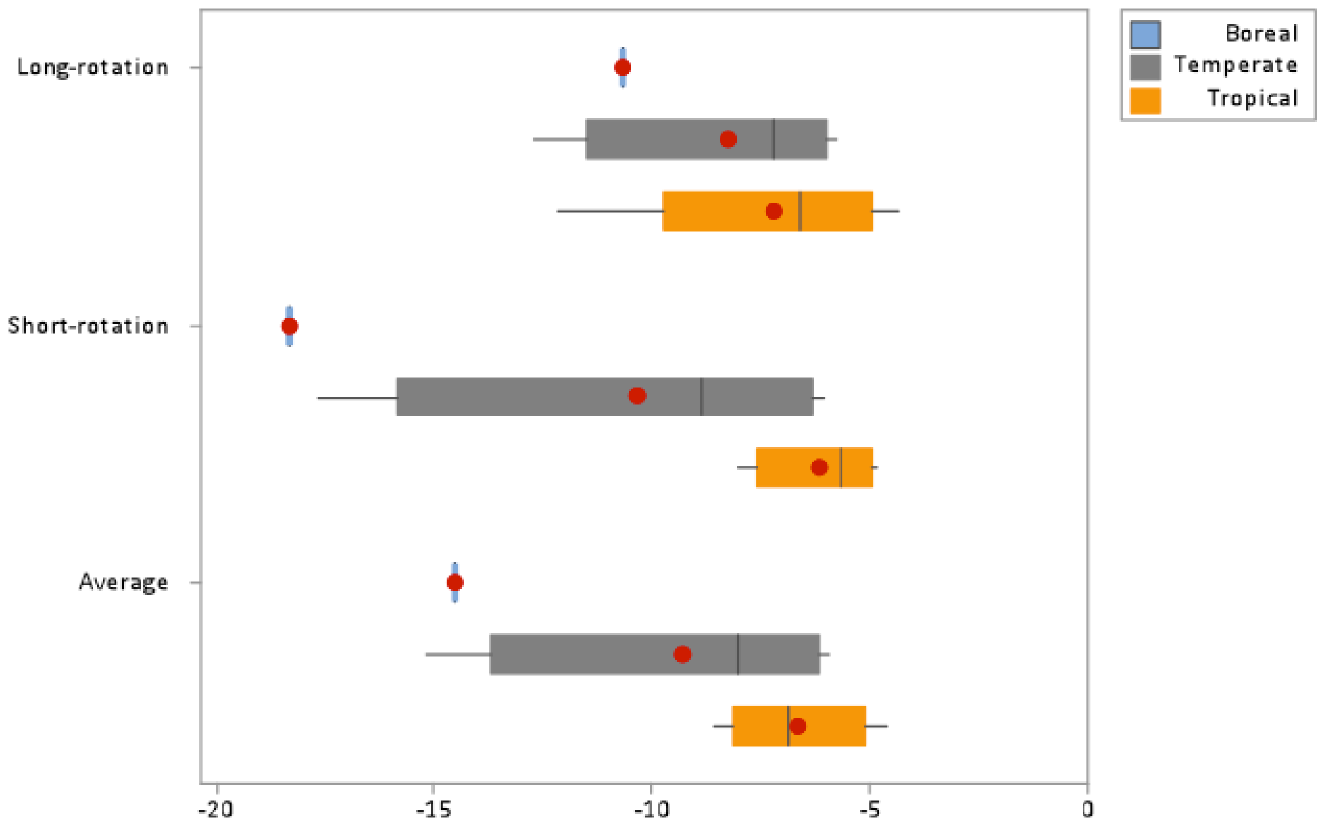


Figure 40; potential changes of emission intensities of Roundwood through implementation of afforestation and reforestation for short rotation and long rotation forestry, expressed as the amount of C sequestrated per unit of Roundwood, derived using data from Sathaye et al. (2005; 2006). Baseline emission is considered zero as only afforestation and reforestation of idle land is considered here.

5.1 INTRODUCTION

In this chapter we explain how company-specific targets can be derived from the average emission intensity pathways as presented in the previous chapter. We will present the online tool that has been developed to support companies in setting science-based targets more easily. In this chapter climate mitigation actions and tools are mentioned that companies can apply to reduce and track their GHG emissions of these commodities, are also discussed.

5.2 REGIONAL CONVERGENCE

Similar as in the Sectoral Decarbonization Approach, we translate the average emissions intensity pathway of a commodity in a specific region to a company-specific emissions intensity target by applying the convergence principle: i.e. the emission intensity of the commodity produced in a certain region converges to the same emissions intensity in 2050 (see Figure 41)

Physical allocation: Convergence to same intensity in 2050

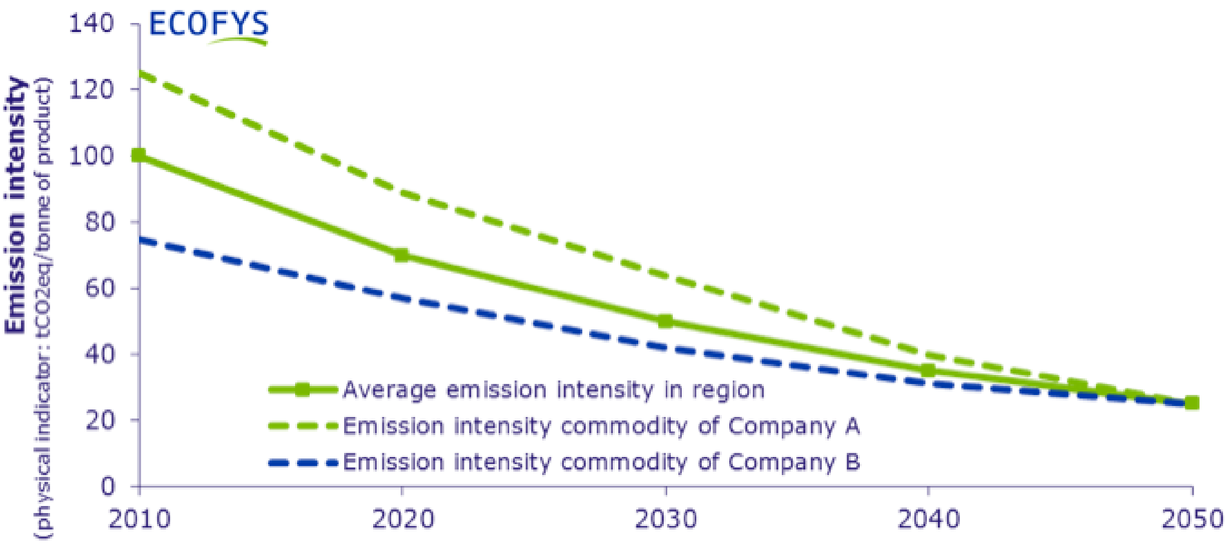


Figure 41; convergence of emission intensity of commodities towards average, regional intensity level in 2050

Company intensity pathways are derived from the company's base year intensity (***CI***) and the average intensity (***AI***) pathway. To account for current performance, a factor d is formulated as the distance from the company intensity (*CI*,) in base year b to the average intensity (***AI***) in the region in year 2050:

$$d = CI_b - AI_{2050}$$

The company intensity in the base year is provided by the company, and the average intensity per commodity per region is provided by the outcome of the SSP2 scenario in the IMAGE model. To converge the company's intensity towards the average decarbonisation pathway, we define ***p*** as a function of year ***y*** that is essentially an index of the average decarbonisation, expressed from 0 to 1:

$$P_y = (AI_y - AI_{2050}) / (AI_b - AI_{2050})$$

All average intensities in this equation are derived from by the outcome of the SSP2 scenario in the IMAGE model. Next we define m_y; a term that accounts for changes in market share (the share of sourcing activity of the company (CA) in the region compared to the total production in that region (TA)):

$$m_y = (CA_b / TA_b) / (CA_y / TA_y)$$

The company's sourcing activity in the base year and the projected activity of the company are provided by the company. The total production activity is retrieved from the SSP2 scenario in the IMAGE model. This means that the total activity is not the actual activity, but rather the projection from the scenario. Note that the term my is not the change in market share, but rather the inverse, resulting in a decreasing my with increasing market share.

The science-based target (company's intensity) in year y can then be expressed as:

$$CI_y = d * p_y * m_y + AI_{2050}$$

5.3 TARGET-SETTING TOOL

A target-setting tool has been developed that applies the above formulae to an agricultural company based on a set of inputs supplied by the company.

5.3.1 OVERVIEW

In the tool, the user can select a commodity and a region, and the accompanying intensity pathway is retrieved from the IMAGE data. The resulting regional intensity pathway of the selected commodity is shown as an aggregate of all different GHGs and emission sources.

The user can also insert the base year and target year to be used for target-setting, and the performance of the company in the base year (in terms of GHG emissions per unit of production). With the production of the company in the base year, and the expected production in the target year, the production is projected using linear interpolation. Using that data, the specific intensity pathway is calculated for the company. This pathway is then also displayed.

The company-specific intensity pathway is multiplied with the projected production to calculate the absolute emissions target for the company.

Land-use change emissions are not included in the intensity pathways in the tool. Land-use change emissions can exceed other emissions significantly in some regions, and as a result the land-use change emissions would dominate the intensity pathway. Because it is very difficult to accurately measure and account for land-use change emissions on company level, we decided not to account for land-use change emissions in the intensity pathways. Instead, we focus on the emissions that can more easily be influenced by the company and display the land-use change impact separately. Figure 42 displays the dashboard of the tool.

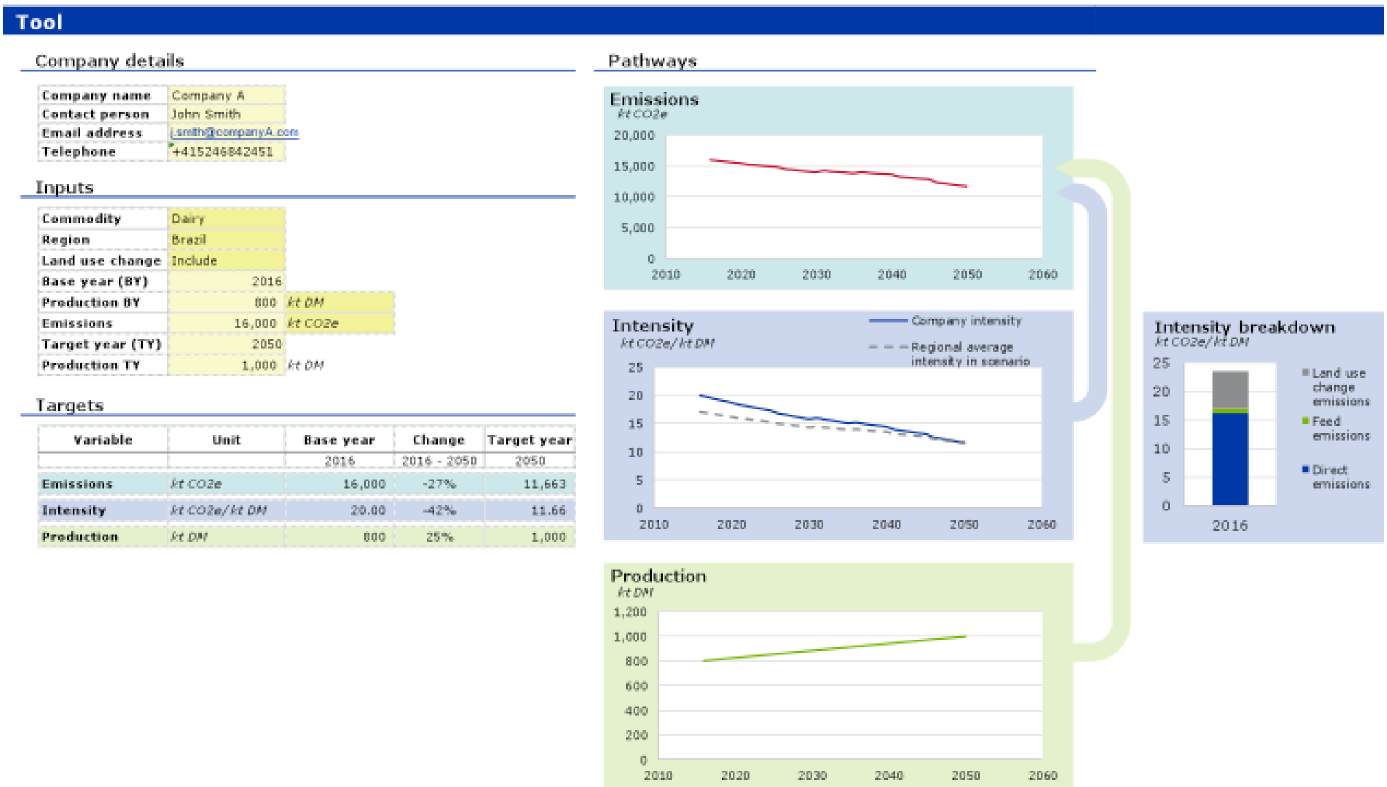


Figure 42; dashboard in the target-setting tool

5.3.2 GUIDELINES AND INSTRUCTIONS

The tool is developed with the end goal in mind: companies should be able to easily identify what is needed for them to align with the 2° C global warming limit. Therefore, the tool includes instructions on how to use it (the "Manual" sheet) and guidance on definitions and boundaries (the "Definitions&Boundaries" sheet). This guidance is important to enable companies to use the tool's outputs, because companies often use different regions or units of production. For example, in the dairy industry the production is often measured in litres instead of in tonnes of dry matter.

Also, the boundaries of the processes covered in the emission figures are defined. For example, beef is defined as *"Meat of bovine animals, fresh, chilled or frozen, with bone in" and the boundary as "Cradle to farm gate (excluding land-use change emissions). Emission sources included: 1) CO_2 emissions arising from land-use change associated with livestock and feed for livestock; 2) Emissions from feed production i.e. direct and indirect N_2O emissions from application of fertilizer, crop residues and deposition of manure on pastures, and CH_4 emission from manure and flooded rice; 3) CO_2 emissions from machinery used for feed production; 4) CO_2 and N_2O emissions from fertilizer production needed for feed production; 5) Direct CH_4 emission from enteric fermentation and manure; 6) Direct CH_4 and N_2O emissions from manure both deposited while grazing and in stables; 7) Indirect N_2O emissions from soil leaching, runoff and volatilization; and 8) CO_2 emission from machinery used on farm."*

For more information on the tool we refer to the manual included in the tool itself.

5.4 HOW TO MEET THE TARGETS AND MONITOR PROGRESS

5.4.1 ACTIONS TO REDUCE AGRICULTURE EMISSIONS (NON-CO_2 AND CO_2 OF ENERGY)

Companies can stimulate various measures to mitigate GHG emissions. The first important step for companies is to identify the hot spots of GHG emission for their products so that they can plan different strategies to reduce their emissions. The next step is to recognise different cost saving or low cost, mitigation measures that can be adopted to reduce emissions with a positive or minimal impact on yield. Below is a short summary of different measures ranked on their cost. Annex 2 presents the details on the different measures, their mitigation potential and description of MACC analysis and MAC curves for different world regions.

Table 6; summary of different agriculture mitigation measures to reduce non-CO_2 emissions.

EMISSION SOURCE	MITIGATION MEASURES
RICE CH_4	Direct seeding
	Replace Urea with ammonium sulphate
	Straw compost
	Alternate flooding / drainage
	Phospogypsum
FERTILIZER N_2O	Improved land manure application
	Spreader maintenance
	Improved agronomy practices
	Sub-optimal fertilizer applications
	Nitrification inhibitors
	Fertilizer free zone
ENTERIC CH_4	Nitrate
	Tannins
	Grain processing
	Reduced herd size (US/Canada)
	Skipping stocker phase (US/Canada)
	Improved milk production
	Improved health monitoring
	Extend productive life

EMISSION SOURCE	MITIGATION MEASURES
MANURE CH_4	Digester warm climate, heat only
	Digester cool climate, heat + electricity
	Digester warm climate, heat + electricity
	Decrease manure storage time
	Manure storage covering
	Housing and bedding
	Manure acidification
MANURE N_2O	Reduced dietary protein
	Decrease manure storage time
	Manure storage covering
	Housing and bedding

Climate actions that companies can take to reduce agriculture emissions (non-CO_2 and CO_2 of energy) can be categorised as:

- For a crop commodity farmer:

1. Increase yields (on existing cropland), while limiting additional GHG emissions by e.g. more appropriate fertilizer use. For example, in Figure 43 the global yield increase of wheat according to the SSP2 scenario is provided, i.e. yields per hectare per year of wheat should increase by over 40% over the period 2010-2050. Companies should increase their yield of wheat to this level or even higher through, for example, sustainable intensification.

2. Implement measures to mitigate emissions, such as those included in Annex 2.

Global yield increase of wheat (ton DM/ha/yr)

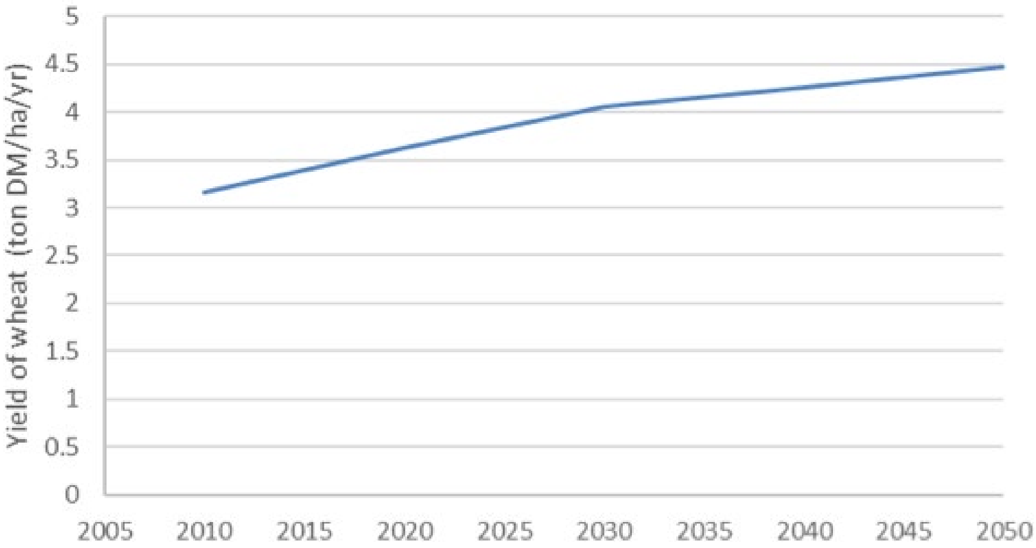


Figure 43; global yield increase of wheat according to SSP2 scenario (ton DM/ha)

- For a livestock farmer:

1. Maximize output/production levels (meat or dairy) by e.g. optimizing feed composition, while limiting the climate impact

2. Implement measures to mitigate emissions, such as those included in Annex 2

3. Improve cow longevity

5.4.2 ACTIONS TO REDUCE LUC-CO_2

Actions that companies can take to reduce LUC-CO_2 are:

- For a crop commodity farmer:

- Increase yields (on existing cropland), while limiting additional GHG emissions by e.g. by more appropriate fertilizer use
- Avoid cropping on high carbon stock areas (such as peatlands)
- "Sustainable expansion" (only into areas with low carbon stocks, i.e. not peatlands or forests)
- "Sustainable abandonment" (into area with a high carbon content of natural vegetation)
- Support good land use planning and REDD+ in the region
- Rewet peatlands on which palm oil is cultivated in Indonesia or Malaysia.

- For a livestock farmer:

- Change feed composition to include feed with lower GHG footprint
- Reduce the area used for grazing
- Choose specific low LUC-CO_2 feedstuffs (from a specific farmer and region)
- Support good land use planning and REDD+ in the region

- Food company or retailer:

- Switch to a different commodity by changing the mix of your end product
- Source the commodity from a different region with a lower LUC-CO_2, while minimising negative sustainability impacts (such as social or environmental impact)
- Choose specific low LUC-CO_2 input (from a specific farmer and region, see above)
- Source only palm oil from rewetted peatlands in Indonesia or Malaysia.
- Reduce waste
- Source from regions with low carbon content of regrowing natural vegetation even when yields are lower.
- Support good land use planning and REDD+ in the sourcing regions, so that the LUC-CO_2 emission factor of that region can be reduced in the next update of the tool

5.4.3 TOOLS TO MEASURE AND MONITOR PROGRESS

To calculate emission reduction target using this new SDA methodology and tool, one of the primary steps is estimation of the corporate's (agriculture farm's) base year GHGs emission. Several GHG reporting tools have been developed in the agriculture sector to facilitate companies to measure the environmental impact of their products. These GHG reporting tools can either be less complex such as Excel, Visual Basic or web-based calculators, or more complex process-based models such as DNDC or DAYCENT. Calculators are generally designed to be used as decision support tools for policy makers and project managers, whereas models tend to be oriented for research (Colomb et al., 2012). Table 7 lists some of the freely available farm-based GHG calculators, their geographical coverage, description, whether land-use change is included or not and the output. The information is mostly based on Denef et al. (2012) and Keller (2015). The main goal of the farm-based tools is to provide a calculation platform to educate farmers about GHG emissions occurring due to their activities and choices of management. These tools can either be used for emissions associated with a single crop or whole farm activities. The system boundaries of different tools vary depending on the sources of emission included i.e. some might follow an LCA approach or some might include emissions until the farm gate by using the IPCC's tier 1 or Tier 2 approach.

TOOLS	DEVELOPER AND PUBLISHED YEAR	GEOGRAPHICAL COVERAGE	DESCRIPTION	APPLICABILITY	LAND USE CHANGE	DATA OUTPUT
Agri-LCI (Commodity level)	Cranfield University (Williams et al., 2006), with financial support from DEFRA (Project IS0205 (2006)	England and wales	A set of Excel-based models that can calculate the environmental burdens and resource use of current and future combinations of agricultural production systems, using the principles of life cycle assessment (LCA),	Arable; Livestock	Not included	kg CO_2 eq per ton of commodity and the distribution by individual GHG (CO_2, CH_4, N_2O direct, N_2O indirect);
C-PLAN (Farm level)	Drew and Jan Coulter, farmers in Central Scotland, who rent a mixed hill farm (2007 v0, 2009 v2)	UK	C-PLAN is a web-based calculator which aims to give farmers and land managers a rapid estimate of the greenhouse gas emissions of their business.	Crops, Livestock, Forest, Woodland	Included	C-PLANv0: Estimates (without uncertainties) of GHG emissions expressed as tonnes Ceq emitted per year C-PLANv2: Estimates (with uncertainties) of GHG emissions expressed as tonnes CO_2, N_2O, CH_4, CO_2eq and Ceq emitted per year for entire farm. Tool also reports on C sequestration through land use change and forestry, and counts these as a negative on the carbon account
CALM (Farm level)	Country Land and Business Association (CLA) working in partnership with Savills and EEDA (Not specified)	England and wales	To offer a tool to farmers/land managers to measure the annual emissions of CO_2, CH_4 and N_2O from their farm/estate and balance this against any carbon which is sequestered (stored) in their soil and trees	Cropland, Horticulture, Specialist pigs, Specialist poultry, Dairy, LFA grazing livestock, Lowland grazing livestock	Included	The overall C balance for the business as a whole is reported in tonnes of CO_2, CH_4, N_2O and CO_2eq per year.

Table 7; overview of Farm-based GHG calculators (continued on the following page).

Table 7; overview of Farm-based GHG calculators (continued from the previous page).

TOOLS	DEVELOPER AND PUBLISHED YEAR	GEOGRAPHICAL COVERAGE	DESCRIPTION	APPLICABILITY	LAND USE CHANGE	DATA OUTPUT
CCAFS-MOT	University of Aberdeen, in partnership with CCAF's , USAID, CIAT, the University of Vermont's Gund Institute for Ecological Economics (2015)	Global	The CCAFS Mitigation Options Tool (CCAFS-MOT) estimates GHGs from various crops and livestock production in different regions. CCAFS-MOT provides policy-makers across the globe with the reliable information needed to make informed decisions about emissions reductions within agriculture.	Cropland, Grassland, Livestock, Agroforestry	Included	GHG emissions are expressed in tCO_2eq/ha (farm scale) or per unit (product scale). Ranks the most effective mitigation options for 34 different crops according to their mitigation potential, and in relation to current management practices and climate and soil characteristics.
COMETFARM (Farm level)	USDA, NRCS and CSU, NREL (2012)	Continental U.S., Alaska, Hawaii, Puerto Rico, and other U.S. Territories with major agricultural or agroforestry practices for which NRCS data on those practices exist.	COMET-Farm is a web-based decision support calculation tool, linked to the CENTURY soil carbon process model, for estimating changes in soil carbon storage and GHG emissions from agricultural management and provides a full GHG accounting at the farm-level, with a spatial user-interface, and linkages to NRCS web-served products.	Cropland, CRP, Rangeland, Grassland, Agroforestry, Vineyards/ Orchar ds, Livestock	Included	Full GHG budget for entire farm, with breakdown by individual fields, livestock and energy use (and production) categories
Cool Farm Tool (Farm level)	Jon Hillier and Pete Smith from the University of Aberdeen, and Christoph Walter et al. from Unilever (2010)	Global	Cool Farm Tool assesses GHG emissions and soil carbon sequestration changes in response to management activities. The tool is designed for farmers, supply chain managers and companies interested in quantifying their agricultural carbon footprint and finding practical ways of reducing it.	Cropland (grass, grass/clover, legume, wetland rice, other crops); Livestock (cows, pigs, buffalo, sheep, goat)	Included (direct LUC)	CO_2 eq emissions for the entire farm, split up by source and by GHG. Output is expressed as total emissions, emissions per unit of area, and emissions per unit finished product
DNDC calculator (Site level)	University of New Hampshire	U.S.	A decision support system for quantifying impacts of management alternatives on greenhouse gas emissions from agroecosystem in the U.S., based on the DNDC model (DeNitrification-DeComposition).	Cropland		Per area GHG emissions (kg $CO_2eq/ha/yr$) Crop production (kg/C/yr)
European carbon calculator	Solagro (contracted by the European Commissions' Joint Research Centre); (2012)	European Union	To assess the life cycle GHG emissions from different farming systems across the EU. It quantifies direct and indirect GHG emissions, proposes mitigation options and sequestration actions suitable for individual farms based on their situation.	All European farming systems including livestock systems, cereals, forage crops, vineyards, orchards, vegetable and industrial crops.	Included	GHG emissions are expressed in tCO_2e/ha (farm scale) or per unit (product scale) including a graphic comparison to a group.

Table 7; overview of Farm-based GHG calculators (continued from the previous page).

TOOLS	DEVELOPER AND PUBLISHED YEAR	GEOGRAPHICAL COVERAGE	DESCRIPTION	APPLICABILITY	LAND USE CHANGE	DATA OUTPUT
FarmGAS (Farm level, multi-enterprise)	Australian Farm Institute	Australia (2009)	FarmGAS is an online GHG calculator tool allowing farmers to estimate their farm's annual GHG emissions, both at the individual enterprise activity level and for the farm as a whole, and to examine the GHG and financial impacts that different greenhouse mitigation options may have on the farm business profitability.	Extensive cropping system, Extensive grazing system, Intensive livestock, Horticulture. Farm trees		The total farm emissions are given in CO_2eq tonnes, as well as the emissions GHG (CH_4 and N_2O), emission source, and enterprise and without and with mitigation measures given Cost of farm emissions included
Fieldprint (Farm level)	Field to Market ; (2009)	U.S.	The Fieldprint Calculator is a simple tool designed to help farmers begin to look at how their crop production operations impact the sustainability of their farm. It provides a fieldprint for assessing the sustainability of a farm in the resource areas of land use, energy use, climate impact, soil loss, and water use (irrigation).	Cropland (corn, soybean, wheat, cotton)		A fieldprint is determined by dividing the resource use/impact by the crop productivity or yield (e.g., Acres/bu for land-use; BTU/bu for energy use; lb CO_2eq/bu for climate impact Cost of fuel for the different practices (e.g., tillage, fertilizer application, irrigation) is presenteds
GHGFarm	Canada (2007)	Canada	The GHGFarm tool was developed to enable scientists, policy makers, and agricultural producers to collectively quantify, interpret and compare alternative farm management scenarios, thereby encouraging the adoption of longer-term sustainable farm practices.	A range of Canadian crops and farming systems including livestock systems, canola, soybean.	Included	Whole farm net GHG emission and emission by source in CO_2eq yr-1. Provides different mitigation scenarios.
HGCA carbon footprint decision support tool (Product level)	HGCA; (2007)	UK	Excel based tool to calculate the GHG footprint of cropping systems to facilitate decision support for farmers to manage their GHG impacts.	Cereals and oilseed crops including wheat, barley, oats, rye, oilseed rape	Not included	kg CO_2eq per product unit (ton) or per area (kg CO_2eq per hectare)
HOLOS (Farm level)	Agriculture and Agri-Food Canada in collaboration with Canadian farms; (2008), v2.2.1 released May 2014.	Canada	Holos is a whole-farm modelling software program that estimates greenhouse gas (GHG) emissions based on information entered for individual farms and using primarily IPCC (IPCC, 2006) methodology. It replaces the older version (GHGFarm). Holos also provides a set of possible mitigation options unique to each farm and lets users explore the impact of these options.	Cropland; Grassland; Livestock (cowbeef and dairy, calf, sheep, swine, poultry, other animals); Lineal tree plantings; (Note: includes organic soils)	Included	CO_2eq emissions for the entire farm, split up by source and GHG. Results are given for each scenario. Output is expressed as total farm emissions

6 CONCLUSION AND RECOMMENDATIONS

In this chapter we present our conclusions and provide recommendation for future analysis and updates of the methodology.

6.1 CONCLUSIONS

In this project we have developed a new methodology to set science-based targets for nine key agricultural commodities and one forestry commodity, taking negative land-use change impacts into account. These ten agriculture and forestry commodities cover over 50% of global GHG emissions from the AFOLU sector.

Based on updated Marginal Abatement Cost Curves and simulations in the IMAGE model of the SSP2 scenario, we have derived average emission intensity pathways from 2010 to 2050 per commodity for 26 regions. Similar to the Sectoral Decarbonization Approach of the Science Based Targets initiative, these average emission intensity pathways of a commodity in a specific region are translated to a company-specific emissions intensity target by applying the convergence principle: i.e. the emission intensity of a commodity produced in a certain region converges to the same average emissions intensity in that region in 2050. Taking projected company growth of production/sourcing in a region into account, the company can calculate the science-based targets for any specific target year.

In addition to mitigating agricultural GHG emissions (non-CO_2 and CO_2 from energy) of these commodities, the CO_2 emissions that result from the conversion of natural land to agricultural land (LUC-CO_2) have also been assessed by exploring four methodological approaches. Although this LUC-CO_2 ranges between the four methods can be viewed as uncertainty, the main message of this project is that the choice of method determines, to a large extent, the value of the emission factor for land-use change CO_2 emissions (LUC-CO_2).

Factors other than choice of method which influence LUC-CO_2 factors, include trade patterns, feed composition, role of by-products, other applications such as bio-energy and manufacturing, management type and reference period. Implicit model settings also play a role. For instance, differences exist between models in assumptions on future yield improvement, where expansion and abandonment take place and role of climate change effects and CO_2 fertilisation effects on yield. They explain differences between studies, which use a similar methodology. The most suitable method depends on the application and the preference of the user. This project recommends method D "Forgone Sequestration", which shows the LUC-CO_2 factor in the case that land currently occupied by agriculture would be returned to natural vegetation. The emission factors of this method are in the middle of the range of methods, and have a valid emission factor for every region.

Overall, the methodology developed in this project has the following key characteristics:

- The methodology is based on a **new least-cost modelled 2° C scenario (SSP2 scenario)** taking into account latest insights in mitigation potential and costs of climate-smart solutions.
- The methodology is based on **intensity pathways per commodity, using physical** indicators (tonne of product) for the selected commodities and differentiates between 26 regions
- Both **carbon intensity and absolute targets** can be set by the methodology
- The methodology can be applied by **farmers up to retailers** to reduce GHG emissions during production and to green their supply chain
- The methodology and tool also provide insights into **land-use change impact per commodity per region**.
- The methodology is **flexible to set targets** for each year until 2050

6.2 RECOMMENDATIONS

In general, we propose that this new methodology will be pilot tested by companies in order to test the practical application of this methodology. These pilot tests could provide valuable feedback as well as allowing the methodology to be refined over time.

In addition, we recommend the following actions with regards to the intensity pathways for the agricultural emissions (non-CO_2 and CO_2 from energy):

- **Disaggregation:** in the IMAGE model certain commodities are modelled in aggregated values, such as cereals and oil crops. We propose to assess further disaggregation as well as the allocation of emissions to by-products (like leather from cattle).
- **GWP of CH_4:** In this project we used the GWP of 25 for CH_4 to compare the results with literature. In the IPCC fifth Assessment Report the GWP value was increased to 28. We may include this value in an update of the tool, though we also wish to retain compatibility with national greenhouse gas inventories which use a value of 25.

With regards to land-use change, we propose that further research is performed on the following items:

- **Zero land-use change:** in the project we have assessed the land-use change impact per commodity per region over a certain reference period. However, no period nor target year has been defined to reach zero land-use change effect globally. Since various zerodeforestation initiatives occur with different target years, we propose to assess this in more detail.
- **Rewarding good land management:** assess the options to take rewarding of good land management into account, since land abandonment is not rewarded in the current results (i.e. we do not allow for negative emission factors if decreasing agricultural land leads to net carbon uptake).
- **Reference period:** The choice of the **reference period** has a large effect on the results, and for future analysis and updates longer reference periods might be considered.
- **Spatial detail:** in using the aggregation of 26 regions in this project, local/national trends in land expansion/abandonment are averaged out. In subsequent updates, more detail may be added.
- **Evaluation/validation:** the amount and location of agricultural land-use change is of crucial importance for the emission factors, and therefore we propose to compare IMAGE land-use dynamics to recent observational data.
- **Certification schemes** are not addressed in this project as means to reduce emission factors, and we have not calculate specific emission factors for certified products. We propose to assess and include this in future projects.

We invite companies that produce or source the selected agriculture and forestry commodities to use the developed methodology and set science-based targets to keep global warming well below 2°C. In addition to setting science-based targets, rapid mitigation action is required to meet these targets. In this report various actions to mitigate GHG emissions and eliminate land-use change effects are listed. Besides this, an overview is also presented on how to measure, monitor and track the progress of reducing GHG emissions of these key agricultural commodities.

7 GLOSSARY OF ACRONYMS

ACRONYM	DESCRIPTION
(I)LUC	(indirect) Land-Use Change
2DS	Two degree scenario (from IEA)
AFOLU	Agriculture, Forestry and Other Land-Use
AR(1-5)	IPCC Assessment Report (1-5)
AWB	Agricultural Waste Burning
BAU	Business-as-usual
CH_4	Methane
CO_2(E)	Carbon dioxide (equivalent)
DM	Dry Matter
EE	Energy Efficiency
EF	Emission Factor
FAO	Food and Agricultural Organization (UN)
GHG	Greenhouse Gas
GWP	Global Warming Potential
IEA	International Energy Agency
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
MACC	Marginal Abatement Cost Curve
N_2O	Nitrous Oxide
NH_3	Ammonia
PBL	Netherlands Environmental Assessment Agency
PFT	Plant Functional Type
RCP	Representative Concentration Pathways
REDD	Reducing Emissions from Deforestation and forest Degradatione
SBT	Science Based Targets
SDA	Sectoral Decarbonization Approach
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USEPA	United States Environmental Protection Agency
WRI	World Resources Institute
WWF	World Wildlife Fund

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9

ANNEX 1

OVERVIEW OF GLOBAL LITERATURE ON BASELINE EMISSION, TECHNICAL MITIGATION POTENTIAL AND ECONOMIC MITIGATION POTENTIAL

Agriculture, Forestry, and Other Land-Use (AFOLU) sector contributes around 17 to 32% i.e. 8.5 to 16.5 $GtCO_2eq$ of all anthropogenic GHG emission (Bellarby et al., 2008). Annual total non-CO_2 GHG emission from agriculture in 2010 are estimated to be 5.2-5.8 $GtCO_2eq\ yr^{-1}$ i.e. about 10-12% of global anthropogenic GHG emission (FAO STAT, 2013; Tubiello et al., 2013). Annual GHG emissions from land use and land-use change are estimated at 4.3-5.5 $GtCO_2eq\ yr^{-1}$ i.e. about 9-11% of the total anthropogenic GHG emissions (IPCC, 2014).

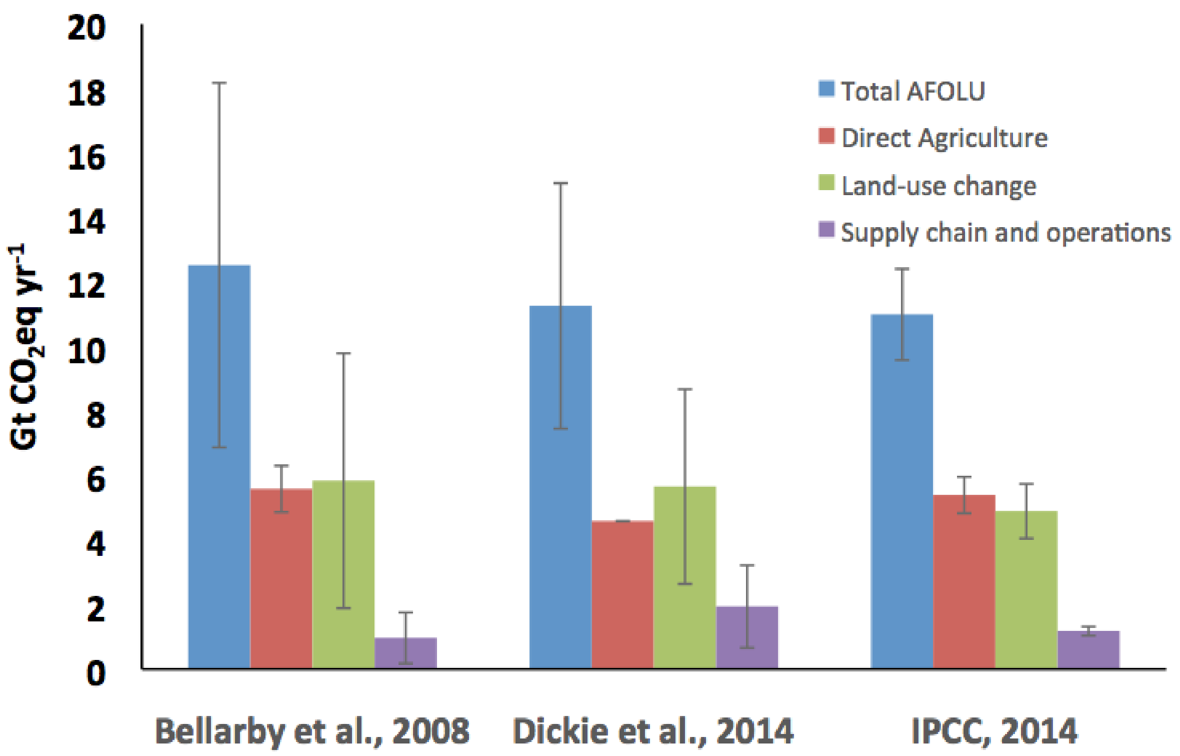

Figure 44; comparison of GHG emission from agriculture sector from published literature.

9.1 BASELINE EMISSION

Defining a baseline or business-as-usual scenario is a key part of assessing the mitigation potential of agriculture sector. Several global estimates of baseline GHG emissions from agriculture have been undertaken. Figure 45 presents estimation from six published sources for the base year (2005 or 2010) reporting CH_4 and N_2O emission from agriculture sector i.e. rice, agricultural soil, livestock enteric fermentation and manure management. Other agricultural non-CO_2 sources is not included here.

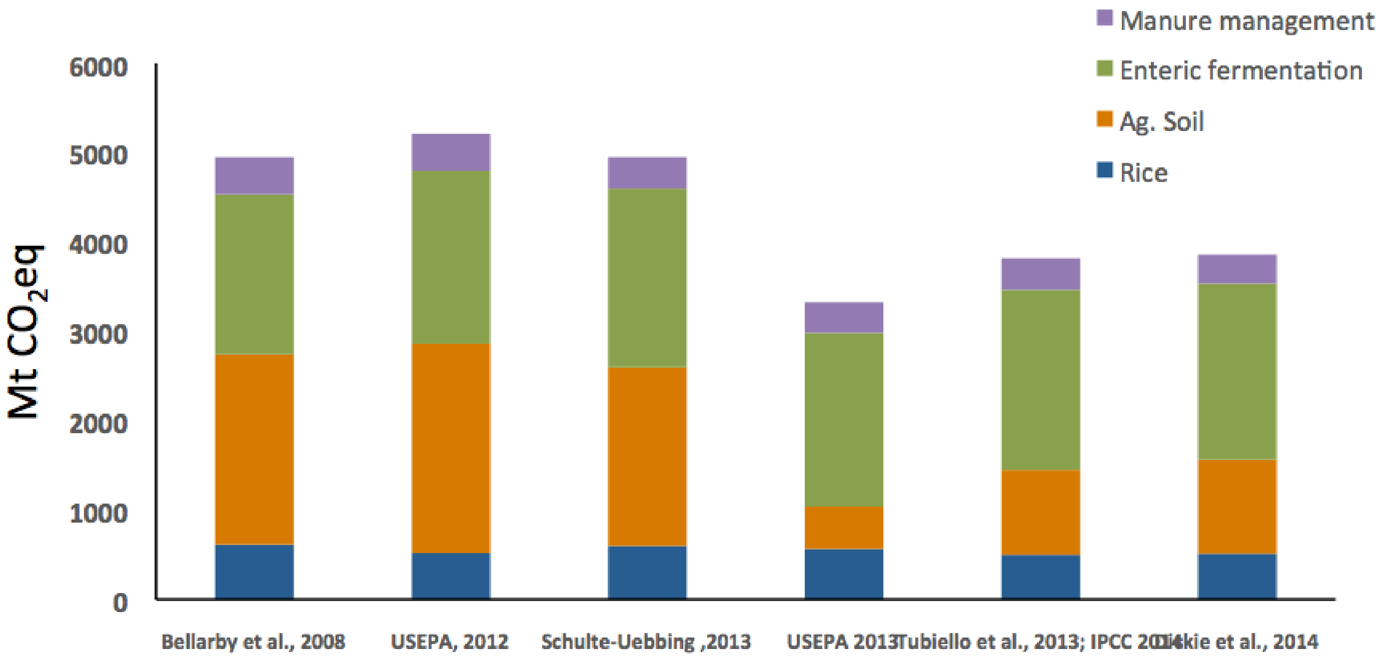

Figure 45; comparison of GHG emissions from different agriculture sub-sectors from literature. Except Bellarby et al., 2008 (base year 2005) the base year for all the other studies are 2010. USEPA (2012) presents estimates of emission from agricultural soils which includes both cropland and pasture whereas baseline for agricultural soil for USEPA (2013) is DAYCENT baseline which includes only maize, wheat, barley, sorghum, oats and related crops, and covers 61% of the global non-rice cropland areas reported by FAO STAT.

Figure 45 shows the agriculture sub-sectors responsible for higher GHG emissions are enteric fermentation (32-40%) and agricultural soils which together accounts for 70% of the total emissions (IPCC, 2014). Paddy rice cultivation contributes around 9-11% of the total emission. Major source of emissions when sub-sector agricultural soils is disaggregated are synthetic fertilizers, manures applied to soils, crop residues which contributes around 71, 12 and 15% of the total agricultural soil emissions (Tubiello et al., 2013). Emissions from supply chain i.e. emissions from all farm practices including agrochemical production and distribution including fertilizer, irrigation is estimated at 1 – 1.94 Gt CO_2eq/yr (Bellarby et al., 2008; Dickie et al., 2014; IPCC, 2014).

Herrero et al (2016) estimated the total emissions for livestock sector from 1995 to 2005, emissions were between 5.6 and 7.5 GtCO_2eq yr^{-1}. This estimation included emissions associated with feed production, pasture extension, CH_4 emission from rice associated with feed production, enteric CH_4, manure CH_4 and N_2O, direct and embedded energy CO_2 and post farm gate CO_2. Most important sources of emissions were enteric CH_4 (1.6 – 2.7 GtCO_2eq yr^{-1}), N_2O emission associated with feed production (1.3 – 2.0 GtCO_2eq yr^{-1}) and land-use change for feed production and pasture extension (1.6 GtCO_2eq yr^{-1}) .

Current global greenhouse gas emissions from livestock (1995 - 2005)

Emissions source	Emissions (GtCO_2e)	Reference
Feed N_2O	1.3–2.0[‡]	9,13,15,16–18
Feed CO_2 (LUC excluded)	0.92	15,17,18
Feed CO_2 (LUC)	0.23	15,17,18
Pasture expansion CO_2 LUC	0.43	15,17,18
Feed CH_4 rice	0.03	15,17,18
Enteric CH_4*	1.6–2.7	9–13,15,17
Manure CH_4*	0.2–0.4	9–13,15,17,18
Manure N_2O*	0.2–0.5	9–13,15–18
Direct energy CO_2	0.11	15,17,18
Embedded energy CO_2	0.02	15,17,18
Post-farm gate CO_2	0.023	15,17,18
Non-CO_2 emissions* (IPCC guidelines)	2.0–3.6	This Review
Total emissions (LCA approach)[†]	5.6–7.5	This Review

*Livestock emissions according to IPCC emissions guidelines[8]. [†]Range estimated using information from global analyses for key emissions source categories. LCA as implemented by FAO[15]. [‡]Includes N_2O emissions from manures applied to pastures, and from fertilizers to croplands for both feed and pasture. Emissions from manure applied to pastures ranges from 0.42–0.95 GtCO_2e. LUC, land-use change.

Figure 46; Current global GHG emissions from livestock. Source: Herrero et al. (2016)

9.1.1 BASELINE PROJECTION

Global CH_4 emissions from rice grew slowly at an average rate of 0.7% yr^{-1} from 1961 to 2010 from 370 $MtCO_2eq$ to 490 $MtCO_2eq$ yr^{-1} (Tubiello et al., 2013). According to USEPA (2012) total CH_4 emission from rice increased by 4.4% between 1990 and 2005, from 480 Mt CO_2eq to 501 $MtCO_2eq$ (Figure 47). CH_4 emission from rice is projected to decrease by nearly 2% from 2010 to 2030 from 519 $MtCO_2eq$ to 510$MtCO_2eq$ (USEPA, 2012) .USEPA (2013) also projected a 0.39 to 2.31% decrease in rice CH_4 emission from 2010 to 2030 and such changes was attributed to relatively constant demand for rice products while global food demand shifts to more livestock and expensive food products. However net GHG emission from rice was projected to increase by 30% from 2010 to 2030 and the increase was mostly due to increased N_2O emission and decreased soil C sequestration (USEPA, 2013).

Agricultural soil N_2O emissions are projected to increase by 13 to 26% from 2010 to 2030 from 1969 $MtCO_2eq$ in 2010 to 2237 $MtCO_2eq$ in 2020 and 2483 $MtCO_2eq$ in 2030 (USEPA, 2012). USEPA 2013 projected 1.2% decrease in soil N_2O emission from 506 $MtCO_2eq$ in 2010 to 504 $MtCO_2eq$ in 2030.

USEPA (2012) estimate includes emissions from agricultural soils which includes both croplands and pasture where as USEPA (2013) baseline study includes only specific crops which covers only 61% of the global non-rice cropped areas.

Enteric CH_4 emission is projected to increase by 20% between 2010 to 2030 from 1932 $MtCO_2eq$ to 2320 $MtCO_2eq$ (USEPA, 2012). USEPA (2013) reported an average annual rate of 0.9% increase in global enteric CH_4 emission. Herrero et al., 2016 estimated the enteric CH_4 emission to grow at rates between 0.9-5% per year by 2050. Manure CH_4 and N_2O is projected to increase by 10 and 16% between 2010 and 2030 (USEPA, 2012). USEPA (2013) projected an increase in total GHG emission of 0.6% between 2010 and 2030. Herrero et al., 2016 reported a 0.9-4% and 1.2-3% annual increase in manure CH_4 and N_2O emission.

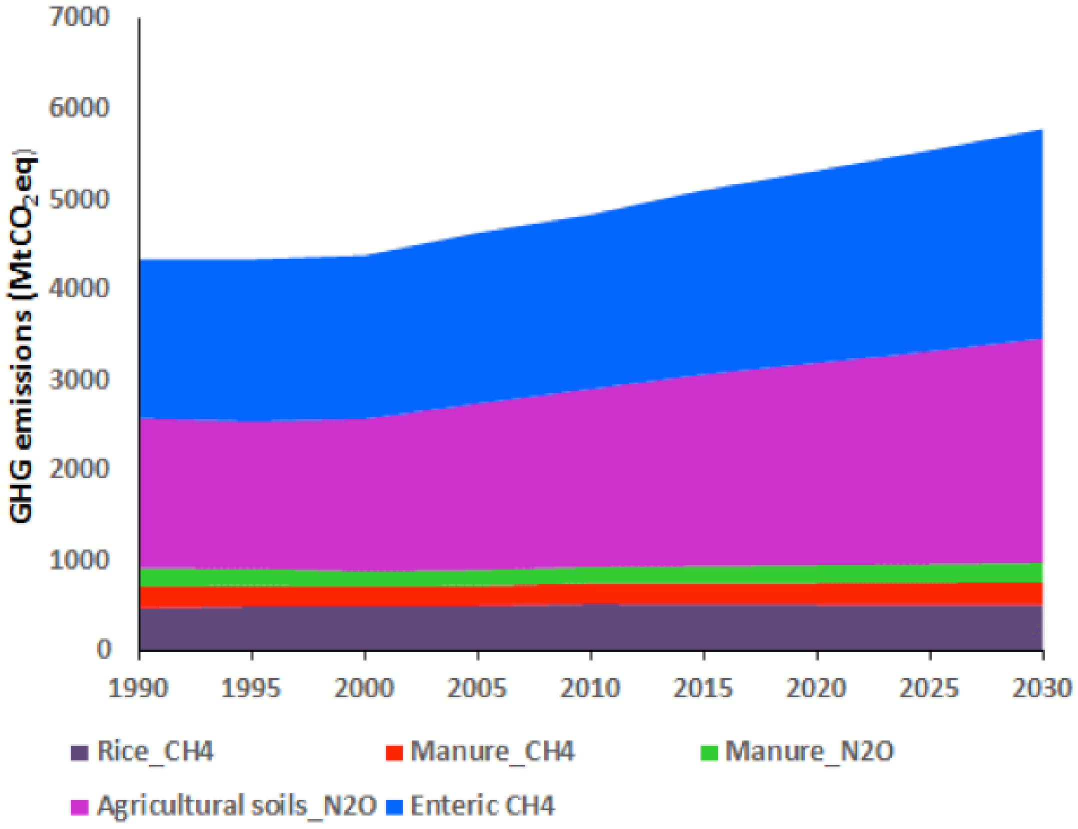

Figure 47; GHG emission from Agriculture sub-sectors (1990-2030) based on data from USEPA (2012)

9.2 TECHNICAL AND ECONOMIC MITIGATION POTENTIAL

Mitigation potential is differentiated as "technical potential", "economic potential" and "market potential" based on the barriers or constraints included. Technical mitigation potential is the full biophysical potential of a mitigation option, taking account of constraints such as land availability and suitability, but without accounting for economic or other constraints. Economic potential is the potential that could be realized at a given carbon price over a specific period, but doesn't take into consideration any social-cultural, political or institutional barriers to practice a technology adoption. Market potential is the mitigation potential actually seen under current or forecast market conditions and it is the biophysically/economically/socially-culturally/Institutionally-politically constrained potential (Smith et al., 2012). Figure 48 shows the interaction between technical, economic and market potential (IPCC, 2014).

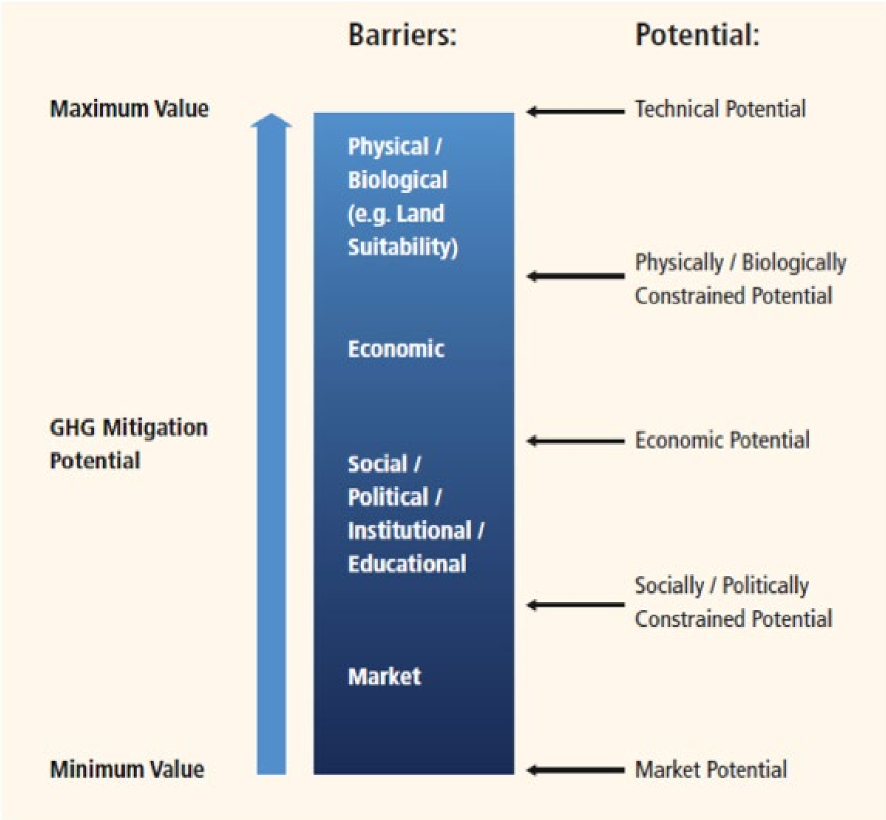

Figure 48; relationship between technical, economic and market potential from IPCC, 2014 based on Smith, 2012.

9.2.1 TECHNICAL MITIGATION POTENTIAL

Technical mitigation potential is the maximum mitigation potential that can be achieved with implementation of a mitigation option (see figure above). There are numerous studies estimating mitigation potential of different agriculture-subsector either globally or at regional level. Figure 49 shows comparison of the maximum reduction potential of GHG emissions for rice paddy from 8 different studies for 5 different time period. Maximum reduction potential (MRP) is the maximum GHG reduction that could be achieved by applying various mitigation measures, as compared to a baseline emission scenario for a particular year. Most of the studies estimated the MRP for the base year (Cole et al., 1997; Bellarby et al., 2008) or short term MRP i.e. up to 2030 (McKinsey, 2009; Schulte-Uebbing, 2013; USEPA, 2013; Dickie et al., 2014). Two studies estimated long term MRP for rice i.e. until 2050 and 2100 (Graus et al., 2004; Lucas et al., 2007). USEPA (2013) analysis shows a decrease in MRP from 35% in 2010 to 26% in 2030; but Graus et al. (2014) estimated 70% decrease in GHG emission from rice by 2050. Lucas et al., 2007 estimated the long term MRP of 80% by 2050 and 90% by 2100. Lucas et al. (2007) assumed technology development and removal of implementation barriers would increase reduction potential in long-term, for rice they assumed 70% implementation by 2050 and 100% implementation by 2100. Global MRP for rice paddy ranged between 120-600 $MtCO_2eq$ in 2030.

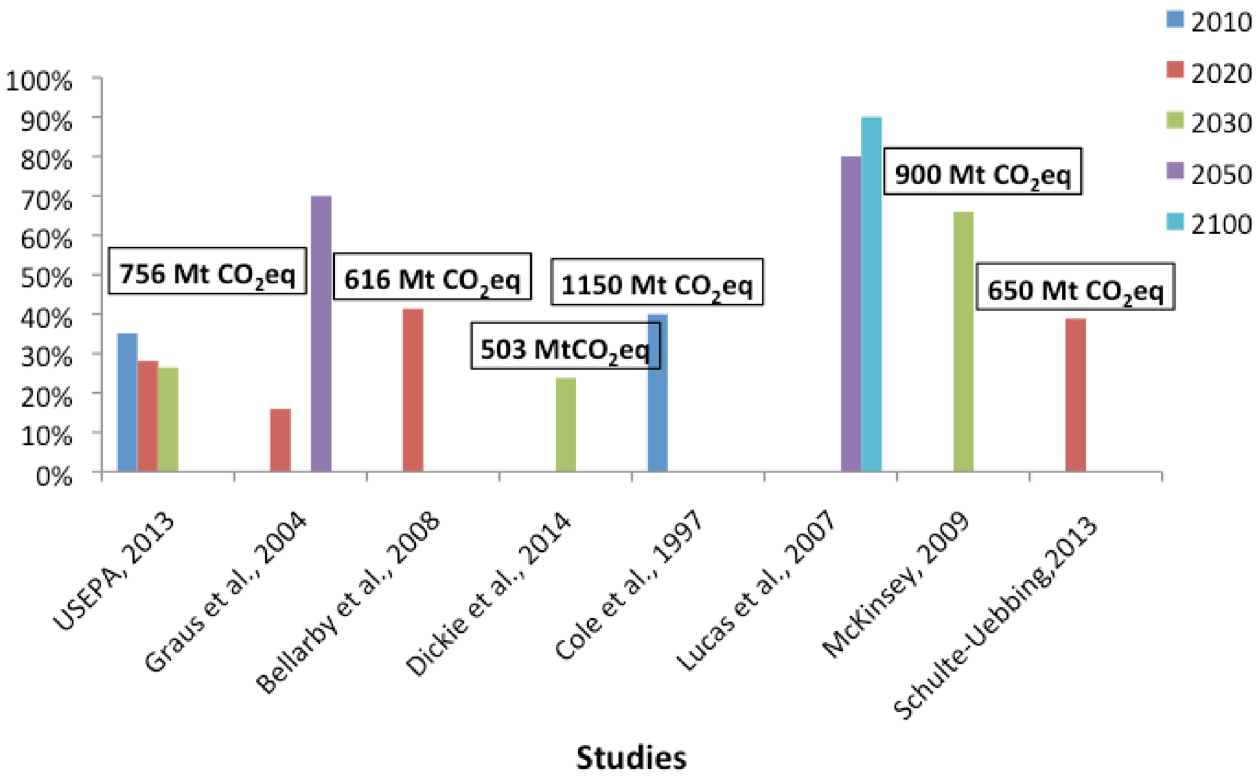

Figure 49; maximum reduction potential (%) of GHGs emission from rice collated from literature. Values in the square boxes are baseline emissions for either base year (Bellarby et al., 2008; Cole etal., 1997) or 2030.

MRP for non-rice crops was much lower than Rice and varied between 14 – 25% in 2010 to 32-35% in 2050. Lucas et al. (2007) estimated a MRP of 40% by 2100 (Figure 50). All the studies included different sets of mitigation measures mostly related to N fertilizer use (Graus et al., 2004; Lucas et al., 2007; Bates et al., 2009) and soil organic carbon management such as conservation tillage, crop residue management (Moran et al., 2008; USEPA, 2013; Dickie et al., 2014). USEPA (2013) analysis identified no tillage and reduced fertilization as measures contributing most to the overall mitigation for non-rice cropland. Also MRP for non-rice cropland decreased with time from 2010 to 2030 for USEPA analysis and the decrease is mainly due to the effect of soils becoming "saturated" with C and reaching a new equilibrium within few years of management change i.e. no tillage accounts for 70% of the total global mitigation potential in 2010 which is reduced to 43.7% in 2030.

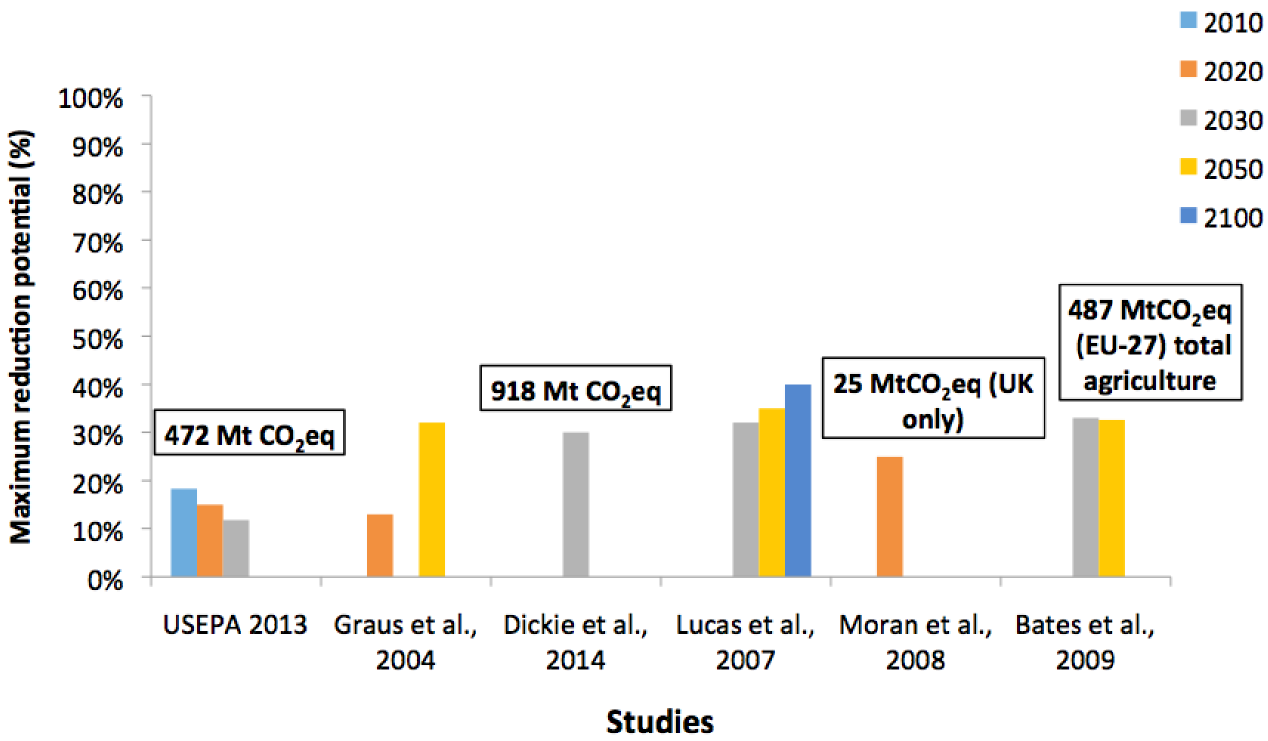

Figure 50; maximum reduction potential (%) of Fertilizer/soil GHG emission from non-rice crops collated from literature. Values in the square boxes are baseline emissions for 2010 (Moran et al, 2008) and 2030 (SERPEC, 2009; USEPA, 2013; Dickie et al., 2014). For Dickie et al., 2014. (2014), baseline emission includes emissions from synthetic fertilizers, crop residues and manure applied to soil. Baseline emissions and mitigation potential for Bates et al.(2009) include both emissions and mitigation from crops and livestock for the year 2005.

The mitigation potential of the livestock sector could represent up to 50% of the global mitigation potential of the AFLOU sector, but most of this potential has yet to be realized, due to low adoption rates of technical practices and uncertainties and trade-offs associated with attempts to reduce the consumption of livestock products (Herrero et al., 2016). MRP for the livestock sector varied between different studies from 13-19% in 2020 to 60% in 2100 (Figure 51).Four studies estimated MRP for year 2030, and it ranged between 12% (USEPA, 2013) to 60% (Havlik et al., 2014). Global MRP for livestock total (enteric CH_4 and manure management) ranged between 319-2000 $MtCO_2eq$ in 2030. In 2030, enteric CH_4 and manure management MRP was 105-940 $MtCO_2eq$ and 22-260 $MtCO_2eq$ respectively.

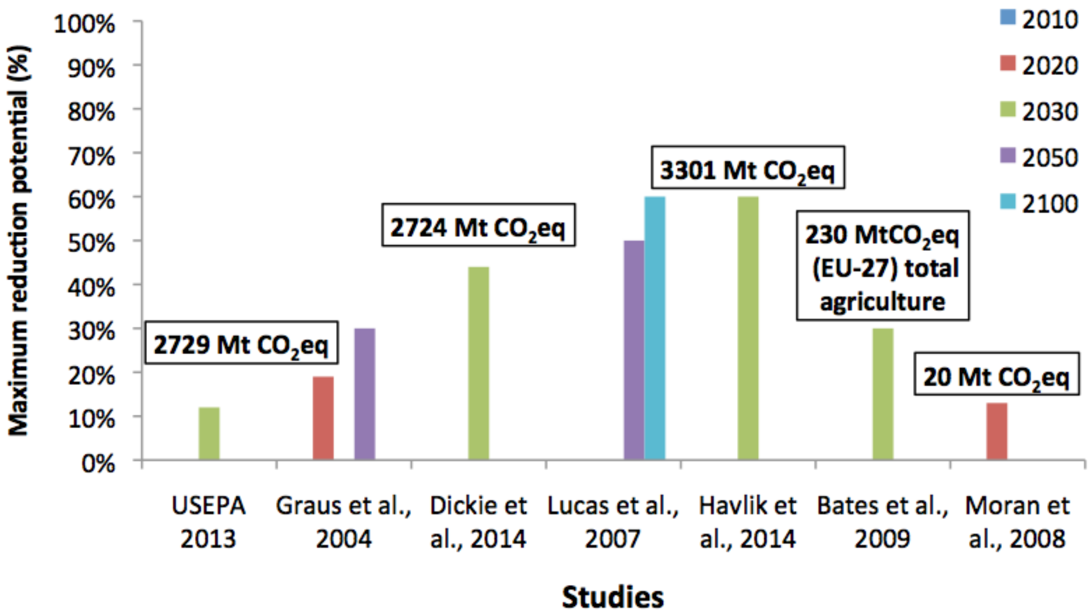

Figure 51; maximum reduction potential (%) of GHGs emission from livestock production system collated from literature. Values in the square boxes are baseline emissions for 2030 except for Moran et al., 2008 it is 2010. Havlik et al. (2014) also take LUC CO_2 into account resulting from livestock activities.

9.2.2 ECONOMIC MITIGATION POTENTIAL

Estimates of economic potential can either be done by top-down models or bottom-up estimates. Available top-down estimates of global mitigation potential in agriculture which mostly covers CH_4 and N_2O from cropland and livestock, emissions from burning of agriculture residues, waste and fossil fuel combustion are: 267–1518 $MtCO_2eq\ yr^{-1}$, 643–1866 $MtCO_2\ eq\ yr^{-1}$ and 604 $MtCO_2eq\ yr^{-1}$ for a carbon price of \$US20 $tCO_2eq\ yr^{-1}$, \$US50 $tCO_2eq\ yr^{-1}$ and \$US100 $tCO_2eq\ yr^{-1}$ respectively (Smith et al., 2007). Bottom up estimates of global economic potential for agriculture are estimated to be 1500–1600 $MtCO_2eq\ yr^{-1}$, 2500–2700 $MtCO_2eq\ yr^{-1}$ and 4000–4300 $MtCO_2eq\ yr^{-1}$ for a carbon price of \$US20 $tCO_2eq\ yr^{-1}$, \$US50 $tCO_2eq\ yr^{-1}$ and \$US100 $tCO_2eq\ yr^{-1}$ respectively (Smith et al., 2008). USEPA (2013) provided an estimation of economic potential of 296.5 $MtCO_2eq\ yr^{-1,}$ 383.8 $MtCO_2eq$ yr-1 and 524.7 $MtCO_2eq\ yr^{-1}$ for a carbon price of \$US20 $tCO_2eq\ yr^{-1}$, \$US50 $tCO_2eq\ yr^{-1}$ and \$US100 $tCO_2eq\ yr^{-1}$ respectively. McKinsey (2009) estimated economic mitigation potential of 4600 $MtCO_2eq\ yr^{-1}$ in 2030 which could be achieved at a lower cost (<\$US70 $tCO_2eq\ yr^{-1}$).

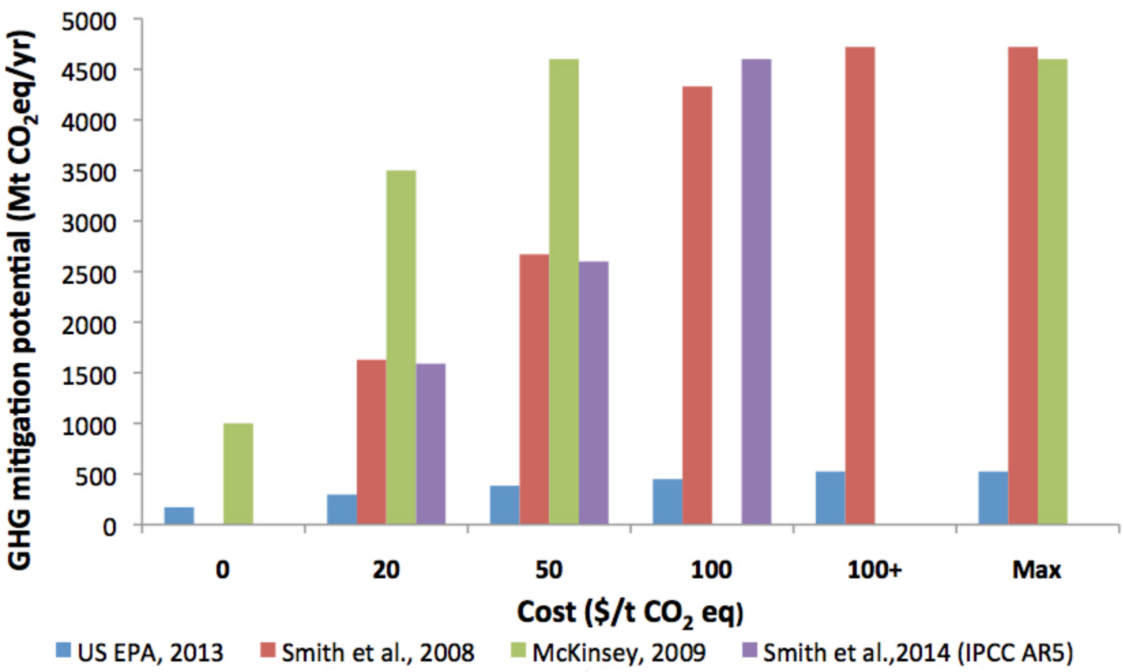

Figure 52; bottom-up estimates of economic mitigation potential of agriculture sector.

10

ANNEX 2

GHG ABATEMENT POTENTIAL AND MAC CURVES

10.1 METHODOLOGY

REDUCTION POTENTIAL

The new MAC curves for agricultural CH_4 and N_2O emissions are built up out of sets of mitigation measures found in literature. These sets are the combinations with the highest estimated maximum reduction potential, determined using the following equation:

$$RP = RE * TA * OVcorr * IP (time)$$

$$MRP = 1 - (1 - RP_1) * (1 - RP_2) * .... * (1 - RP_x)$$

With:

MRP	= Maximum Reduction Potential of all measures combined
RP	= Reduction Potential of one measure
RE	= Reduction Efficiency, relative reduction of targeted emissions compared to baseline
TA	= Technical Applicability, or part of the baseline covered by the measure
OVcorr	= Correction for overlap
IP	= Implementation potential, dependent on barriers in future years

The estimated RE for a specific measure is the average of all the RE values for this measure found in literature. Maximum and minimum RE values can be used to construct MAC curves with higher and lower range estimates, but will not be used here.

The TA is in many cases 100%, when a measure can be applied to all emission sources. However, in some, measures are not applicable worldwide, for instance where the measures are already in place

or cannot be combined with an emission source (e.g. drainage in the case of upland (irrigated) rice, excessive flooding that would prohibit drainage for rice, or optimizing fertilizer application when all fertilizer is effectively used). TA estimates have been based on Graus et al. (2004).

In the case of mutually excluding measures (e.g. mid-season drainage and alternate flooding /drainage), the measures with the lowest reduction potential were excluded. In the case of partial overlap, with a diminished benefit of the second measure (e.g. different food supplements that reduce enteric fermentation), a correction factor, OVcorr, was applied to the reduction potential of the

second measure to account for the reduced effectiveness. We made a distinction between high, medium, low and no interaction. It was assumed that with high overlap, the second measure had 20% of the original reduction efficiency. With medium overlap this was assumed to be 50%, and with low overlap 70%. See below for an overview of the assumed interaction between measures.

The implementation potential of the measures is based on Graus et al, 2004. This value is expected to increase in time due to increased technology diffusion and implementation. Assumed values are 10% in 2020, 70% in 2050 and 100% in 2100 for Rice CH_4 and Fertilizer N_2O emissions. For livestock measures, the implementation potential is assumed to be slightly higher, particularly in the short term; 20% in 2020, 90% in 2050 for enteric fermentation, 20% in 2020, 80% in 2050 for animal waste.

TECHNOLOGY IMPROVEMENTS

It can be expected that the future MRP values are actually higher than the MRP values derived from the MACs, with all the abatement measures from this assessment fully included. This is the case for two reasons: 1) Some existing technologies might not have been included in this assessment, which could have added to the reduction potential 2) Future technology improvements and currently nonexisting future technologies can potentially do the same in the future. It can be expected that the second argument is stronger in the far future. Therefore, we assume that in 2050, after implementing all measures included in the MAC the remaining emissions can be reduced 10% more. For 2100, we assume that the remaining emissions can be reduced 20% more than what is expected based only on the MAC. So:

$$MRP_{2050} = 1 – (1 – MRP_{MAC}) * 90\%$$

$$MRP_{2100} = 1 – (1 – MRP_{MAC}) * 80\%$$

Between 2050 and 2100, the MRP values are linearly interpolated to arrive at a MRP for each year. It is assumed that the additional technology improvements occur at very high GHG prices: at or above 3000 $/tC or 818 $/tCO_2$. In the IMAGE model, this MaxPrice is introduced as the carbon price at which the maximum reduction takes place. In earlier model versions this price was set much lower: 1000 $/tC for most agricultural sources (Lucas et al., 2007). This update therefore leads to an added emission reduction benefit at higher carbon prices.

MARGINAL COSTS

The assumption for the construction of the MAC curves is that the least costly measures are taken first. Only a selection of the studies included estimates of marginal costs of reduction measures. As with the reduction efficiency, the best estimate of the marginal costs of a specific measure was based on the average of cost estimates in literature. The available cost data was converted to 2005 $ / tCO_2eq (as 2005 dollars are used as the cost metric in the IMAGE model), and made regionally specific where data was available.

Marginal costs presented in literature need to be corrected for diminishing returns of measures, when multiple measures are implemented. The cost of a certain mitigation measure is based on the assumption that the measure can be fully applied to its emission source. When multiple measures are in place, the relative reduction per measure decreases, while the implementation costs may remain the same. Two factors lead to an expected cost increase (in terms of $ / tCO_2eq mitigated):

1. Interaction / overlap between measures that are implemented in parallel (e.g. multiple food supplements that are used to reduced the same emissions).

2. Diminishing reduction effect when measures are placed in series. (e.g. manure storage covering and digesters to reduce animal waste emissions). Following the assumption that least cost measures are implemented first, we corrected the cost of every subsequent (more expensive) measure, considering the two cost increasing factors:

3. In case of parallel overlap, cost per t/CO_2 of the subsequent measure are multiplied by a factor that represents the inverse of the reduced reduction potential (where x stands for the added measure):

$$Cost\ new_x = Cost\ old_x * 1/OVcorr_x$$

4. When a subsequent measure is implemented in series, the cost change of this measure is also assumed be proportional to the inverse of the reduced reduction potential (where x stands for the added measure):

$$Cost\ new_x = Cost\ old_x * (MRP\ before – MRP\ after) / RP_x$$

One result of this approach is that more expensive measures that are implemented in a later stage (and have a relatively lower added reduction benefit) need a larger cost correction. Another result is that the marginal costs of individual measures are assumed to be higher when the implementation potential is higher, so towards the end of the century (which can be seen from the “steps” in the MAC curves that represent new measures and are assumed to occur at slightly higher prices in later years).

INERTIA

In IMAGE, the yearly change in non-CO_2 reductions is restricted to prevent unrealistically fast implementation of reduction measures. This means that a very high, sudden increase in the carbon price, the calculated emission reduction might be lower than the reduction level based on the MAC curve alone.

This inertia in the implementation of measures is determined as follows. A maximum yearly increase in emission reduction compared to the previous year is determined (in percentage points), based on the number of years in which the maximum reduction potential estimated for 2050 can be achieved. As default, it is assumed that the maximum reduction potential of 2050 can be achieved in 20 years. We have deviated from the default 20 years for sources where it is thought to be unrealistically short (for wetland rice) or long (for fertilizer application), based on expert judgement.

The table below shows the maximum reduction change by source. For example, if in 2030 30% of the wetland rice emissions have been reduced (compared to the baseline), then in 2031 it is only possible to reduce 32.7% compared to the baseline.

EMISSION SOURCE	MAXIMUM REDUCTION POTENTIAL (AS DE DESCRIBED IN LUCAS ET AL. 2007)		MINIMUM # OF YEARS NEEDED FOR MAXIMUM REDUCTION	MAXIMUM REDUCTION CHANGE PER YEAR
	IN 2050	IN 2100		
CH_4 WETLAND RICE	80%	90%	30	2.7%
CH_4 FROM ANIMALS / ENTERIC FERMENTATION	50%	60%	20	5%
N_2O FROM FERTILIZER USE	35%	40%	10	3.5%
N_2O FROM ANIMAL WASTE	35%	45%	20	1.8%
CH_4 FROM ANIMAL WASTE	50%	60%	20	2.5%

Table 8

In this project we re-evaluated the inertia variables for the agricultural emission sources. As a result, we made a correction for CH_4 from animals / enteric fermentation. The minimum number of years to reach the MRP is now assumed to be 20 years (was 10). The reason for the correction is the fact that much livestock is produced and traded in the informal sector where it will be more difficult to implement abatement measures in a short time span.

10.2 MAC CURVE FOR RICE

10.2.1 MITIGATION OPTIONS FOR RICE

The mitigation measures that have been used to construct the MAC curve are the following (taking into account overlap between measures and aiming for the highest MRP):

1. Alternate flooding/ drainage: this measure reduces anaerobic conditions. **Varying costs, depending on the region, average cost-effectiveness 148 $/tCO_2eq (Nguyen et al., 2014; Nalley et al., 2015) , average CH_4 reduction efficiency 57%**

2. Direct wet seeding: replaces transplanting; exact CH_4-reducing mechanism unclear. **Varying costs, depending on the region, average cost-effectiveness 0-63 $/tCO_2eq (Graus et al., 2004), average CH_4 reduction efficiency 20%**

3. Phosphogypsum: addition of this by-product (3t/ha) releases sulphate, which inhibits methanogenesis. **High cost, average cost-effectiveness 61-385 $/tCO_2eq (Graus et al., 2004), average CH_4 reduction efficiency 39%**

4. Replace urea with ammonium sulphate (AS): replaces commonly used urea; sulphate inhibits methanogenesis. **Very low cost, average cost-effectiveness 1-15 $/tCO_2eq (Graus et al., 2004), CH_4 reduction potential 24%**

5. Rice straw compost: substitutes for fresh rice straw; lowers organic matter. **Medium high cost, average cost-effectiveness 24-142 $/tCO_2eq (Graus et al., 2004), average CH_4 reduction efficiency: 48%.**

The following measures have been excluded from the MAC curve (due to overlap with the measures above and/or lower reduction potentials):

6. Midseason drainage and no organic matter: reduces anaerobic conditions; lowers organic matter source. **Low cost, average CH_4 reduction efficiency 77%**

7. Conservation tillage: changing from conventional to conservation tillage or reduced tillage in rice based cropping system. **Reduced cost as compared to conventional tillage, average CH_4 reduction efficiency 22%.**

8. Enhance efficiency fertilizer which includes nitrification inhibitors, slow release fertilizers: decreases both CH_4 and N_2O emission. **Increased cost, average CH_4 reduction efficiency 18%, average N_2O reduction efficiency 27%.**

9. Off season straw application: shifting straw amendment from in- season to off-season, reduces CH_4 emission by reducing availability of DOC (dissolved organic carbon) and thus methanogenesis. **No change in cost, average CH_4 reduction efficiency 17%**

10. Straw mulching: Ditch or strip mulching of straw instead of evenly incorporating reduces CH_4 emission with exposure of fresh straw to more light and more CH_4 oxidation. **No change or low cost, average CH_4 reduction efficiency 11% to 32%.**

Impact of different management practices on CH_4 emission from rice

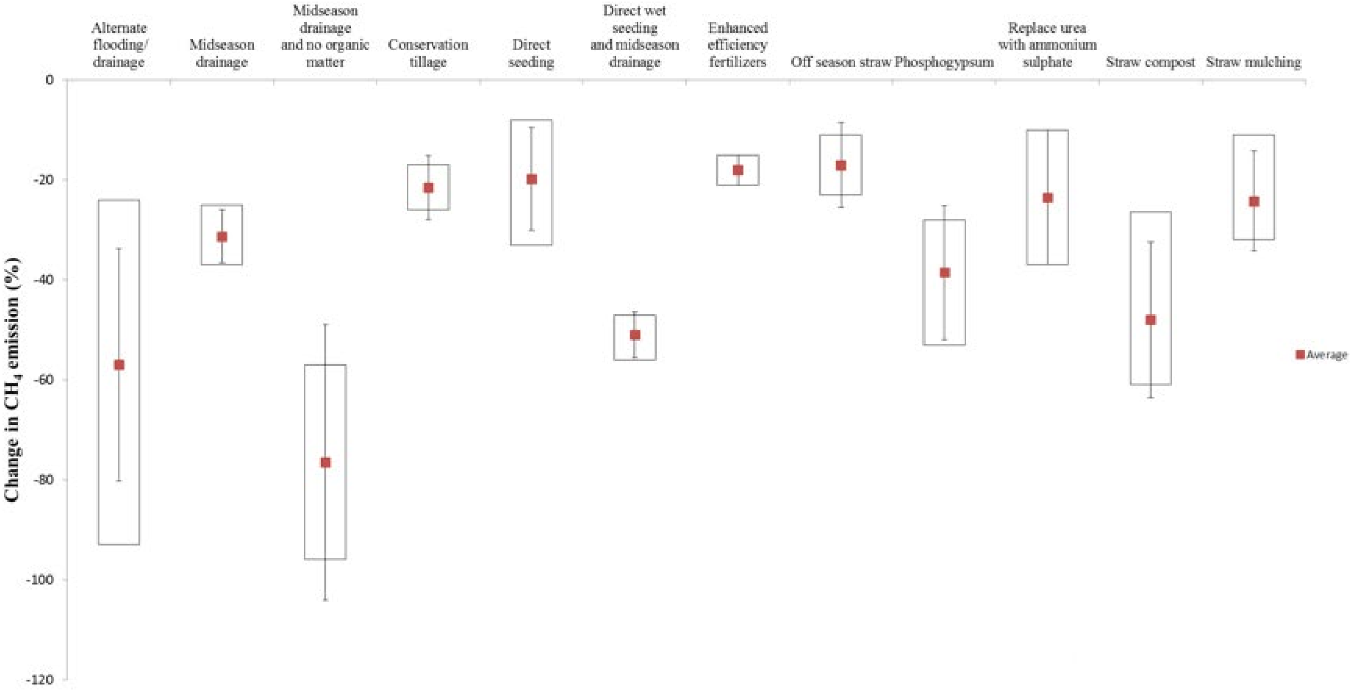

Figure 53; impact of different management practices on CH_4 emission from rice.

10.2.2 MEASURES INTERACTION

MITIGATION MEASURES	ALTERNATE FLOODING/ DRAINAGE	MID-SEASON DRAINAGE	MID-SEASON DRAINAGE/NO ORGANIC MATTER	CONSERVATION TILLAGE	DIRECT SEEDING	DIRECT SEEDING/ MIDSEASON DRAINAGE	OFF SEASON STRAW	PHOSPHOGYPSUM	REPLACE UREA WITH AMMONIUM SULPHATE	DSTRAW COMPOST	STRAW MULCHING
ALTERNATE FLOODING/ DRAINAGE											
MID SEASON DRAINAGE	H*										
MID-SEASON DRAINAGE NO ORGANIC MATTER	H*	H									
CONSERVATION TILLAGE	N	N	H*								
DIRECT SEEDING	N	N	N	L							
DIRECT SEEDING/ MIDSEASON DRAINAGE	H*	H	H	L	H						
OFF SEASON STRAW	N	N	H*	H*	N	N					
PHOSPHOGYPSUM	N	N	N	N	N	N	N				
REPLACE UREA WITH AMMONIUM SULPHATE	N	N	N	N	N	N	N	N			
STRAW COMPOST	N	N	H*	H*	N	N	H*	N	N		
STRAW MULCHING	N	N	H*	H*	N	N	H*	N	N	H*	

H: High, indicates strong interaction, may not be able to do together, if applied together mitigation potential for the second measure could be only 20% of the real potential (Interaction factor = 0.2).

M: Medium interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

L: low level interaction, can be practised together, if applied together mitigation potential for the second measure could be only 70% of the real potential (Interaction factor = 0.7).

N: No interaction, can be used together, mitigation potential are additive, if applied together mitigation potential for the second measure could be 100% of the real potential (Interaction factor = 1).

10.2.3 MAC CURVE FOR RICE

MAC CH_4 Rice-Asia

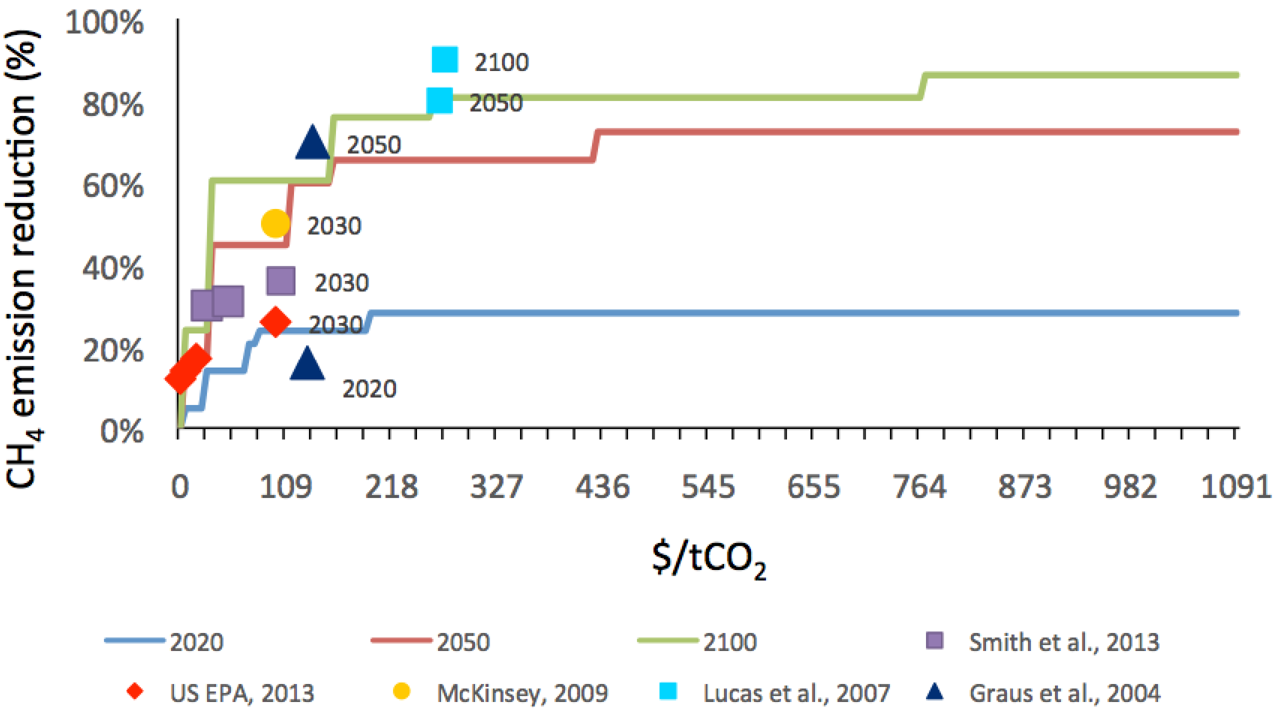

Figure 54; MAC curve for rice for Korea, China and South East Asia.

MAC CH_4 Rice-Rest of World

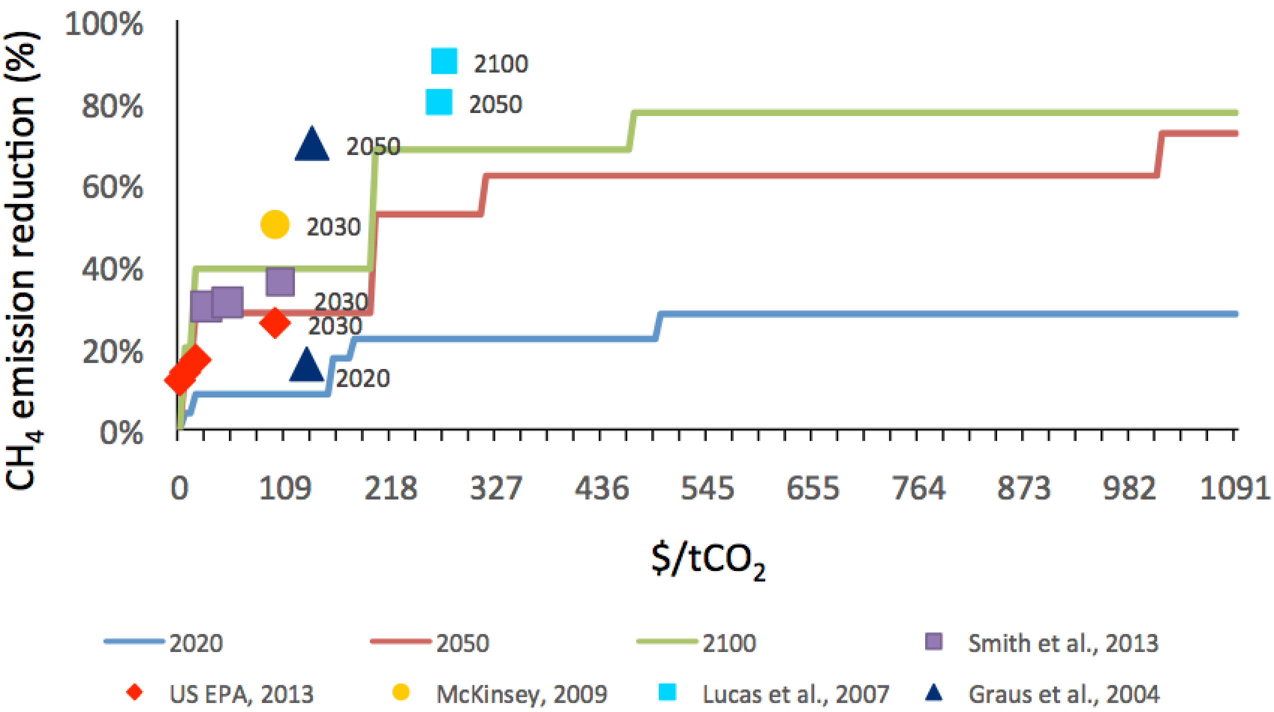

Figure 55; MAC curve for rice for Rest of the world i.e. excluding Korea, China and South East Asia.

10.3 MAC CURVE FOR FERTILIZER NO_2

10.3.1 MITIGATION OPTIONS FOR FERTILIZER N_2O

1. Use of nitrification inhibitors: Nitrification inhibitors such as DCD, Nimin reduces N_2O emission by slowing the conversion of ammonium to nitrate. ***Cost increases by 9% to 10% as compared to only inorganic fertilizer, average cost-effectiveness 32-177 $/tCO_2eq$ (Eory et al., 2015), average N_2O reduction efficiency 38%.***

2. Sub-optimal fertilizer applications, winter wheat: reduce N-based fertilizer by 50 kg/ha. ***Medium high cost, average cost-effectiveness -17 - 851 $/tCO_2eq$ (Graus et al., 2004), average N_2O reduction efficiency 26%***

3. Spreader maintenance: more uniform spreading to increase efficiency; avoid overapplication and under-application. ***Reduced cost, average cost-effectiveness -59 - -1 $/tCO_2eq$ (Graus et al., 2004), reduction potential estimate: 22%***

4. Improved land manure application: Options such as reducing inorganic N application with allowance for manure/residual N, improved timing of slurry and manure application, separating slurry/manure applications from fertiliser applications by several days, applying manure to dry rather than wet areas, applying solid rather than liquid manure could be included to this category. ***Mostly reduced cost, average cost-effectiveness -78 $/tCO_2eq$ (Moran et al., 2008; Macleod et al., 2010), average N_2O reduction efficiency 14%***

5. Improved agronomy practices. Adopting systems less reliant on inputs (nutrient, pesticides), plant varieties with improved N-use efficiency, use of rotations with legume crops, use of catch or cover crops reduces N_2O emission. ***Low cost, average cost-effectiveness 4 $/tCO_2eq$ (Eory et al., 2015; Smith et al., 2008), average N_2O reduction efficiency 20%***

6. Fertilizer free zone: avoiding fertilizer loss by leaving fertilizer free zones at field edges. ***Very high cost, average cost-effectiveness 103 -1036 $/tCO_2eq$ (Graus et al., 2004), average N_2O reduction efficiency 4%***

The following measures have been excluded from the MAC curve (due to overlap with the measures above and/or lower reduction potentials):

1. Controlled release fertilizer: Slow or controlled release fertilizers could increase recovery of N and minimize N losses to environment. ***Increased cost, average N_2O reduction efficiency 23%***

2. Optimizing timing of N application: Synchronous timing of N application or split application of N according to crop demand may reduce N loss, including N_2O emission. ***Increased cost, average N_2O reduction efficiency 7%***

3. Improved placement of N: Deep placement of N as compared to shallow placement particularly in reduced or no tillage system could decrease N_2O emission by 26%. In the US, improved N fertilizer placement was achieved through banding. ***Increased cost with requirement of specialized equipment and increased labour, average N_2O reduction efficiency 13%***

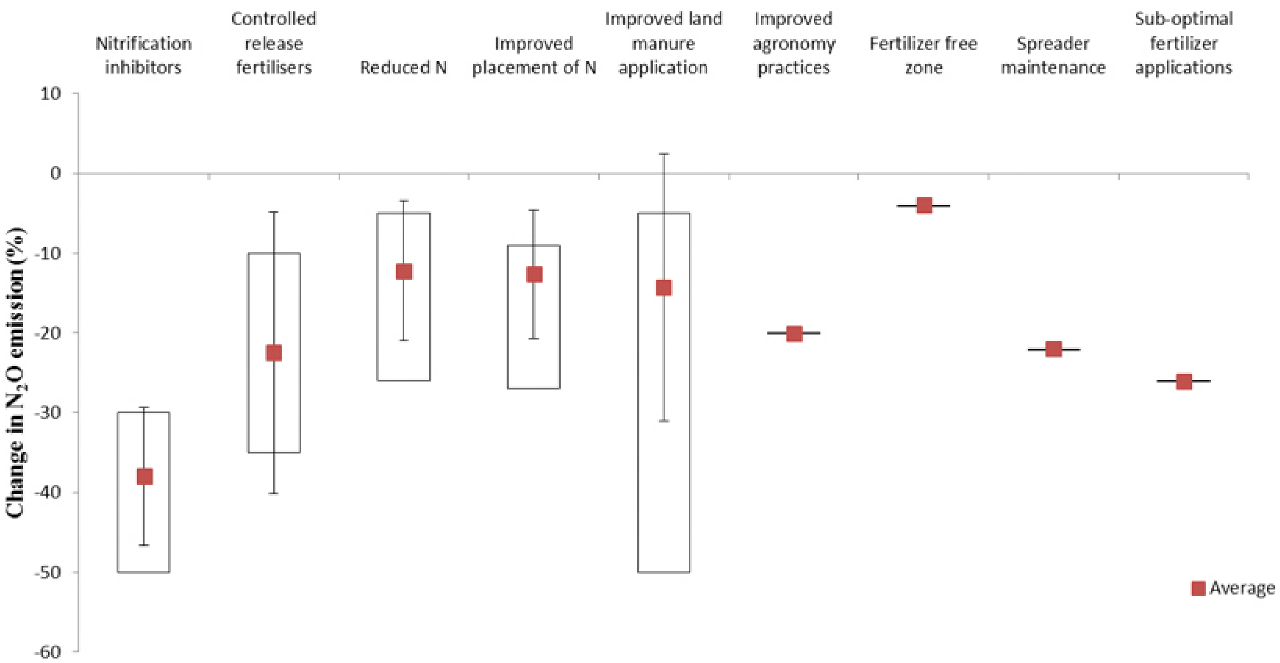

Figure 56; Reduction potential of different N_2O fertilizer mitigation measures.

10.3.2 MEASURES INTERACTION

	FERTILIZER FREE ZONE	SUBOPTIMAL FERTILIZER APPLICATION	SPREADER MAINTENANCE	NITRIFICATION INHIBITORS	CONTROLLED RELEASE FERTILIZER	OPTIMIZING TIMING OF N APPLICATION	IMPROVED PLACEMENT OF N	IMPROVED LAND MANURE APPLICATION	REPLACE UREA WITH AMMONIUM SULPHATE	IMPROVED AGRONOMY PRACTICES
FERTILIZER FREE ZONE										
SUB-OPTIMAL FERTILIZER APPLICATION	N									
SPREADER MAINTENANCE	N	M								
NITRIFICATION INHIBITORS	N	L	L							
CONTROLLED RELEASE FERTILIZER	N	L	L	H*						
OPTIMIZING TIMING OF N APPLICATION	N	N	L	N	M					
IMPROVED PLACEMENT OF N	N	L	L	N	M	N				
IMPROVED LAND MANURE APPLICATION	N	L	N	N	N	M	M			
IMPROVED AGRONOMY PRACTICES	N	M	L	L	L	L	L	N		

H: High, indicates strong interaction, may not be able to do together, if applied together mitigation potential for the second measure could be only 20% of the real potential (Interaction factor = 0.2).

M: Medium interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

L: low level interaction, can be practised together, if applied together mitigation potential for the second measure could be only 70% of the real potential (Interaction factor = 0.7).

N: No interaction, can be used together, mitigation potential are additive, if applied together mitigation potential for the second measure could be 100% of the real potential (Interaction factor = 1).

10.3.3 MAC CURVE FOR N_2O FERTILIZER USE

MACC N_2O Fertilizer – USA & Canada

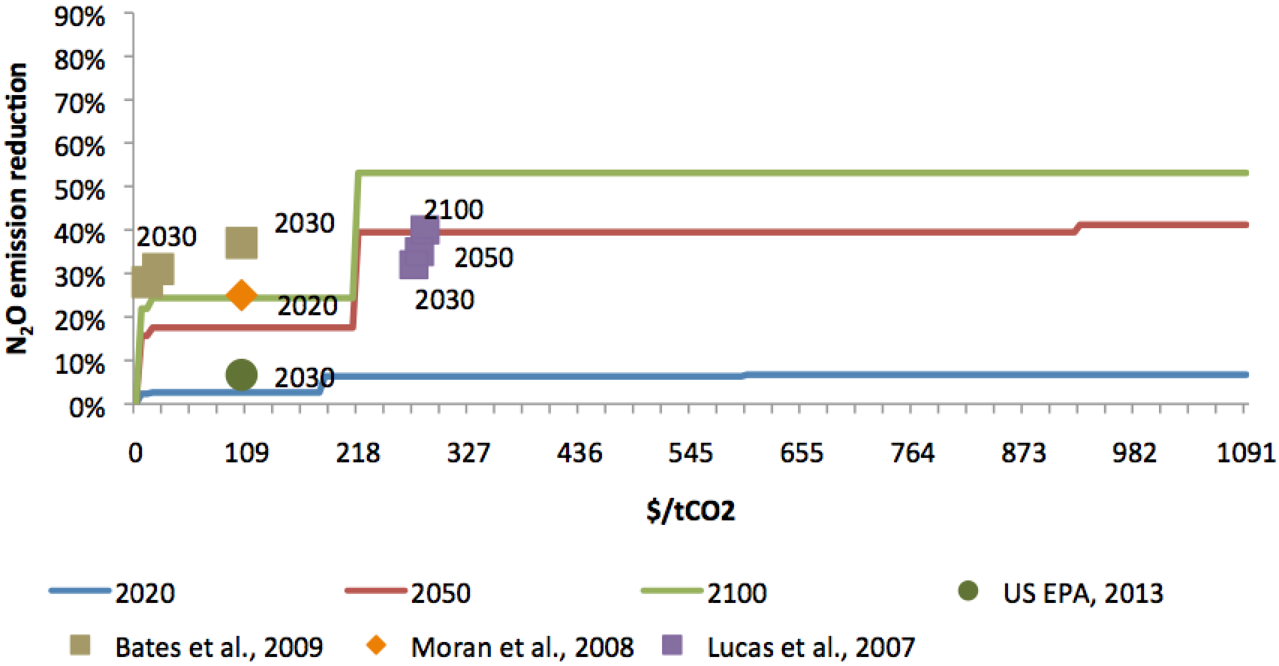

Figure 57; MAC curve for fertilizer N_2O for USA & Canada.

MACC N_2O Fertilizer – Eastern Europe & Former USSR

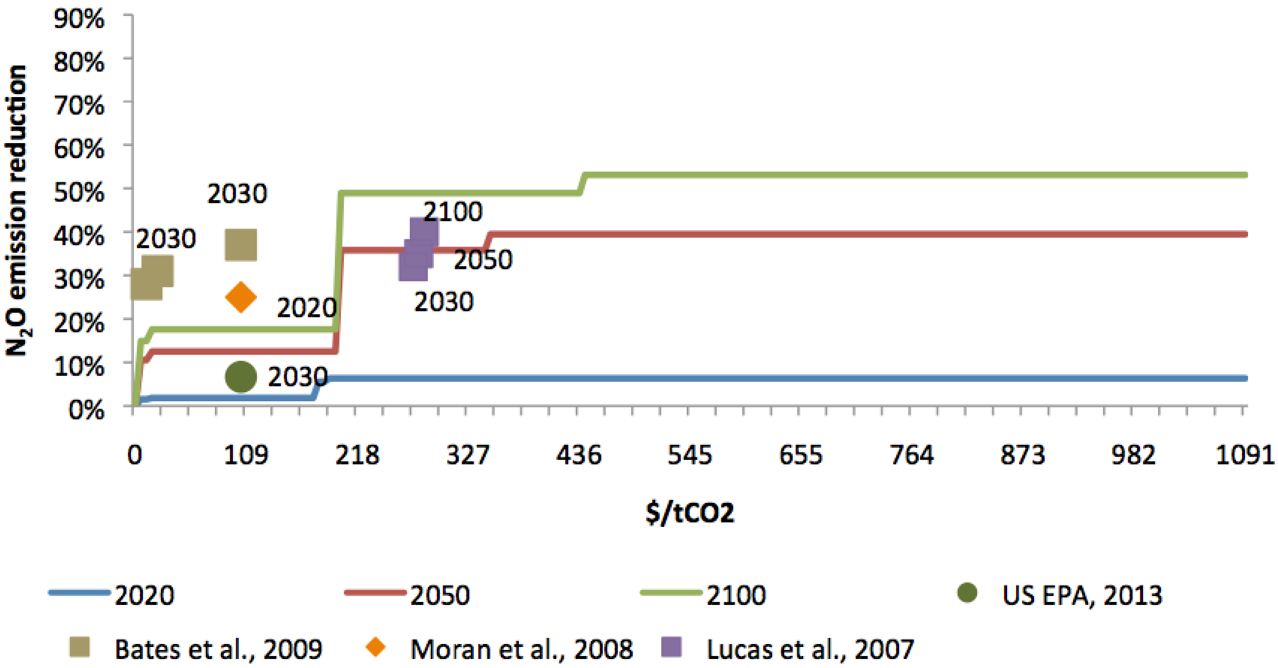

Figure 58; MAC curve for fertilizer N_2O for Eastern Europe and former USSR.

MACC N_2O Fertilizer – South, South East Asia

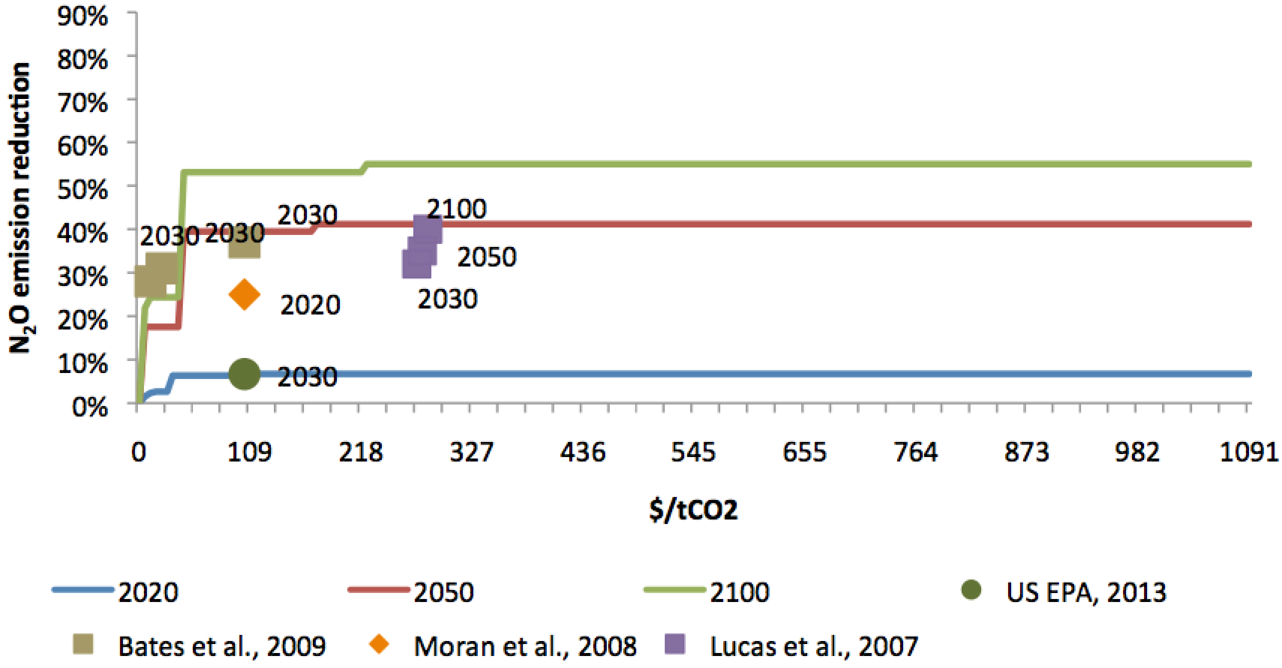

Figure 59; MAC curve for fertilizer N_2O for South Asia and South East Asia.

MACC N_2O Fertilizer – South and Central America

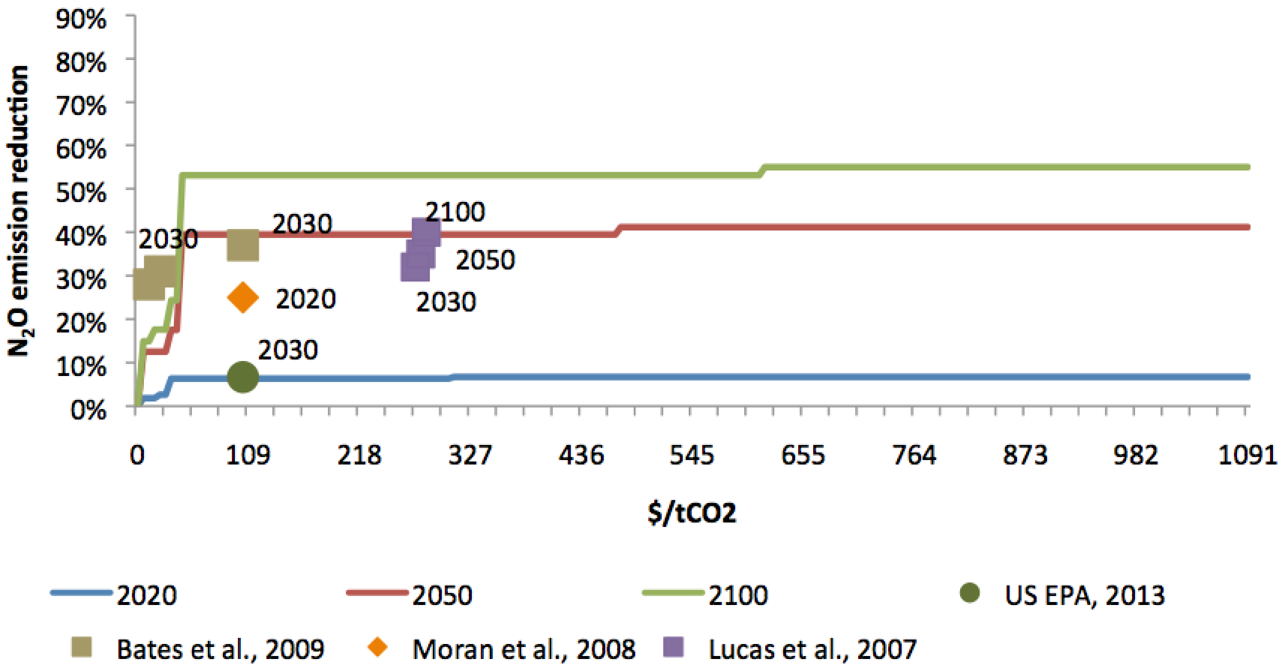

Figure 60; MAC curve for fertilizer N_2O for South America and Central America.

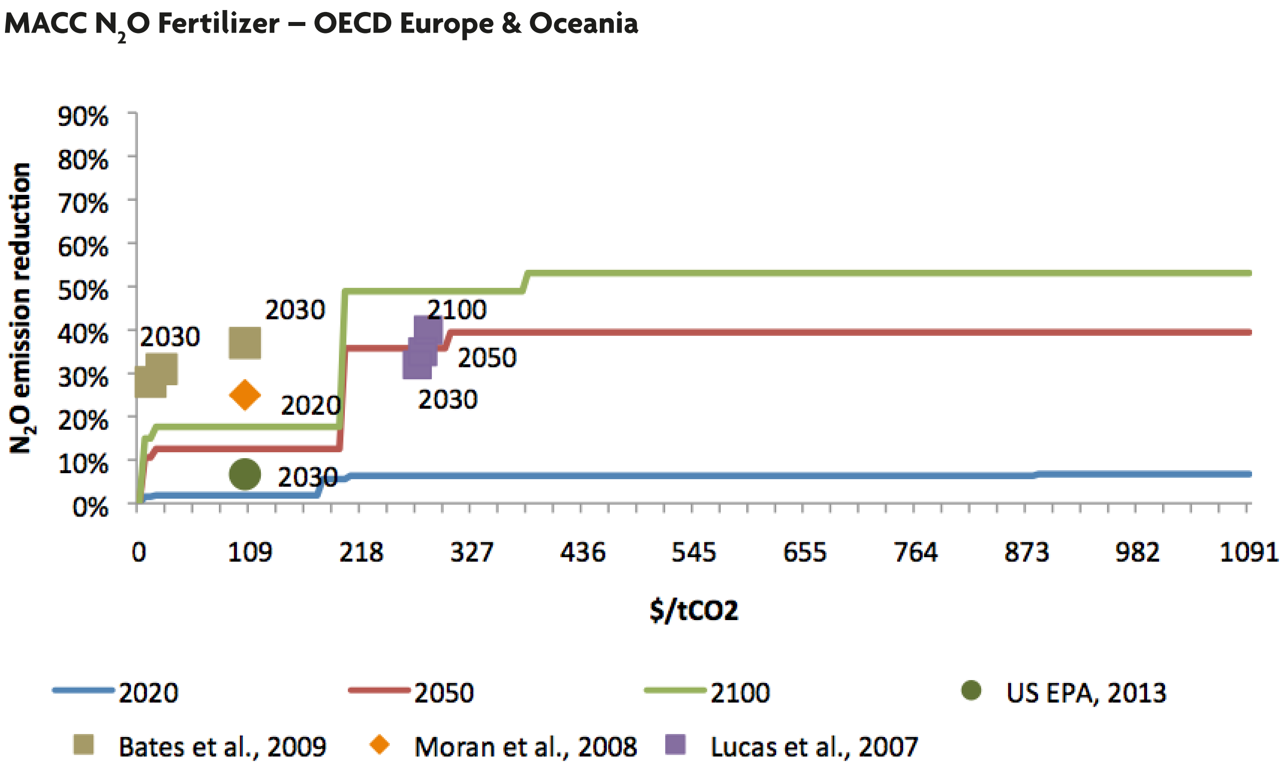

Figure 61; MAC curve for fertilizer N_2O for Europe & Oceania.

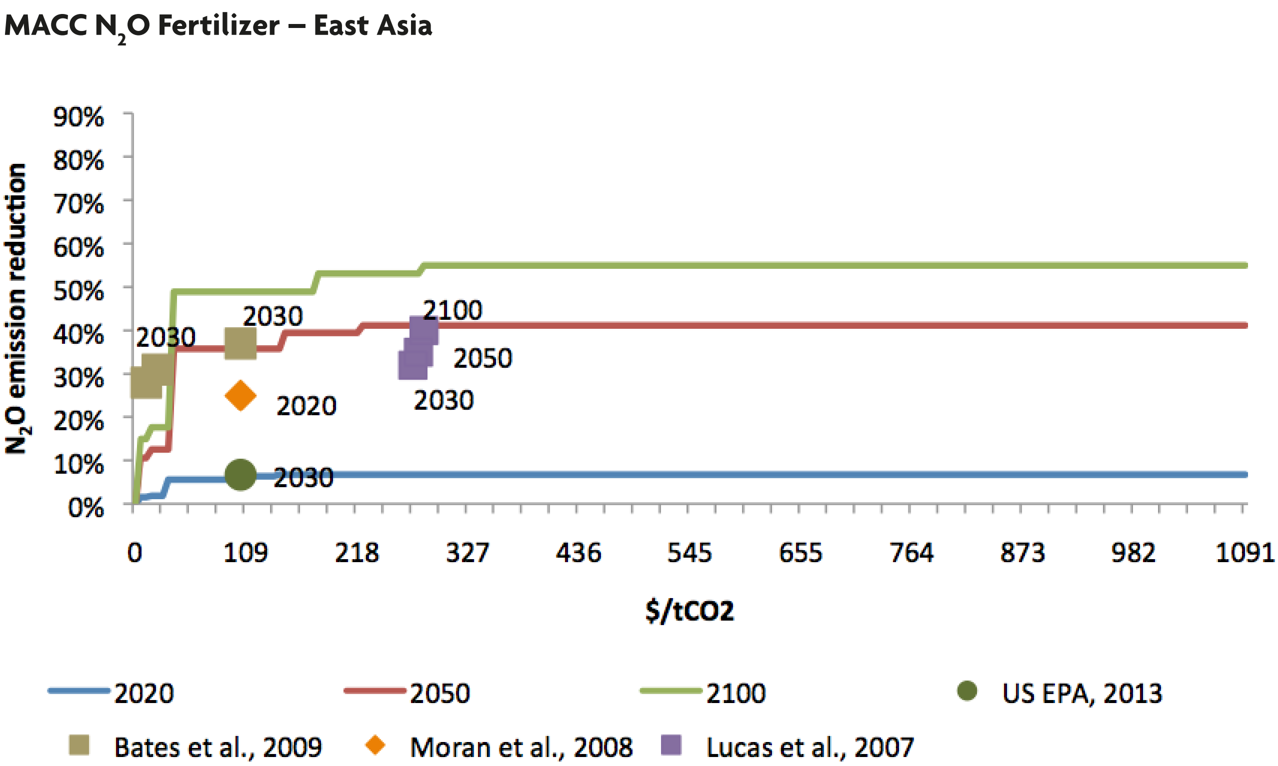

Figure 62; MAC curve for fertilizer N_2O for East Asia.

MACC N_2O Fertilizer – Africa

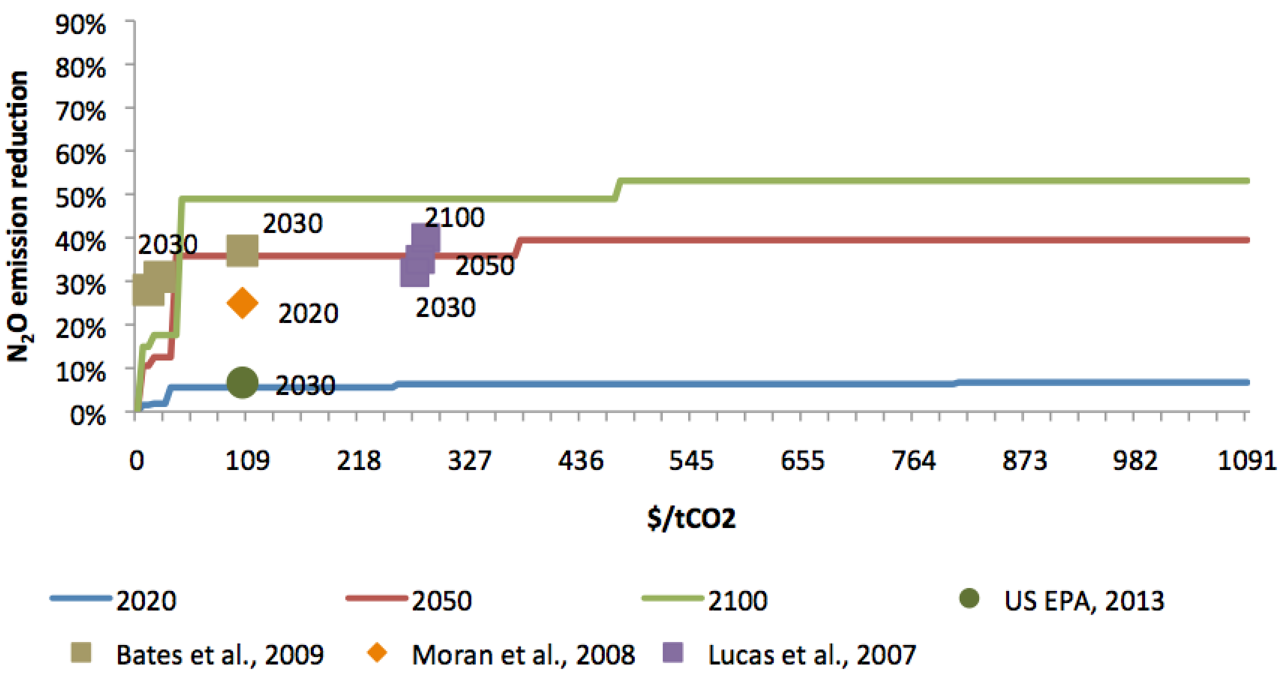

Figure 63; MAC curve for fertilizer N_2O for Africa.

MACC N_2O Fertilizer – Japan

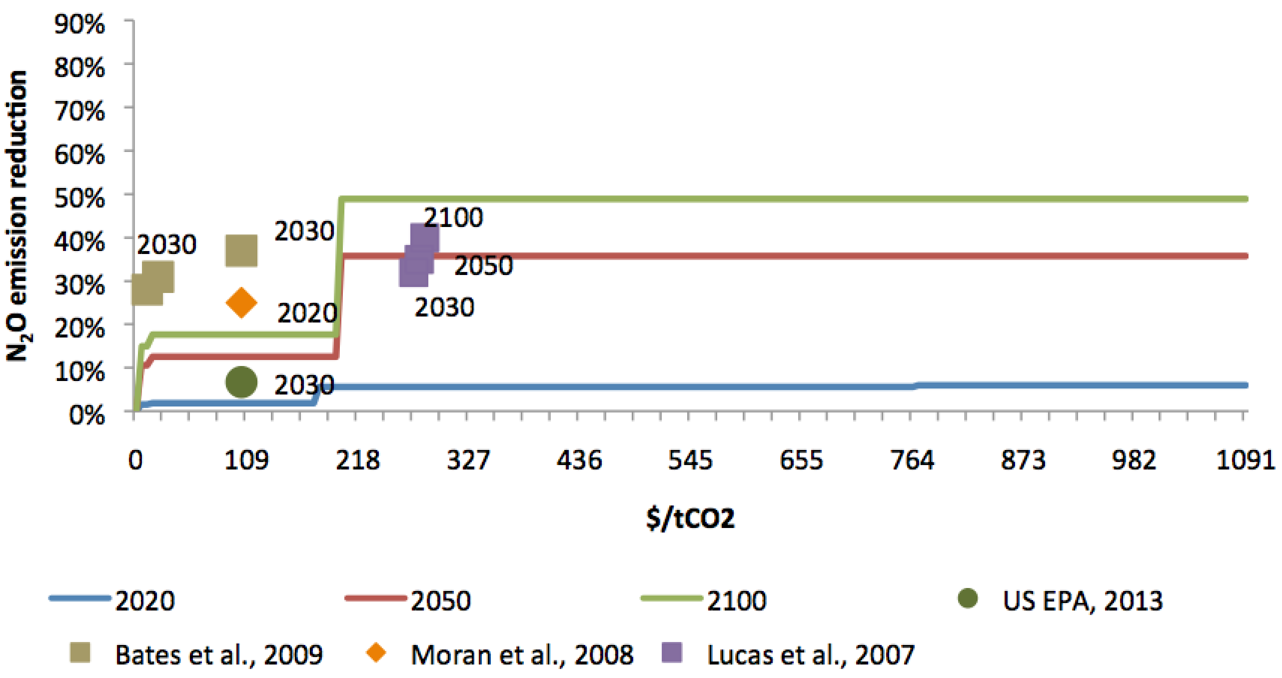

Figure 64; MAC curve for fertilizer N_2O for Japan.

10.4 MAC CURVE FOR ENTERIC CH_4

10.4.1 MITIGATION OPTIONS FOR ENTERIC CH_4

1. Nitrate: Addition of electron receptors such as nitrate may reduce CH_4 emission by 30 to 50% and increase productivity. ***Low to moderate cost, average cost-effectiveness 107 $/tCO_2eq (Eory et al., 2015), average CH_4 reduction efficiency 40%.***

2. Tannins: Plant extracts such as tannins or saponins are very effective in reducing rumen CH_4 emission. ***Low cost, average cost-effectiveness 15 $/tCO_2eq (McKinsey, 2009), average CH_4 reduction efficiency 14%.***

3. Grain processing: Improving starch digestibility of grain through mechanical processing such as steam flaking instead of dry rolling may reduce CH_4 emission by 10%. This also improves productivity. ***Low to moderate cost, average cost-effectiveness 50 $/tCO_2eq (No data, estimated value used), average CH_4 reduction efficiency 10%.***

4. Increase milk production per animal by 20% by altering nutrition. ***Negative cost, average costeffectiveness 0 $/tCO_2eq (Graus et al., 2004), average CH_4 reduction efficiency 22%***

5. Improved health monitoring and illness prevention or Prevention. Controlling or eradicating endemic livestock diseases. ***Small to medium economic benefit, negative cost, average cost-effectiveness 0 $/tCO_2eq (Eory et al., 2015; McKinsey, 2009), average CH_4 reduction efficiency 15%.***

6. Reduce herd size by 20% while maintaining beef production (only in US/Canada). ***Negative cost, average cost-effectiveness 0 $/tCO_2eq (Graus et al., 2004), average CH_4 reduction efficiency 9%***

7. Skipping the stocker phase: placing young cattle directly into the feedlot rather than allowing them to develop for a few years in a stocker program (only in US/Canada). ***Low cost, average cost-effectiveness 0-16 $/tCO_2eq (Graus et al., 2004), average CH_4 reduction efficiency 41%***

The following measures have been excluded from the MAC curve (due to overlap with the measures above and/or lower reduction potentials):

1. Antibiotics: Addition of antibiotics or ionophores such as Monensin to diet may reduce CH_4 emission by <10%. Monensin is banned in Europe but it is normally used in beef production system in North America. Ionophores improve feed efficiency. ***Moderate cost, average CH_4 reduction efficiency 15%.***

2. Improved feeding practices: Includes replacing roughage with concentrate, improving forages/inclusion of legumes and feeding extra dietary oil. ***Low to moderate cost, average CH_4 reduction efficiency 9%.***

3. Precision feeding: Accurate prediction of animal requirements and accurate feed analyses go hand-in-hand with minimizing feed waste, maximizing production, and minimizing GHG emissions per unit of animal product. ***Moderate to high cost, average CH_4 reduction efficiency 20%.***

4. Longer term management changes and animal breeding: Increasing productivity through breeding and better management practices spreads the energy cost of maintenance across a greater feed intake, often reducing methane output per kilogram of animal product. ***Moderate cost, average CH_4 reduction efficiency 3%.***

5. Enhance milk production by use of metabolic modifier: bovine somatrotropin. Non-Dairy production. ***Very low cost, average CH_4 reduction efficiency 3%***

6. Increase the body weight of cattle at time of slaughter. ***Very high cost, average CH_4 reduction efficiency 5%***

7. Intensive grazing: change the feeding to include grazing in pasture rather than all processed feed mixture. ***Very low cost, average CH_4 reduction efficiency 13%***

8. Increasing level of feed intake to change volatile fatty acid (VFA) in rumen to generate more propionate with improved genetics. ***Very low cost, average CH_4 reduction efficiency 9%***

9. Increased Conversion Efficiency - High Fat Diet: Addition of fats to diet meets energy requirements and increases propionate in rumen. Very low cost, average CH_4 reduction efficiency 5%

10. Increased Conversion Efficiency: Include more non-structural carbohydrates in concentrate; leads to lower rumen pH. ***Very low cost, average CH_4 reduction efficiency 10%***

11. Increased Conversion Efficiency - Replace roughage with concentrates: Replacement of roughage that contains high portions of structural carbohydrates with concentrates to improve propionate generation in rumen ***Very low cost, average CH_4 reduction efficiency 8%***

12. Increased rumen efficiency: Addition of propionate precursors in daily supplements. ***Medium high cost, average CH_4 reduction efficiency 15%***

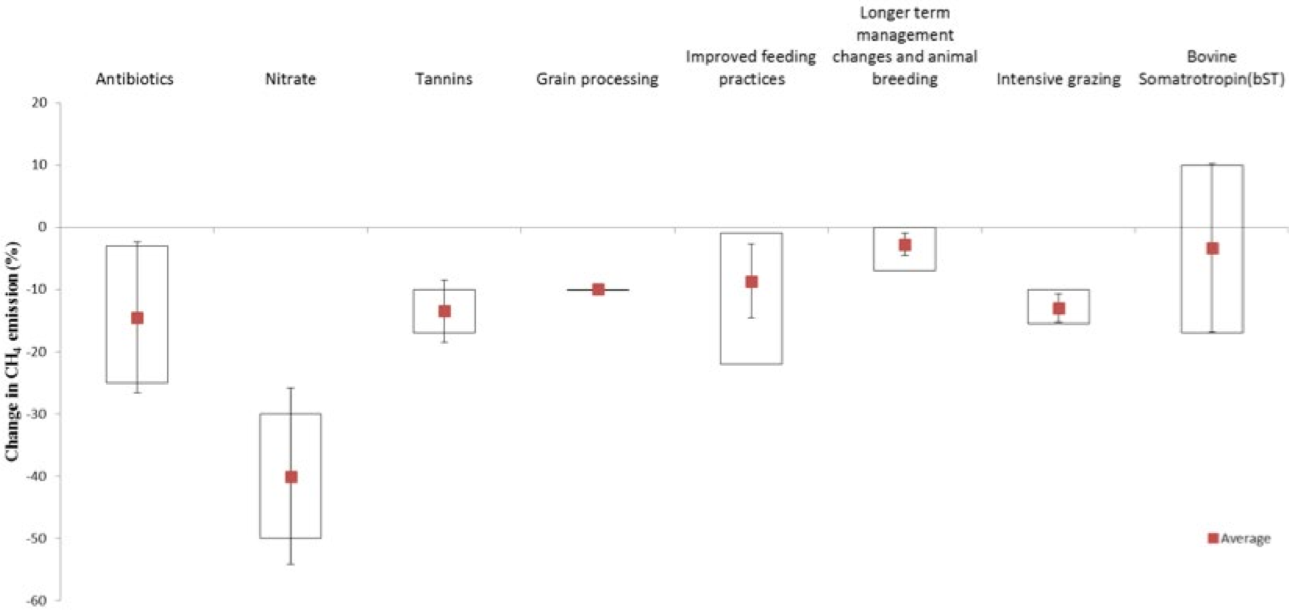

Figure 65; reduction potential of different CH_4 mitigation measures for enteric fermentation.

10.4.2 MEASURES INTERACTION

	IMPROVED FEED INTAKE AND GENETICS	HIGH FAT DIET	MORE NONSTRUCTURAL DIET	REPLACE ROUGHAGE WITH CONCENTRATE	PROPIONATE PRECURSORS	ANTIBIOTICS	NITRATE	TANNINS	FEED PROCESSING	IMPROVED HEALTH MONITORING	EXTENDED PRODUCTIVE LIFE	SKIPPING STOCKER PHASE (US/CANADA)	REDUCED HERD SIZE BY 20% (US/CANADA)
IMPROVED FEED INTAKE AND GENETICS													
HIGH FAT DIET	M												
MORE NON-STRUCTURAL DIET	M	H											
REPLACE ROUGHAGE WITH CONCENTRATE	M	H	H*										
PROPIONATE PRECURSORS	M	H	H	H									
ANTIBIOTICS	M	H	H	H	H								
NITRATE	H	H	H	H	H	H							
TANNINS	H	M	M	M	M	H	H						
GRAIN PROCESSING	M	M	M	M	M	H	H	M					
IMPROVED HEALTH MONITORING	L	M	L	L	L	M	L	L	L				
EXTENDED PRODUCTIVE LIFE	H	M	L	L	L	L	L	L	L	M			
SKIPPING STOCKER PHASE (US/CANADA)	M	M	M	M	M	M	N	N	N	N	H		
REDUCED HERD SIZE BY 20% (US/CANADA)	L	L	L	L	L	L	L	L	L	L	L	L	
INCREASE MILK PRODUCTION	L	L	L	L	L	L	L	L	L	M	L	L	L

H: High, indicates strong interaction, may not be able to do together, if applied together mitigation potential for the second measure could be only 20% of the real potential (Interaction factor = 0.2).

M: Medium interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

L: low level interaction, can be practised together, if applied together mitigation potential for the second measure could be only 70% of the real potential (Interaction factor = 0.7).

N: No interaction, can be used together, mitigation potential are additive, if applied together mitigation potential for the second measure could be 100% of the real potential (Interaction factor = 1).

10.4.3 MAC CURVE FOR CH_4 ENTERIC FERMENTATION

MACC CH_4 enteric – USA & Canada

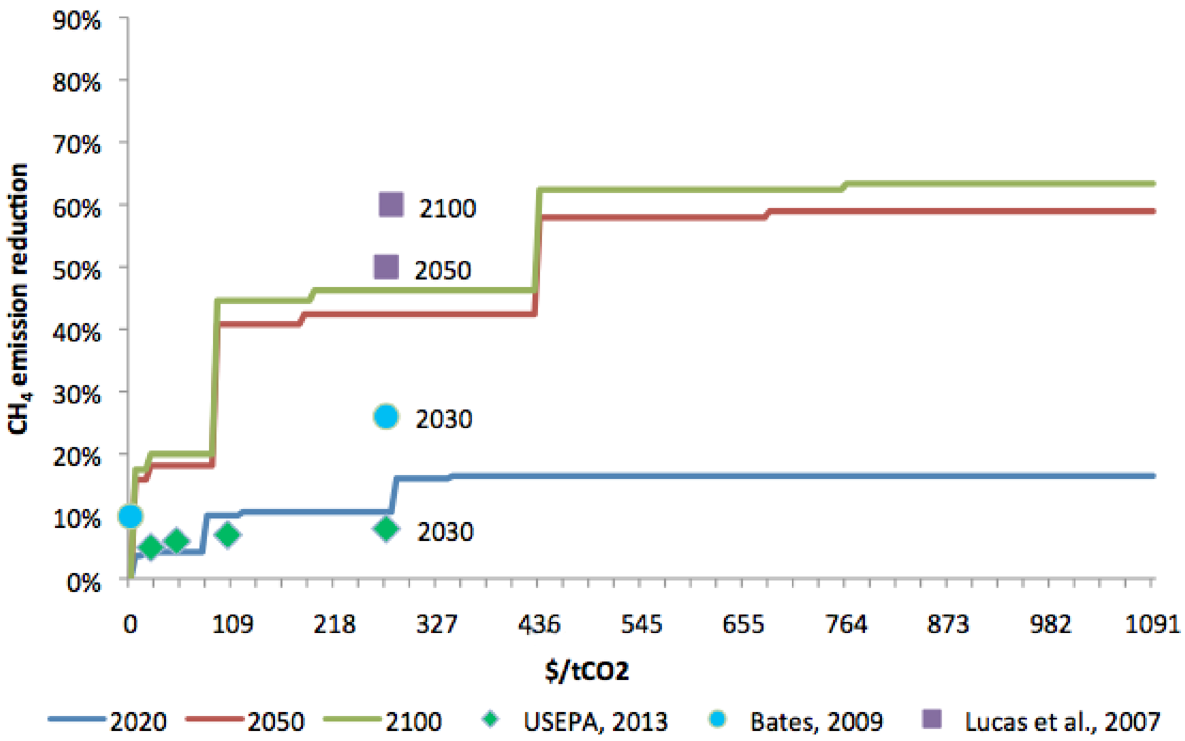

Figure 66; MAC curve for enteric fermentation for Canada and USA.

MACC CH_4 enteric – Rest of the World

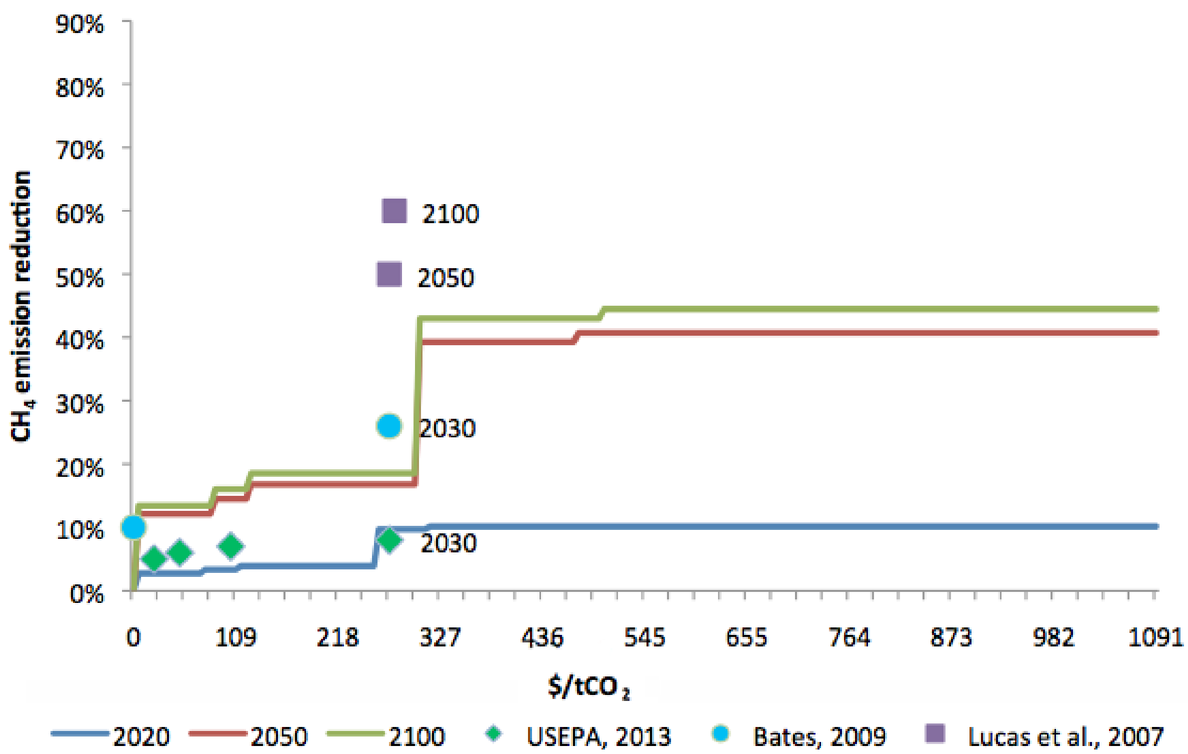

Figure 67; MAC curve for enteric fermentation for Rest of the world.

10.5 MAC CURVE FOR MANURE CH_4

10.5.1 MITIGATION OPTIONS FOR MANURE CH_4

The mitigation measures that have been used to construct the MAC curve are the following (taking into account overlap between measures and aiming for the highest MRP:

1. Farm scale digesters: Application of anaerobic digester for small-scale farm systems. The biogas generated from anaerobic digestion is used to produce heat or both heat and electricity. ***Medium high cost, average cost-effectiveness 0-52 \$/tCO_2eq (Graus et al., 2004), average CH_4 reduction efficiency 75% (warm climates), 50% (cool climates)***

2. Decreased manure storage time: Reduced storage time through frequent land application to avoid the anaerobic conditions that create CH_4; can also reduce N_2O emissions depending on application timing. ***Low to medium cost, average cost-effectiveness 30 \$/tCO_2eq (No data, estimated value used), average CH_4 reduction efficiency 35%***

3. Manure storage covering: Covering manure storages with permeable or impermeable covers is an effective mitigation practice. However with an impermeable cover the CH_4 captured under the cover is burned using a flare system or engine-generator to produce electricity; otherwise the captured CH_4 would build pressure inside the storage creating an explosion hazard and/or escape through leaks and cover ruptures. ***Low cost, average costeffectiveness 70 \$/tCO_2eq (Weiske and Michel., 2007), average CH_4 reduction efficiency 30%***

4. Housing systems and bedding: Concrete slatted floors with drainage/flush systems result in fewer emissions than solid floors with hay or other bedding may reduce both CH_4 and N_2O emission. ***Medium cost, average cost-effectiveness 149 \$/tCO_2eq (Weiske and Michel., 2007), average CH_4 reduction efficiency 35%.***

5. Manure acidification: Manure acidification decreases NH_3 volatilization by 14 to 100%. Ammonia volatilization is directly proportional to the proportion of NH_3-N in the total ammoniacal nitrogen (TAN) in manure. At constant temperature, the dissociation constant (Kd), which is a function of medium pH, determines the equilibrium between ammonium and NH_3 in aqueous systems. ***Lower manure pH results in lower proportion of NH_3 and, therefore, decreased potential of NH_3 volatilization. Average cost-effectiveness 83 \$/tCO_2eq (Eory et al, 2015), average CH_4 reduction efficiency 77%.***

The following measures have been excluded from the MAC curve (due to overlap with the measures above and/or lower reduction potentials):

1. Manure composting: Composting of animal manure causes significant N and CO_2 losses, but the benefits of reducing odour and CH_4 emissions, compared with anaerobically-stored manure, make it a recommended GHG mitigating option. Nitrogen losses, predominantly as NH_3 but also as N_2O, however, are large. ***Moderate cost, average CH_4 reduction efficiency > 30%.***

2. Animal Husbandry: Improved health monitoring and illness prevention or Prevention, control and eradication of diseases: Controlling or eradicating endemic livestock diseases represents an opportunity to reduce emission intensity of livestock products without compromising productivity. Identification and prioritization of region specific target diseases, estimating their abatement potential and cost would be important to assess contribution of this mitigation measure to reduce GHG emission from global livestock sector. ***Small to medium economic benefit, average CH_4 reduction efficiency 15%.***

3. Animal Husbandry: Improved productive life: Extending productive lifetime of animals can decrease total GHG emissions per total product over the animal's lifetime and is already classified as a best practice (Joint report by GRA and SAI). Different approaches include improved conception rates, earlier time of first reproduction and increasing reproductive lifetime, and adjusting overall lifetime to minimise overall GHG emissions per unit of product (which implies increasing longevity for dairy cows, but also reducing time to slaughter for beef cattle through higher growth rates). ***Small economic benefit, average CH_4 reduction efficiency 10%.***

4. Animal Husbandry: Improving animal productivity and reducing herd size: In most part of the world, the single most effective GHG mitigation strategy is to increase animal productivity while reducing the herd size aiming the same amount of edible product output. The two major constrains for increasing animal productivity is the genetic potential of the animals and availability of quality feed. The genetic production potential of an animal can be achieved through planned cross breeding or selection within breeds and proper nutrition. ***Average CH_4 reduction efficiency ≥30%***

10.5.2 MEASURES INTERACTION

	DIGESTER (AVERAGE VALUE GRAUS ET AL)	DECREASE MANURE STORAGE TIME	MANURE STORAGE COVERING	HOUSING AND BEDDING	MANURE ACIDIFICATION	MANURE COMPOSTING
DIGESTER						
DECREASE MANURE STORAGE TIME	N					
MANURE STORAGE COVERING	M	M				
HOUSING AND BEDDING	N	M	M			
MANURE ACIDIFICATION	L	N	N	N		
MANURE COMPOSTING	L	N	N	N	L	

H: High, indicates strong interaction, may not be able to do together, if applied together mitigation potential for the second measure could be only 20% of the real potential (Interaction factor = 0.2).

M: Medium interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

L: low level interaction, can be practised together, if applied together mitigation potential for the second measure could be only 70% of the real potential (Interaction factor = 0.7).

N: No interaction, can be used together, mitigation potential are additive, if applied together mitigation potential for the second measure could be 100% of the real potential (Interaction factor = 1).

10.5.3 MAC CURVE FOR CH_4 ANIMAL WASTE

MACC CH_4 animal waste – Canada

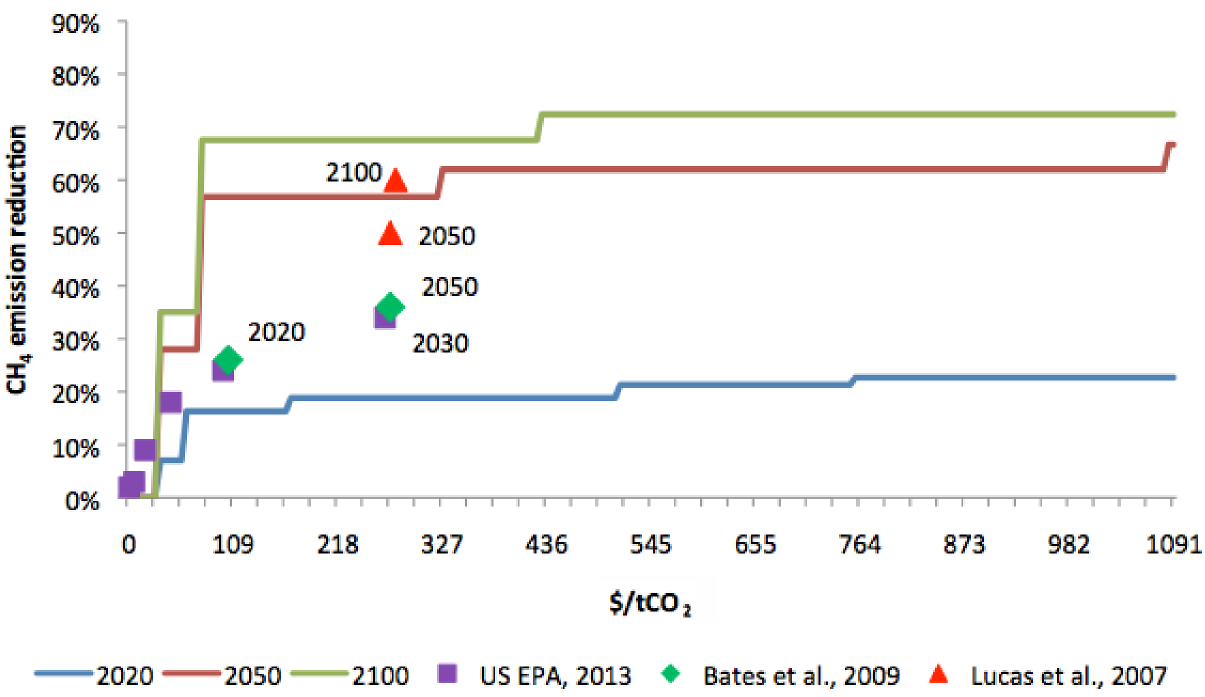

Figure 68; MAC curve for animal waste CH_4 in Canada.

MACC CH_4 animal waste – USA

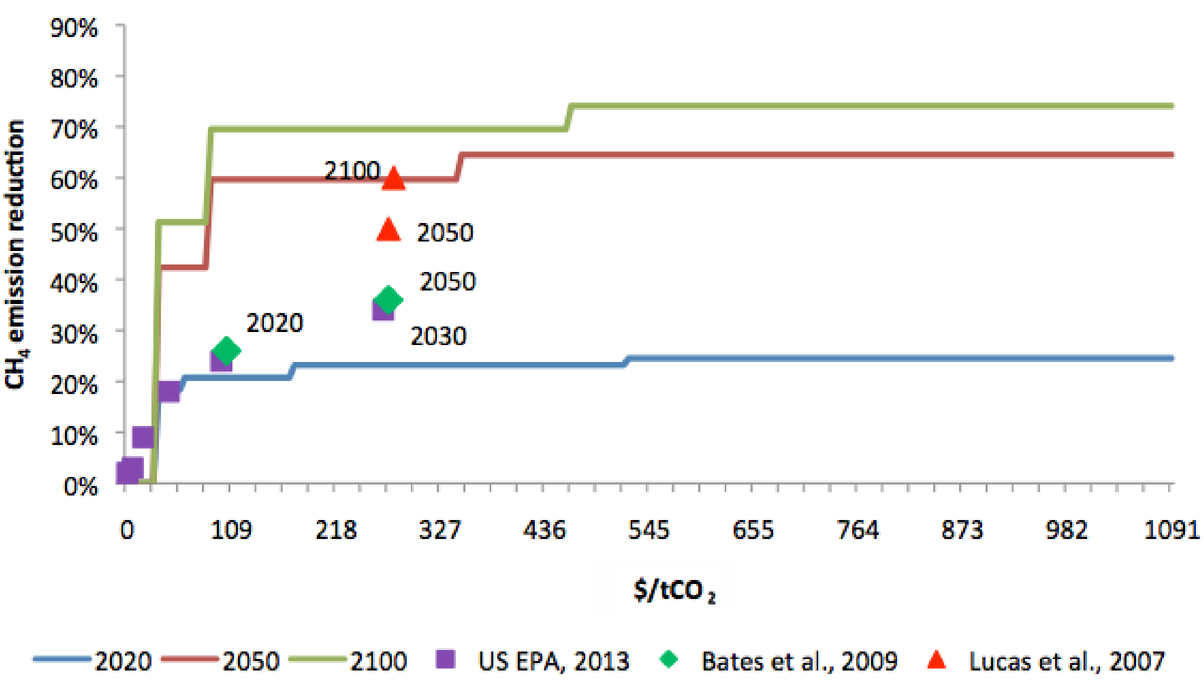

Figure 69; MAC curve for animal waste CH_4 in USA.

MACC CH_4 animal waste – East EU

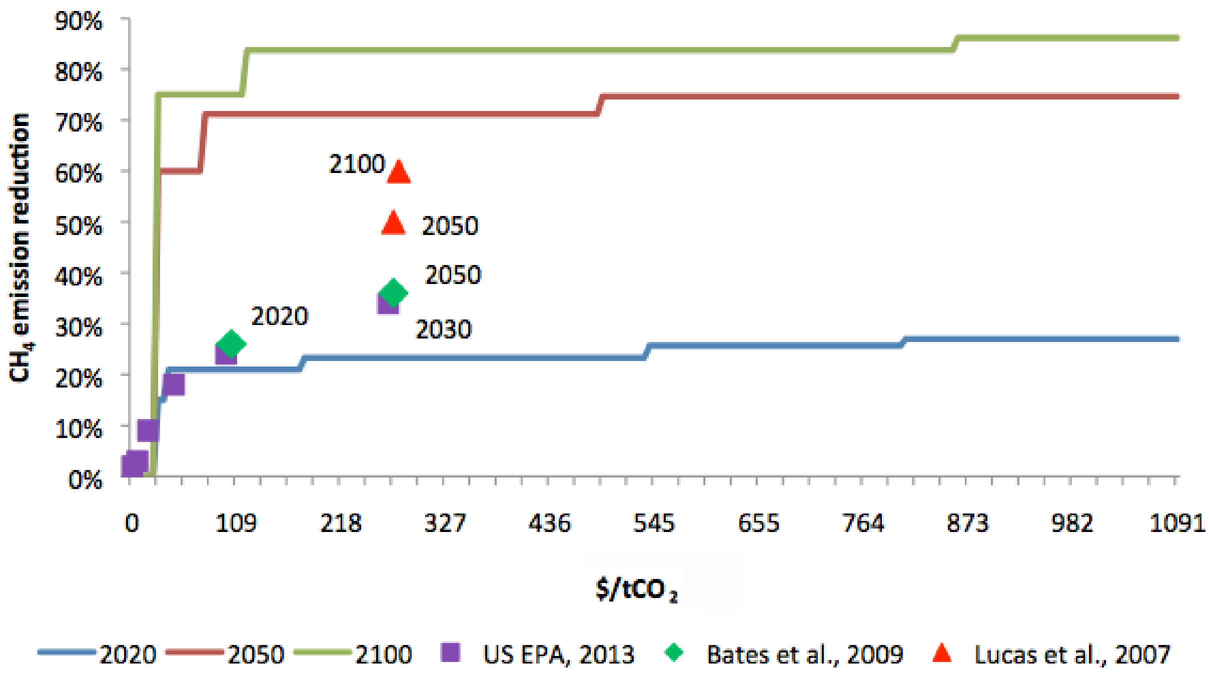

Figure 70; MAC curve for animal waste CH_4 in Eastern Europe.

MACC CH_4 animal waste – Ukr / Kaz / Rus

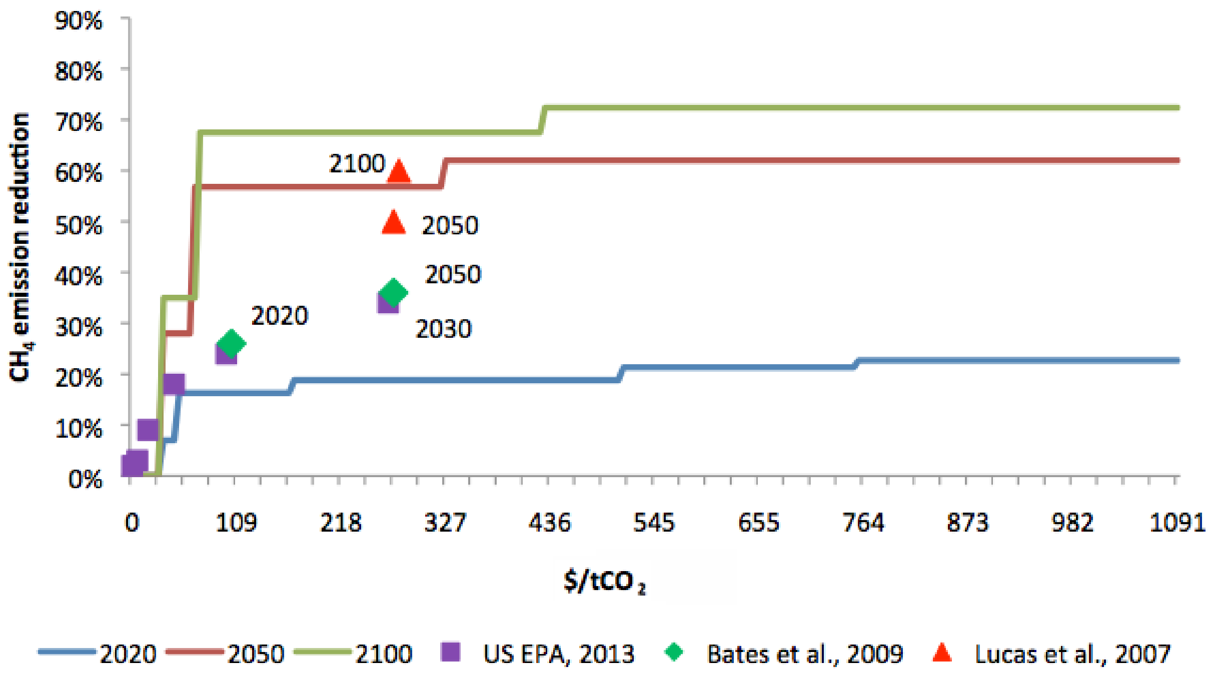

Figure 71; MAC curve for animal waste CH_4 in Ukraine, Kazakhstan and Russia.

MACC CH_4 animal waste – India / Indo / SEA

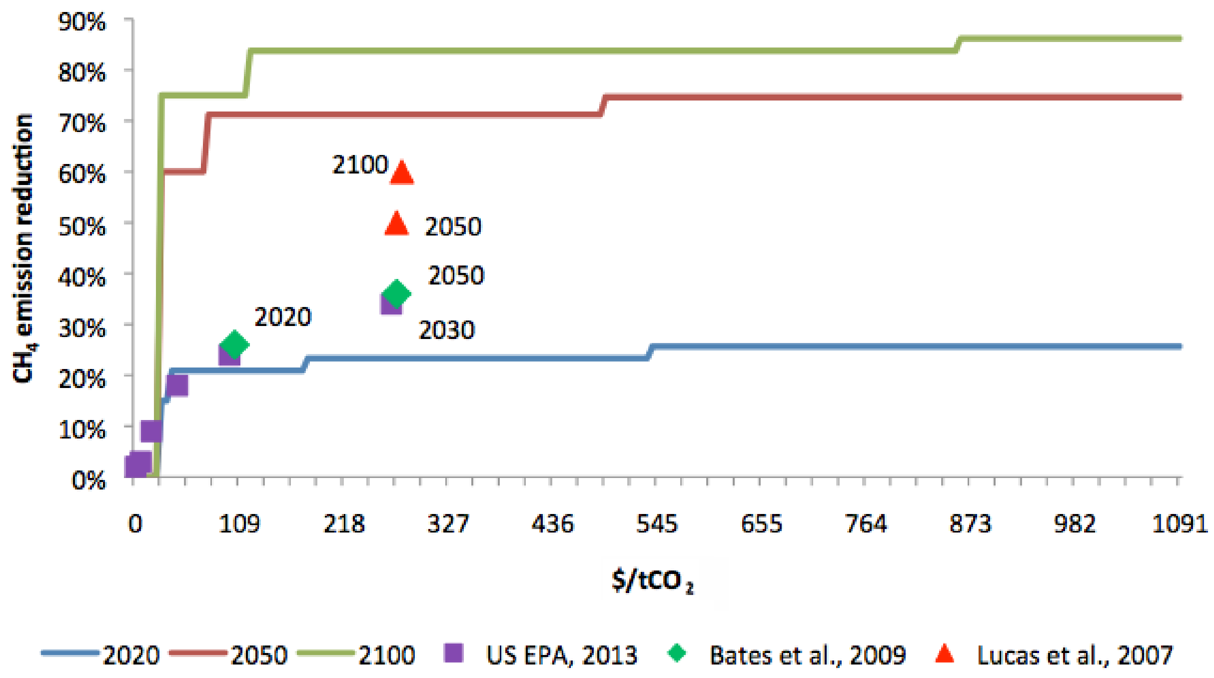

Figure 72; MAC curve for animal waste CH_4 in India, Indonesia and South East Asia.

MACC CH_4 animal waste – Rest of the World

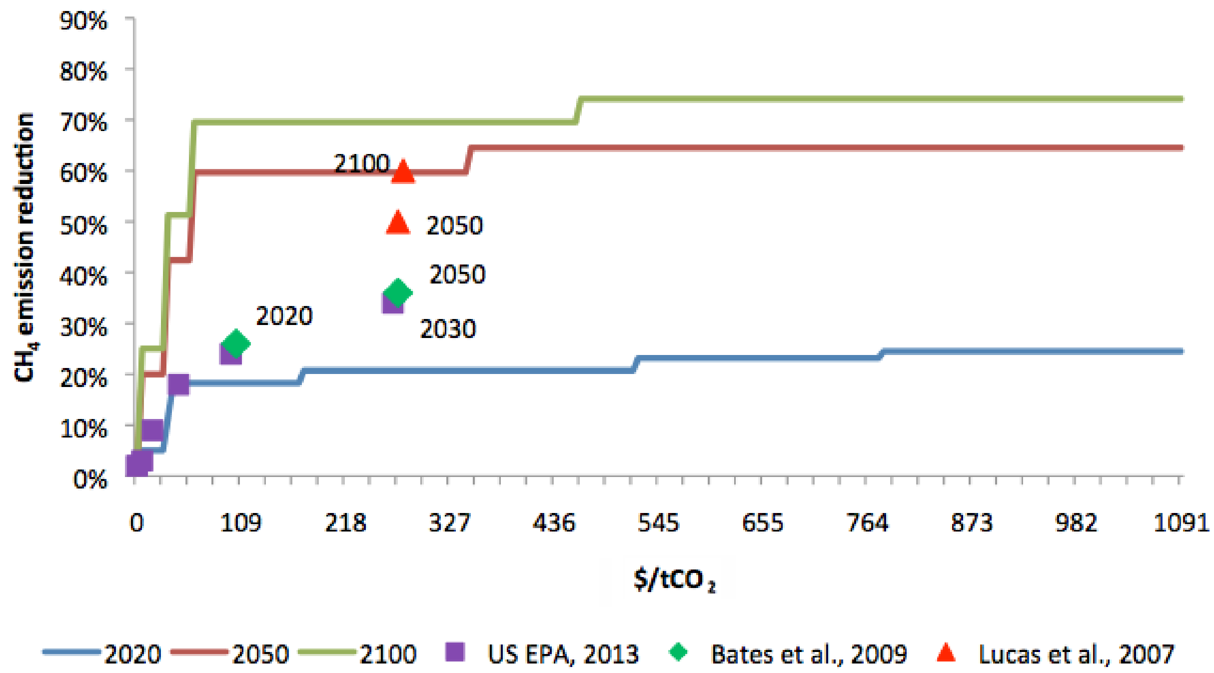

Figure 73; MAC curve for animal waste CH_4 in the rest of the world.

10.6 MAC CURVE FOR MANURE N_2O

10.6.1 MITIGATION OPTIONS FOR MANURE N_2O

The mitigation measures that have been used to construct the MAC curve are the following (taking into account overlap between measures and aiming for the highest MRP):

1. **Reduced dietary protein:** An important opportunity to reduce N_2O emissions from animal manure is to maintain dietary protein close to animal requirements. Studies with pigs, poultry, and beef and dairy cattle have consistently shown that a reduction in dietary protein results in a reduction of excreta N losses, which results in reduced NH_3 and potentially N_2O emissions from manure. ***Low cost, average cost-effectiveness 86 $/tCO$_2$eq (McKinsey, 2009), average N_2O reduction efficiency 25%.***

2. **Manure storage_ decreased storage time:** Reduced storage time through frequent land application to avoid the anaerobic conditions that create CH_4; can also reduce N_2O emissions depending on application timing. ***Low to medium cost, average costeffectiveness 32-177 $/tCO$_2$eq (No data, estimated value used), average N_2O reduction efficiency 35%***

3. **Manure storage_covering:** Covering manure storages with permeable or impermeable covers is an effective mitigation practice. However with an impermeable cover the CH_4 captured under the cover is burned using a flare system or engine-generator to produce electricity; otherwise the captured CH_4 would build pressure inside the storage creating an explosion hazard and/or escape through leaks and cover ruptures. Low cost, average costeffectiveness 70 $/tCO$_2$eq (Weiske and Michel., 2007), average N_2O reduction efficiency 30%

4. **Housing systems and bedding:** Concrete slatted floors with drainage/flush systems result in fewer emissions than solid floors with hay or other bedding may reduce both CH_4 and N_2O emission. ***Varies (depends on existing system), average cost-effectiveness 149 $/tCO$_2$eq (Weiske and Michel., 2007), average N_2O reduction efficiency 35%***

The following measure has been excluded from the MAC curve (due to overlap with the measures above and/or lower reduction potentials):

1. **Manure separation and composting of solid manure:** Separation of manure into liquid and solids and aerobically composting the solids has been shown to reduce CH_4 but may have a variable effect on N_2O emissions and will increase NH3 and total manure N losses. Estimated N_2O, average N_2O reduction efficiency 35%

10.6.2 MEASURES INTERACTION

	DECREASE MANURE STORAGE TIME	MANURE STORAGE COVERING	HOUSING AND BEDDING	REDUCED DIETARY PROTEIN
DECREASE MANURE STORAGE TIME				
MANURE STORAGE COVERING	M			
HOUSING AND BEDDING	N	M		
REDUCED DIETARY PROTEIN	N	N	N	

H: High, indicates strong interaction, may not be able to do together, if applied together mitigation potential for the second measure could be only 20% of the real potential (Interaction factor = 0.2).

M: Medium interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

L: low level interaction, can be practised together, if applied together mitigation potential for the second measure could be only 70% of the real potential (Interaction factor = 0.7).

N: No interaction, can be used together, mitigation potential are additive, if applied together mitigation potential for the second measure could be 100% of the real potential (Interaction factor = 1).

10.6.3 MAC CURVE FOR N_2O ANIMAL WASTE

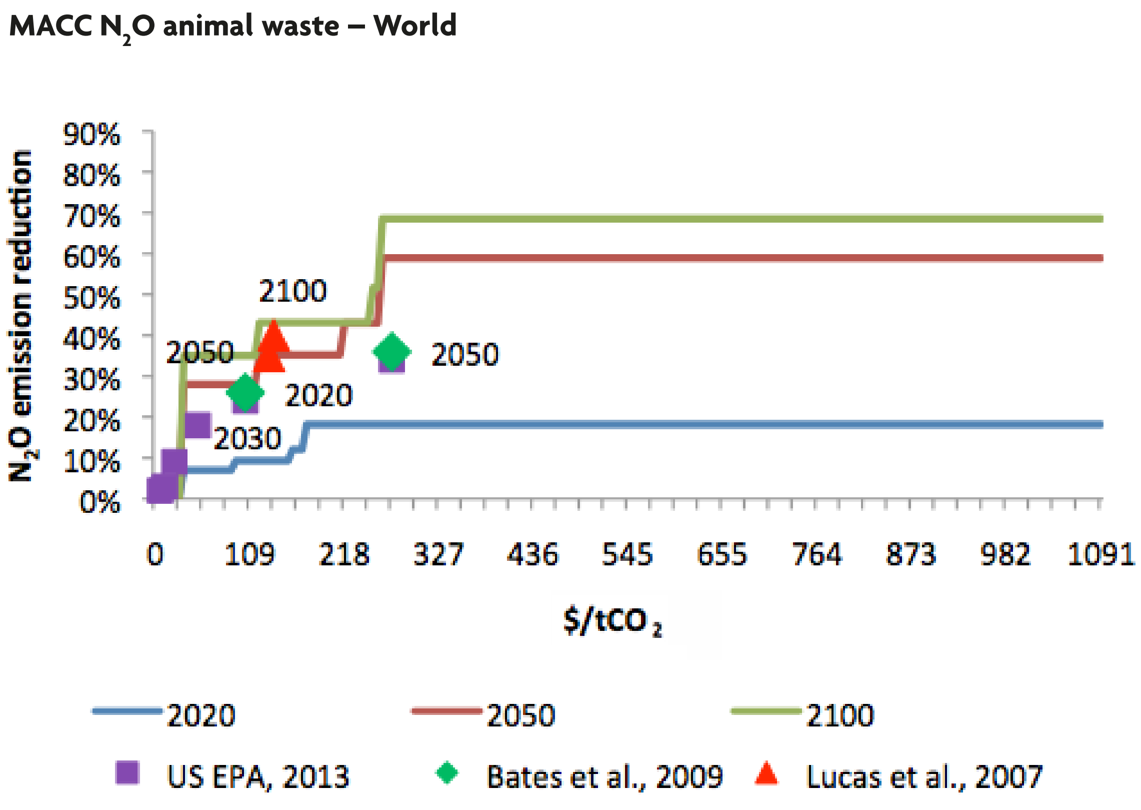

Figure 74; MAC curve for animal waste N_2O.

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