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The role of agriculture in global GHG mitigation

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THE ROLE OF AGRICULTURE IN GLOBAL GHG MITIGATION

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Agriculture is a major emitter of greenhouse gases. Its potential to contribute to limiting global warming to less than 2°C by the end of the century is substantial by reducing direct emissions in crop and livestock production, by reducing indirect emissions associated with changes in land use, and by increasing carbon sequestration. Technological advancements and changes in consumer preferences that result in land-sparing are particularly promising options given food security concerns. Gains in total factor productivity will also enhance the sector's competitiveness. Changes in domestic and trade policies are essential to maximize mitigation potential. In the absence of global application of carbon pricing, international co-ordination is needed to ensure that national mitigation efforts result in carbon reallocation, i.e. shifts in the location of production to low emissions sources. Measures of emissions relative to the economic contribution of agricultural activities can be insightful for identifying national mitigation priorities.

Keywords: Climate change, mitigation, global agriculture

JEL codes: Q01, Q18, Q54

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Executive Summary

Global efforts to contain climate change have concentrated on sectors generating carbon dioxide (CO₂) emissions. While CO₂ is the largest contributor to global warming, methane (CH₄) and nitrous oxide (N₂O), the non-CO₂ greenhouse gases (GHGs) directly emitted by the agricultural sector through crop and livestock production are also major contributors to increases in total atmospheric GHG concentrations and to climate change.

Agriculture is the largest emitter of methane and nitrous oxide, and is a major contributor to net CO₂ emissions through land use in agricultural production and land-use changes, via CO₂ sinks (e.g. forests, organic soils) cleared for agricultural activities. Agriculture's direct and indirect emissions associated with land uses are accounted for under the agriculture, forestry, and other land uses (AFOLU) sector.

Taken together, emissions in AFOLU include non-CO₂ GHGs from agriculture, net emissions of CO₂ from the soils used in agriculture, and net CO₂ emissions from forests and other land uses (FOLU). Negative emissions derive from carbon uptake from the atmosphere and sequestration in soils and FOLU. Agriculture largely determines net emissions from soils and FOLU.

AFOLU emissions grow as a result of expansion in agricultural land area, increases in livestock numbers, and more intensive use of inputs, such as soil and fertilizers. These all lead to higher agricultural output. The rate of growth of emissions relative to the growth in agricultural output defines the impact on emissions intensity. Livestock, and especially ruminants, are the largest source of agriculture's direct emissions and a major cause of land-use change. Synthetic fertilizers are also a large contributor to agriculture's direct emissions and are the fastest growing source of those emissions.

Developing countries are the largest and the fastest growing source of global AFOLU emissions, where direct emissions from agriculture show a strong upward trend. Despite deceleration in deforestation in recent years, land use is still a significant net emitter. The growth in ruminant emissions in the developing world is due to dietary changes caused by income growth, agricultural land expansion, and cultural factors such as the prohibition on slaughtering cattle in India and the accumulation of ruminant animals as a source of wealth in Africa. Differences in emissions drivers among regions underline the necessity for regional approaches to mitigation.

In developed countries, AFOLU emissions have been declining in recent years, and direct emissions from agriculture show a slight downward trend. Land-use change (afforestation) has made a net contribution to carbon sequestration. Developed countries have benefited from input-conserving technical change that has reduced emissions per unit of output.

The contribution of agriculture to climate change is expected to increase relative to other sectors, if agriculture is exempted from future global mitigation efforts. AFOLU emissions will continue to grow, while other sectors, already adjusting to global mitigation requirements, reduce their emissions.

In this context, the agriculture sector has an important role to play in combatting climate change. In order to be in line with the 2°C limit for global warming, projected global emissions across all sectors in 2030 under a business as usual scenario (68 gigatonnes of equivalent carbon dioxide (GtCO₂e) per year) must be reduced by nearly 40%, or 26 GtCO₂e per year. Using a series of global models, Wollenberg et al. (2016) conclude that a feasible target for the reduction of direct (non-CO₂) emissions in agriculture that is consistent with the 2°C limit is 1 GtCO₂e per year. This would contribute 4-5% to the annual mitigation needed across sectors in 2030, compared with agriculture's current contribution of 10-11% to total global anthropogenic emissions.

Mitigation options that are compatible with food security and target non-CO₂ emissions are estimated to be capable of achieving only 21-40% of the 1 GtCO₂e reduction. Other mitigation options, including

the reduction of CO₂ emissions relating to the use of land and land-use change would be needed to supplement reductions in emissions from crop and livestock production. Options that are compatible with food security include soil carbon sequestration through improved cropland and grazing land management and restoration of degraded lands (estimated contribution of 1.2 GtCO₂e/yr), a reduction of food loss and waste by 15% (estimated contribution of 0.79-2.00 GtCO₂e/yr), and changes in human diets on the basis of recommendations by the World Health Organisation for health reasons (estimated contribution of 0.31-1.37 GtCO₂e/yr). Reducing the expansion of agricultural land also has a high potential to mitigate climate change (estimated contribution of 1.70-4.31 GtCO₂e/yr) but may conflict with food security if it leads to a reduction in output. Collectively, these options would increase the total mitigation potential of AFOLU to approximately 5-9 GtCO₂e/yr, which amounts to 27% of the mitigation needed across all sectors, a larger share than AFOLU's current contribution of 24% to global emissions.

Agriculture can also contribute to mitigation by supplying non-fossil-fuel inputs in energy production. The types of bioenergy used to displace CO₂-intensive fossil fuels have different implications. The use of food crops (i.e. first-generation biofuels such as maize, wheat, sugarcane, and sugar beet) is potentially incompatible with food security and has a questionable overall effect on mitigation since the production of these biofuels generates emissions. Second-generation biofuels that do not compete directly with food crops for the use of scarce natural resources are more consistent with food security goals. The cultivation of dedicated bioenergy crops, having limited nutrient and input needs, is a low-emitting activity with mitigation potential.

Land-sparing technological progress and practices are highly desirable for mitigation since spared land promotes soil carbon sequestration, reduces the possibility of converting FOLU sinks to sources of emissions, and can be used in bioenergy crop production with less risk for food security.

Technologies and practices that increase total factor productivity or alter relative prices in favor of less emissions-intensive inputs and outputs provide “natural incentives” for mitigation. Improvements in total factor productivity can promote both the objectives of food security and mitigation, but their relative impact differs by sector. The literature suggests that productivity gains in the crop sector benefit food security relatively more, whereas productivity gains in the livestock sector have the greatest mitigation impact. Significant productivity gains will be more difficult to achieve in both sectors as the impact of climate change intensifies. Besides, resource-saving technological innovation and gains in total factor productivity could result in higher emissions if reduced output prices lead to increased food demand and subsequent expansion in production (the rebound effect).

Emissions can also be reduced by removing policies that subsidise high-emitting outputs (e.g. ruminant protein) and high-emitting inputs (e.g. inorganic fertilizer and fossil-fuel energy), and through policies that enhance the efficiency of food processing and distribution, and reduce associated loss and waste.

Existing carbon sinks can be preserved through effective implementation of regulatory instruments or through financial incentives. Such measures can also be used to promote enhanced carbon sequestration through agroforestry and the reconversion of land with major sequestration potential to non-agricultural uses (such as wetlands, organic soils, land reforestation or afforestation). These mitigation options provide the highest potential in AFOLU and should be a major priority for all regions, especially where feasible mitigation options in agriculture are limited.

Reduction goals may target the level of national emissions; emissions per unit of input; emissions per unit of physical output; emissions per unit value of production; or emissions per unit of value added. The criteria used for reducing emissions can have different implications for productivity, competitiveness, food security and sustainable development, depending on the conditions prevailing in each country or region.

Despite promising trends in reducing emissions relative to the value of output across the world, regional differences point to further global potential for mitigation. Detailed analysis of the drivers of emissions at the individual commodity level and the measurement of emissions by activity relative to economic contribution (value added) can provide insight into priorities for emissions reduction at the

national level. In addition, empirical methods that take into account the costs of achieving mitigation targets and their implications for economic activity and other objectives like food security can play a valuable role in helping to identify mitigation policy options.

The implementation of national reduction targets runs the risk of carbon leakage, or in other words replacing relatively low-emitting domestic production by imports of higher emitting products from other countries. International co-ordination of national reduction targets is needed to achieve carbon reallocation (i.e. the replacement of high-emitting production by low-emitting production at the global level), thereby reducing global emissions.

Effective global mitigation requires that mitigation targets linked to the 2°C limit on global warming in 2100 be set for agriculture, soil carbon sequestration, and the food system at a global level. This would help regions to set effective regional goals and would minimize the possibility of carbon leakage, associated with the implementation of national mitigation policies.

The achievement of carbon reallocation requires that international trade play an important role in meeting the future global demand for food and that increases in exports originate from low-emitting producers (i.e. traded products that have a lower emissions intensity than their domestically-produced equivalents). This means accounting for the impacts on global carbon reallocation in agriculture of measures that influence trade, such as product standards and tariffs.

Introduction

Global efforts to contain climate change have concentrated on sectors generating carbon dioxide (CO₂) emissions (e.g. energy). While CO₂ is the largest contributor to global warming, methane (CH₄) and nitrous oxide (N₂O), the greenhouse gasses (GHGs) directly emitted by crop and livestock production, are also major contributors to increases in total atmospheric GHG concentrations and to climate change.

Agriculture is the largest emitter of CH₄ and N₂O. It is also a major contributor to CO₂ emissions through land use and land-use change, as land occupied by CO₂ sinks (e.g. forests, organic soils) is cleared for agricultural activities. Agriculture's direct emissions and indirect emissions associated with land use are accounted for under the AFOLU sector (Agriculture, Forestry, and Other land uses).

Under the UN Climate Agreement concluded in Paris in November 2015, countries have agreed to take actions to keep the rise in global average temperature this century below 2°C from pre-industrial levels. In the light of this agreement, this report addresses the following questions:

- How would agriculture contribute to global GHG emissions (directly and indirectly through land- use change) in the absence of mitigation targets or policies for the sector?
- Why must agriculture, forestry and other land uses (AFOLU) in both developed and developing countries be included in global GHG emissions mitigation efforts?
- What potential contribution of the agricultural sector to GHG reduction targets (directly or indirectly through land-use change) might be envisaged?
- How would such mitigation targets affect the sector's productivity, competitiveness and food security?
- How would countries differ in terms of their national options for mitigation and their potential consequences?

1. Past and Future Role of Agriculture in Global Warming

How would agriculture contribute to global GHG emissions (directly and indirectly through land-use change) in the absence of mitigation targets or policies for the sector?

Agriculture as a significant direct and indirect contributor to anthropogenic emissions of greenhouse gases

Human activities contribute to climate change by emitting greenhouse gases (GHGs), which as they accumulate in the atmosphere cause global warming. Since the start of the industrial era, the concentration of atmospheric CO₂, CH₄ and N₂O has risen by nearly 40%, 150% and 20%, respectively (Tian et al., 2016).

CO₂, emitted mainly from the use of fossil-fuel energy and from deforestation, is the largest single contributor to human-induced climate change, both because it is emitted in higher volumes than other greenhouse gases and because it stays for a very long time in the atmosphere (Hollis et al., 2016). CH₄ and N₂O are the second and third largest contributors, after CO₂, to anthropogenic climate change.

Agriculture contributes to climate change directly by emitting CH₄ and N₂O in crop and livestock production, and indirectly by affecting net CO₂ emissions through its impact on soil, forests and other land uses (AFOLU).¹ Agriculture's direct and indirect emissions make AFOLU the second largest contributing sector to total anthropogenic global emissions (Figure 1). Total AFOLU GHG contributions in 2010 reached 10-12 GtCO₂e, accounting for 24% of total global anthropogenic emissions (49 GtCO₂e) (Smith et al., 2014). Direct emissions from agricultural production were estimated to be 5.0-5.8 GtCO₂e per year during the period 2000-10, whereas indirect emissions from land use and land-use change (FOLU) were 4.3-5.5 GtCO₂e per year.

Soil and the biomass of growing trees and plants have the unique capacity to act as natural CO₂ sinks, thus reducing the anthropogenic effect of GHG emissions. The way land is used for food production and changes in land use caused by agriculture's expansion cause carbon stock changes and CO₂ emissions. Despite agriculture's direct and indirect capacity to sequester carbon, net total (direct and indirect) emissions from AFOLU are positive. During the period 2001-10, the cumulative warming capacity of non-CO₂ anthropogenic GHG emissions from agriculture and "landfills and waste" (see below) alone was equivalent to twice the offsetting cooling effect resulting from the global land uptake of CO₂ (Tian et al., 2016: 227).

Agriculture also contributes CO₂ emissions by using fossil-fuel energy on farms (e.g. to power machinery and pump irrigation water; for heating and cooling) and by consuming inputs that are produced in an energy-intensive manner (e.g. fertilizers, pesticides). Despite the fact that these CO₂ emissions are counted as emissions from the energy sector, they can be affected by changes in agricultural activity. Fossil-fuel energy used in agricultural activities accounts for 0.87% of total global emissions (Figure 1). Emissions from on-farm energy use and in the production of fertilizers (i.e. pre-production stage of the food system) collectively account for approximately 8% of global agricultural emissions (Wirseni, Hedenus and Mohlin, 2011: 162).

Agriculture is the largest contributor to global anthropogenic non-CO₂ (direct) GHG emissions, accounting for 56% of those emissions in 2005 (Smith et al., 2014: 822). CH₄ is emitted mainly through enteric fermentation in ruminants and through rice cultivation (Figure 2). It is also emitted by agricultural soils as a result of: the application of synthetic fertilizers and manure (organic fertilizer); manure left on pasture by animals; crop residues; and the cultivation of organic soils (peatland). Manure management and biomass burning (i.e. burning of crop residues and savanna) generate emissions of both non-CO₂ GHGs.

Land use generates CO₂ emissions by changing the carbon stock in forest land (soil and biomass), and in the soil of cropland, grassland, and wetlands (peatlands and flooded land). The conditions of poorly drained wetlands give rise to the development of organic soils (e.g. peat and muck), which are high in content of organic matter and particularly susceptible to carbon stock changes caused by land use. All

1. Land-uses in AFOLU comprise forest land, cropland, grassland, wetlands (peatlands and flooded land), settlements, and other land (IPCC, 2006). Overall, agricultural activities account for at least 90% of emissions due to land-use change (Bennetzen, Smith and Porter, 2016: 764).

other soils (mineral soils) contain relatively low amounts of organic matter and predominate in most ecosystems, except wetlands.

Figure 1. Greenhouse gas emissions by economic sectors (2010)

Source: IPCC (2014).

When organic soils are drained to be converted to cropland or grassland, they emit CO₂. If they are burned, they emit additional CO₂, as well as CH₄ and N₂O. All organic soil emissions generated by fires or drainage (land-use change) fall under the land use category. The emissions generated by the cultivation of organic soils (N₂O) are counted in agricultural production (Figure 2).

Mineral soils, too, are affected by land-use and management activities. Conversion of native grassland and forest land to cropland can lead to 20-40% loss of the original soil carbon stocks (IPCC, 2006). Within a category of land use (e.g. grassland, cropland), management practices can have a significant impact on soil organic carbon storage, depending on their net effect on carbon additions (e.g. restoration of degraded soils, carbon left after crop harvest, fire, or grazing) and removals (e.g. soil disturbance) under the specific moisture, temperature, climate and soil conditions. Finally, the combination of land-use change and management activity can affect soil carbon sequestration by impacting soil erosion.

Deforestation is the main source of agriculture's indirect emissions, accounting for 59% of land-use emissions during the period 2012-14 (Figure 3). Peat and forest fires were the second largest source of emissions (25%) during that period. Drainage of organic soils for conversion to cropland and grassland accounted for 15% and 1%, respectively.

Emissions related to food are also generated by post-production activities in the food chain including processing, packaging, transportation, refrigeration, retail activities, catering and domestic food management, and consumer waste (Table 1). Globally, waste accounts for 30-40% of the food produced. In the developing world, this loss is primarily due to poor food-chain infrastructure (e.g. lack of storage and technology). In the developed world, most losses occur at the retail, food service and home-usage stages of the food chain (Godfray et al., 2010: 816). Food waste contributes CH₄ emissions directly from landfills (Vermeulen, Campbell and Ingram, 2012: 202).

Figure 2. Composition of AFOLU emissions by decade since the 1970s

Source: Smith et al. (2014).

Figure 3. Sources of land-use emissions in AFOLU (2012-14)

Note: Burning biomass comprises forest and peat fires. Drainage of organic soils converted to cropland and grassland is reflected in cropland and grassland use emissions, respectively. Currently, FAOSTat data relating to changes in soil carbon stock (i.e. in cropland and grassland) are limited to organic soils.

Source: FAOSTat data.

AFOLU's total emissions are estimated to account for 80-86% of the emissions generated by the global food system, which in turn contributes 19-29% of total anthropogenic GHGs (Vermeulen, Campbell and Ingram, 2012). The pre-production and post-production stages of the food chain, including food waste, are estimated to contribute approximately another 4% to global total anthropogenic emissions (Table 1).

Table 1. Estimates of the relative contributions of sub-sectors of the food chain to global GHG emissions

Stage of food chain		Emissions (MtCO ₂ e)	Year of estimate
Pre-production	Fertilizer manufacture	282 – 575	2007
	Energy use in animal feed production	60	2005
	Pesticide production	3 – 140	2007
Production	Direct emissions from agriculture	5 120–6 116	2005
	Indirect emissions from agriculture	2 198 – 6 567	2008
Postproduction	Primary and secondary processing	192	2007
	Storage, packaging and transport	396	2007
	Refrigeration	490	2004
	Retail activities	224	2007
	Catering/domestic food management	160	2007

Note: See original source for data sources and additional detail on estimates

Source: Vermeulen, Campbell and Ingram (2012).

Trends in AFOLU GHG emissions

In 2010, total global GHG emissions from all sectors (49 GtCO₂e) were 80% higher than in 1970 (Blanco et al., 2014: 357). During the period 1970-2010, CO₂ from all sources was the fastest growing GHG (Blanco et al., 2014: 354). Total emissions of CH₄ and N₂O also increased (Blanco et al., 2014: 354) and in 2010 accounted for 16% and 6% of total global anthropogenic emissions, respectively (Blanco et al., 2014: 358).

AFOLU has been the second largest contributing sector (after fossil-fuel energy) to CO₂ emissions, despite its declining share associated with the industrialization of developing countries. This is the result mainly of the high growth in fossil-fuel consumption (Figure A1.1), but also the declining trend in AFOLU emissions associated with land use since the 1990s (Figure 4).

The decrease in total land-use emissions (i.e. emissions from deforestation and other land uses net of removals by forests) resulted mainly from a combination of a slow-down in deforestation and through afforestation (Figure 5), which took place in different parts of the world. During the period 1990-2014, emissions from deforestation and other land uses dropped by nearly 25% (calculated from FAOStat data).

Other major sources of land-use CO₂ emissions were forest fires and peat fires, and the drainage of organic soils for conversion to cropland and grassland. The annual variability of emissions associated with fires is high. The variability of emissions from fires and the reduced deforestation is reflected in the evolution of the composition of total land-use emissions over the years (Figure 6). During the period 1990-2014, total land-use emissions comprised those from forest land (45%), forest and peat fires (i.e. burning biomass in FOLU, 34%), and drainage of organic soils for conversion to cropland (21%) and to grassland (1%). Recently (average of 2012-14), emissions from forest land had dropped to 35%, while emissions from burning biomass had risen to 40% and emissions from organic soils drained for cropland use had reached almost 25% of total land-use emissions.

Figure 4. Global AFOLU emissions (1990-2010)

Figure 5. Forest land emissions and removals (1990-2014)

Figure 6. Major sources of land-use emissions (1990-2014)

Figure 7. AFOLU emissions and agricultural land use (1990-2014) **Figure 8. Agricultural land in crop and livestock production (1961-2014)**

While emissions from land use have been on a downward trend, agriculture's direct emissions have been increasing (Figure 4). During the period 1990-2014, emissions from agriculture rose by 15% (calculated from FAOStat data) and agriculture's share in total AFOLU emissions increased from 41% in 1990 to 48% in 2010. The share of emissions from deforestation and other land-use changes fell from 59% to 52% (calculated from FAOStat data). The period of decelerating emissions from deforestation coincides with a downturn in the land used in agriculture (Figure 7).

Agriculture's direct emissions from crop and livestock production account for 10-12% of global anthropogenic GHGs. As noted earlier, agriculture is the largest contributor to global anthropogenic non-CO₂ emissions (i.e. CH₄ and N₂O) and it is not expected to lose that position, at least in the mid-term (EPA, 2012: 15). Livestock contribute 80% of all agriculture's direct emissions and ruminants account for more than 80% of total livestock-related GHG emissions (Havlík et al., 2014: 3709-3710). We can see from Figure 8 that an expansion in the area of

grassland for the production of ruminants was the principal contributor to an expansion in agricultural land area up to 2010.

Over the period 1970 to 2010, agriculture's direct emissions increased by 54% (calculated from FAOStat data). Emissions of N₂O account for a smaller share of agriculture's direct emissions than CH₄, but during the years 1970-2010 they rose faster than CH₄ emissions. In 2010, N₂O and CH₄ emissions had risen by 73% and 18 %, respectively from their 1970 levels (Agrawala et al., 2014: 1105). During the period 1990-2010, for which relevant FAOStat data are available, the share of N₂O in agriculture's direct emissions rose from 42% in 1990 to 44% in 2010 at the expense of CH₄ (from 58% in 1990 to 56% in 2010) (calculated from FAOStat data).

The increase in direct emissions was due to an expansion in the use of synthetic fertilizers (N₂O) and livestock numbers (CH₄, N₂O). Calculations from FAOStat data show that during the period 1970-2010, global emissions from enteric fermentation (CH₄ only) increased by 33%, whereas emissions from synthetic fertilizers tripled (200%) and those from agricultural soils (N₂O only, including fertilizers) more than doubled (112%).² Livestock rearing, which occupies 30% of the global land area, was a major cause of land-use change (Havlík et al., 2014: 3709) and related emissions. Expansion of irrigated cropped area also contributed to higher emissions (Blanco et al., 2014: 384). Figure 9 shows the composition of agriculture's direct emissions over the period 1990-2014.

Figure 9. Composition of direct global emissions from agriculture (1990-2014)

On average, during the period 2012-2014, the largest sources of agriculture's direct GHG emissions were enteric fermentation (40%), manure deposited from livestock on pasture (16%), synthetic fertilizers (12%), rice cultivation (10%) and manure management (7%) (Figure 10).

The three largest sources (i.e. enteric fermentation, manure left on pasture and synthetic fertilizers) contributed more than 80% of the increase in agriculture's direct emissions during the period 1990-2014 (Figure 11). Two of these, enteric fermentation and manure left on pasture, are associated with the production of ruminants. The burning of savanna has been highly variable, but the last couple of years have showed a decrease relative to 1970 emission levels.

Emissions from synthetic fertilizers and manure left on pasture exhibited the two largest percentage increases after crop residues (Figure 12), which however, contribute only a small share (4%) to direct emissions (Figure 10).

2. Emissions from agricultural soils refer to N₂O emissions resulting from the use of synthetic fertilizers, manure applied to soils, manure left on pasture, crop residues and the cultivation of organic soils.

Thus, the increase in agriculture's direct emissions is mainly due to the expansion of the number of ruminants (enteric fermentation, CH₄), the expansion of grazing systems for ruminants (increase in manure left on pasture, N₂O) and the growth in the use of synthetic fertilizers (N₂O).

Figure 10. Global direct emissions from agriculture by source (average 2012-14)

Source: FAOSTat data.

Figure 11. Contribution to the increase in global direct agricultural emissions (1990-2014)

Source: FAOSTat data.

Figure 12. Changes in global direct emissions from agriculture by source (1990-2014)

Source: FAOStat data.

Developed or developing countries: Which group is more responsible for agricultural GHG emissions?

Non-annex I (developing) countries are the largest source of global AFOLU net emissions, accounting for 92% of the total in 2012-14 (Figure A1.2).³ Moreover, in recent years, AFOLU emissions in developing countries have been increasing, whereas they have been declining in developed countries (Figure 13).

Figure 13. Trends in net AFOLU emissions in developed and developing countries (1990-2014)

Source: FAOStat data.

Land use in developing countries is still a significant net emitter, despite decreasing emission trends in recent years. Developed countries have been making a net contribution to carbon sequestration (Figure 14).

In developing countries, direct emissions from agriculture show a strong upward trend. This is expected to persist and to boost future AFOLU emissions due to increases in both direct emissions from food production and indirect emissions from land conversion (Agrawala et al., 2014: 1105). Agriculture's emissions in developed countries show a slight downward trend.

3 Annex 1 and non-Annex 1 countries refer to groups defined under the UN Framework Convention on Climate Change (UNFCCC).

Figure 14. Evolution of emissions from agriculture and land use in developed and developing countries (1990-2014)

Source: FAOStat data.

Asia is the largest regional contributor to agriculture's global direct GHG emissions (Figure 15). During the period 2012-14, Asia (mainly the People's Republic of China, India and Indonesia) accounted for nearly half (44%) of agriculture's global direct GHG emissions; the Americas (mainly Brazil and the United States) contributed an additional 25%; Africa ranked third (16%). Europe has been reducing its agricultural emissions relative to other regions, lowering its share in global agricultural emissions to 11% in 2012-14. Finally, Oceania contributed 4% to the global total.

Figure 15. Shares of global direct agricultural emissions by region (average 2012-14)

Source: FAOStat data.

At a more disaggregated level, the People's Republic of China (hereafter "China"), India, Brazil, the European Union and the United States accounted for the largest direct emissions from agriculture during the period 2012-14, collectively contributing roughly half of the global total (FAOStat).

More than half of China's emissions in that period were generated by enteric fermentation (CH₄) and synthetic fertilizers (N₂O), but rice cultivation (CH₄) was also a large source (Table 2).⁴ Almost half (45%) of India's emissions resulted from enteric fermentation, whereas almost 85% of Brazil's agricultural emissions were generated by enteric fermentation and manure deposited on soil (N₂O), associated mainly with an expansion in beef production (Havlík et al., 2014: 3709). In other developing countries, such as Ethiopia, where extensive ruminant grazing systems are also important, enteric fermentation and manure left on pasture (N₂O) dominate direct emissions from agriculture (almost 90% in Ethiopia). Indonesia's emissions resulted mainly from rice cultivation (37%) (CH₄) and cultivation of organic soils (21%) (N₂O).

The most important sources of EU direct emissions are livestock (enteric fermentation and manure management accounting for roughly 55% of the total) and synthetic fertilizers, accounting for almost one fifth of the total. The structure of emissions from US agriculture is broadly similar to that in the European Union, except for fertilizers. US agriculture generates a higher percentage of direct emissions from the use of synthetic fertilizers than the European Union which generates a larger share from the use of organic fertilizers.

Table 2. Percentage of direct agricultural emissions by source in selected countries (2012-14)

Agricultural source	AUS	BRA	CHN	ETH	EU	IND	IDN	NZD	USA
	%								
Enteric fermentation	33.2	59.9	28.4	52.1	38.6	45.3	12.4	54.9	34.5
Manure management	3.4	2.5	10.5	2.1	15.6	4.5	4.4	8.2	12.2
Rice cultivation	0.4	0.7	16.1	0.1	1.1	15.3	37.3	0.0	2.3
Synthetic fertilizers	5.3	5.9	22.1	1.4	17.7	17.3	11.4	5.2	23.1
Manure applied to soils	0.7	2.7	5.4	0.8	8.7	2.4	2.8	1.2	4.7
Manure left of pasture	19.5	23.3	11.6	36.5	7.0	10.3	6.5	29.3	10.9
Crop residues	2.0	2.6	5.0	1.3	4.9	4.0	3.6	0.2	8.2
Cultivation of organic soils	0.2	0.0	0.1	1.6	5.9	0.1	20.9	1.0	2.8
Burning – crop residues	0.3	0.4	0.7	0.2	0.4	0.6	0.6	0.0	1.0
Burning – savanna	34.9	1.9	0.0	3.9	0.0	0.0	0.1	0.0	0.3

Source: Computed from FAOStat data - CO₂ equivalents.

We now turn to examine regional drivers that generate agriculture's direct and indirect emissions.

Regional contributions to changes in carbon dioxide emissions (deforestation, drainage of organic soils, and burning of non-agricultural biomass)

The decrease in land-use emissions (i.e. deforestation and other land uses) resulted mainly from the combined result of a slow-down in deforestation and from afforestation in parts of the world. Reduction in deforestation began in East and South Asia in the 1990s and continued in Latin America (e.g. Brazil) after 2000. Afforestation in other regions in the world (e.g. Europe) helped to increase CO₂ removal from the atmosphere (Blanco et al., 2014: 359-360), even though its effects were partially offset by an increase in deforestation in tropical countries during the period 2000-12 (Tian et al., 2016: 227) (Figure 16).

Africa is the largest contributor of net emissions from land use. Its share in 2012-14 averaged 41.5% of global land-use emissions. Asia has increased its share considerably over the years and accounted for 36.1% in 2012-14. In contrast, the Americas decreased their contribution to global land-use emissions over the years to 22.4% in 2012-14 (Figure 17).

4. Data obtained from FAOStat for China in this report refer to the People's Republic of China (PRC).

Indonesia has been and still is the top net emitter from land use. In 2012-14, Brazil was the third largest and India the ninth largest net emitter from land use (FAOStat data). Europe is a major sink in total land use. Oceania is also a net sink, even though of small significance.

As seen earlier, forests have been a major source of CO₂ removals from the atmosphere and deforestation has been a major source of CO₂ emissions. The combination of these two effects gives aggregate emissions/removals from forest land. In 2012-2014, Africa accounted for 41% of the net emissions from forest land (i.e. emissions from deforestation net of any removals from remaining forests), Asia 32.8%, and the Americas 26.2% (Figure 18.)

Brazil and Indonesia have been the top two sources of net emissions from forest land due to deforestation, during the period 1990-2014. The United States, China, India, and many EU countries are net sinks, when CO₂ emissions and removals from forest land are taken into account.

Figure 16. Estimated carbon stock in forests by region (1990-2013)

Source: FAOStat data.

Figure 17. Net emissions from land use by continent (2012-14)

Source: FAOStat data.

Figure 18. Net emissions from forest land, by continent (2012-14)

Source: FAOStat data.

Regional drivers of increases in methane emissions

Enteric fermentation is the largest source of CH₄ emissions in agriculture and the largest contributor to total direct emissions of GHGs from the sector (Figure 10). Emissions from enteric fermentation grew at an average rate of 0.7% per annum over the period 1961-2010 (Smith et al., 2014: 824).

The global growth in emissions from enteric fermentation conceals significant regional differences in the development of these emissions and underlying drivers. Over the period 1961 to 2014, emissions from enteric fermentation grew at an annual rate of 1.9% in Africa, 1.6% in South America and 1.3% in Asia, whereas they shrank at an annual rate of 1.0% in Europe and 0.3% in Northern America. In 2014, 78% of global emissions from enteric fermentation were estimated to come from developing (non-Annex I) countries (calculations based on FAOStat data).

The growth in CH₄ emissions from enteric fermentation and manure production has been associated with a 1.4-fold increase in the number of ruminants (cattle, sheep and goats) and, in the case of manure, with 1.6 and 3.7-fold higher numbers of non-ruminant pigs and poultry, respectively, in the last forty years (Blanco et al., 2014: 384).

A key driver in the expansion of livestock numbers has been increased demand for animal products, especially in Asia (Blanco et al., 2014: 384). The largest contributor to global CH₄ emissions in agriculture in 2014 was India (14%, FAOStat data), where cattle slaughter is restricted for cultural reasons. India poses a significant challenge for mitigation policy, since its emissions are unavoidably linked to cultural characteristics that keep livestock numbers high, albeit largely decoupled from meat production. Figure 19 shows the increase in emissions in India from cattle through enteric fermentation and manure left on pasture.

In China, the second largest source of CH₄ emissions (12%), the key driver has been dietary changes, including higher consumption of meat associated with income growth. Figure 20 shows the rapid growth in emissions from enteric fermentation and manure left on pasture.

Brazil (10%), the European Union (7%) and the United States (6%) follow in the ranking for CH₄ emissions in 2014. Brazil's expansion of livestock emissions (Figure 21) is associated with expansion of output under slightly improving emissions intensity (emissions per unit of output) in the production of beef, associated with higher yields (Figures A1.3 and A1.4).

In the European Union, emissions from enteric fermentation have been decreasing (Figure 22) due to productivity gains and reduced livestock numbers, associated with agricultural policy reforms in the 1980s that replaced output subsidies with payments that are more decoupled from production.

Finally, in the United States emissions from enteric fermentation have been decreasing since the 1970s (Figure 23), mainly as a result of productivity gains in cattle production (Figures A1.4 and A1.5).

Figure 19. India: Sources of direct agricultural emissions (1961-2014)

Source: FAOStat data.

Figure 20. China (PRC): Sources of direct agricultural emissions (1961-2014)

Source: FAOStat data.

Figure 21. Brazil: Sources of direct agricultural emissions (1961-2014) **Figure 22. European Union: Sources of direct agricultural emissions (1961-2014)** **Figure 23. United States: Sources of direct agricultural emissions (1961-2014)**

In all regions, enteric fermentation from the production of ruminants is the leading source of direct emissions from agriculture (Figures A1.6 to A1.10). In Africa and the Americas manure left on pasture, also typically associated with ruminant production, is the second largest source. Synthetic fertilizers are the second largest source of direct emissions in Europe; the burning of savanna occupies that position in Oceania primarily due to emissions from that source in Australia. The burning of savanna is also a significant source of emissions in Africa.

In Asia, the second leading source of emissions in agriculture is rice cultivation (Figure A1.8). During the period 1990-2010, Asia contributed almost 90% of global emissions from that source. Emissions from rice cultivation grew at an annual rate of 0.4% during 1961-2010, but the rate of growth has slowed in recent decades, in line with the trend in cultivated rice area. The largest growth in emissions took place in Africa (2.7% per year) (Smith et al., 2014: 824). During the period 2000-10, 94% of emissions from rice cultivation came from developing countries, and Asia continued to account for almost 90% of the total (Smith et al., 2014: 824).

Regional drivers of increases in nitrous oxide emissions

The growth in global agricultural emissions of N₂O during the period 1970-2010 was mainly due to the increased use of synthetic fertilizer (+230%). Higher usage in crop production, especially in the developing countries, accounted for 70% of global N₂O emissions from synthetic fertilizer in 2010 (Tubiello et al., 2013; Blanco et al., 2014: 384). N₂O emissions from agricultural soils tripled in developing (non-Annex I) countries during 1970-2010, in contrast to an increase of 15% for developed (Annex I) countries.

In 2014, China contributed 16% of global N₂O emissions in agriculture, followed by India (10%), the European Union (9%), the United States (8%), and Brazil (7%) (FAOStat data).

Eastern and Southern Asia, Europe, and North America are the largest contributors to N₂O emissions from the use of synthetic fertilizers.

Asia, Europe, and the Americas also have the largest share of emissions from the use of organic fertilizer (manure applied to soils), whereas Asia, Africa, and Brazil are the largest contributors to emissions from manure deposited on soil by grazing animals (Annex 1, Figures A1.6 – A1.9 and Figure 21).

Emissions, efficiency in production, and technological advancements

Total direct emissions from global agricultural production can be expressed simply as:

$$E = \frac{E}{Q} \cdot Q \quad (1)$$

where:

E = direct emissions from agricultural production (e.g. in kg of CO₂ equivalent),

$\frac{E}{Q}$ = emissions intensity (emissions in kg of CO₂e per unit of output, e.g. per kg of crops or meat),
and

Q = the total volume of output (e.g. in kg).

According to this equation, changes in global agricultural emissions can occur as the result of a) changes in agricultural output (level and composition) and/or b) changes in emissions intensity. The implications for total emissions depend on the combined effect of each of these changes on direct emissions from agricultural production and on indirect emissions through induced changes in land use.⁵

Equation (1) can be further expanded, as follows:

$$E = \frac{E}{x} \cdot \frac{x}{Q} \cdot Q \quad (2)$$

5. As indicated in Table 1 changes in the level of agricultural activity can induce additional changes in emissions through upstream and downstream activities associated with agriculture.

where:

$\frac{E}{x}$ = emissions intensity of inputs (i.e. emissions per unit of land, per animal or per unit of other inputs, such as fertilizer) and

$\frac{x}{Q}$ = the amount of inputs used per unit of output (e.g. crops or meat), an inverse representation of productivity.

According to the expanded equation, changes in global agricultural emissions can also be effected through changes in the emissions intensity of inputs and changes in productivity.

In crop production, the emissions intensity in the use of land results from the combined outcome of emissions per unit of another input used (e.g. fertilizer) and the intensity at which this other input is used in relation to land.

In livestock systems that use land (e.g. ruminant production, free-range non-ruminant production), the emissions intensity of an animal is the result not only of the gases emitted directly by the animal (e.g. through enteric fermentation), but also of the emissions from the use of land by the animal (e.g., land extensive vs land intensive production systems) and the associated emissions from soil (e.g. manure left on pasture).

The efficiency of production, i.e. whether the maximum output is being achieved from a given bundle of inputs consistent with profit maximization (cost minimization), is clearly a factor of importance in determining emissions intensity. Policy distortions, market imperfections, subsistence agriculture (i.e. production for self-consumption), as well as socio-cultural factors, can affect the combinations and amounts of inputs used, and hence emissions intensity.

An increase in emissions intensity is not always associated with an increase in input use; it can be the outcome of emission-intensive management and practices. Changes in production practices that result in reductions in the use of high-emitting inputs or the substitution of lower-emitting for high-emitting inputs will reduce emissions intensity. Finally, productivity improvements through technological advances that increase the amount of output generated from a given amount of inputs will also affect emissions intensity.

Each of the contributory factors to total emissions can be influenced by the impact of climate change on, for example, the availability and quality of natural resources (land and water), yields or the soil's capacity to sequester carbon. Changes in temperature, precipitation and elevated atmospheric concentrations of CO₂ affect agricultural production, individually and in combination (Section 4).

Climate change is expected to affect yields in ways that vary regionally, as well as across activities and products. AFOLU, being particularly vulnerable to climate change, needs to minimize the short-term risks relating to climate-change hazards, take full advantage of potential opportunities and develop long-term resilience to the phenomenon. Such adjustments (adaptation), once tailored to local environmental, climatic, and socio-economic particularities, can reduce the risks of climate-change impacts. Nevertheless, the effectiveness of adaptation is limited, especially as climate change intensifies with increases in global temperatures (IPCC, 2014).

Some insight into the factors that affect total emissions can be obtained by examining recent changes in the emissions intensity of agricultural production. Figure 24 shows trends in global direct GHG emissions from agriculture (i.e. excluding land-use change) per dollar of agricultural output.⁶ It shows that since 1990 the amount of emissions (kg of CO₂e) per constant dollar of global agricultural output has declined by roughly one third. Figure 25 shows that emissions efficiency has increased (i.e. emissions intensity has declined) in all geographical regions, although there are substantial differences among them. In Africa and Oceania, the emissions ratio in 2013 was roughly double that in other regions.⁷ Figure 26 shows that emissions intensities (i.e. kg of

6. Output is valued in constant “international” dollars using representative international prices for commodities produced.

CO₂e relative to kg of output) for ruminant and non-ruminant livestock products and rice have decreased since the 1960s, but emissions intensity for cereals has increased, due to increased use of fertilizer.

Figures A1.11 to A1.15 chart the ratio of total emissions to total volume of agricultural output for geographical sub-regions over the period 1995 to 2013. The good news is that there has been a tendency for emissions intensity to decline in all sub-regions. The bad news is that food demand and thus agricultural production, especially of emissions-intensive products, is growing faster.

Figure 24. Global direct emissions from agriculture per dollar of agricultural output (1990-2012)

Source: FAOStat data.

Figure 25. Regional trends in direct agricultural emissions per dollar of agricultural output (1990-2012)

Source: FAOStat data.

7. As shown in Annex 1, Figure A1.10, the burning of savanna is the second largest contributor to direct emissions attributed to agriculture in Oceania. While some of this burning is directly related to the clearing of land for agricultural use, it is also affected by the impact of periodic drought on the natural incidence of fire.

Figure 26. GHG emissions intensities for different AFOLU commodities for the decades 1960s through 2000s

Note: Cattle meat includes dairy and non-dairy meat; emissions from cereals are for synthetic fertilizers only; wood is carbon loss from harvest/roundwood produced.

Source: Smith et al. (2014): 851.

In Africa, the most significant decline has occurred in the middle Africa sub-region, from around 9 kg per dollar of output to less than 6 kg. Eastern Africa – the region with the highest emissions ratio in the most recent period – has also seen a decline, although there is evidence of an upswing in recent years, due primarily to increased use of synthetic fertilizers. The most significant decline in the Americas has been in South America, where the emissions ratio has fallen from over 4 kg in 1995 to less than 3 kg in 2013. In the other American sub-regions, emissions ratios have tended to be relatively flat in recent years. Significant reductions have occurred in the emissions ratios of Southern, South-eastern and Eastern Asia, although the ratio for Western and Central Asia has been relatively flat in recent years. In Europe the largest decline has occurred in Eastern Europe. After declining, ratios in other European sub-regions (Northern, Western and Southern) have tended to be relatively flat in recent years. In Oceania, emissions ratios in Melanesia, Micronesia and Polynesia have also tended to be relatively flat in recent years. The ratio in Australia/New Zealand has tended to decline but has been highly variable due to the effects of climate-induced variability in Australia's emissions (discussed further below).

Emissions intensity in agricultural production is strongly affected by productivity. One unambiguous way to reduce emissions intensity is to increase total factor productivity in agriculture (i.e. increasing the volume of output from the same volume of inputs) (equation 2).

Table 3 summarizes annual rates of growth in agricultural output and estimates of the change in total factor productivity (TFP) in various countries and sub-regions for the period 2001-12.

For the world as a whole, growth in TFP of 1.7% per annum made a major contribution to the 2.6% annual growth in agricultural output over the period. In several of the countries/regions listed (South Africa, North America, Europe and Oceania), TFP growth exceeded the growth in output; the two growth rates were equal in west Asia and North Africa. Growth rates in TFP have been lower than the growth in output in Latin America and the Caribbean, Asia (excluding west Asia) and the former USSR.

A noticeable outlier is Sub-Saharan Africa (SSA) (excluding South Africa). While agricultural output increased by an annual average of 3.3% from 2001-12, TFP increased by only 0.6% per year. The low productivity in Africa as a whole is also reflected in low regional yields of beef and milk (Figures A1.4 and A1.11). Low productivity growth in SSA is clearly a cause for concern with regard to potential future growth of emissions, particularly since this is the region with the highest population growth rate in the world, and with high income elasticities of demand for agricultural products, especially high-emitting livestock products. The demand-side impact on future emissions is discussed further below.

Output growth in SSA has largely been achieved by using additional quantities of inputs, rather than through higher total factor productivity, and this has probably contributed to increased emissions. The effect on emissions would be even more pronounced if the growth were due to the increased use of inputs that are likely to contribute disproportionately to emissions.

Figures 27 and 28 shed some light on this issue by comparing differences in percentage changes for key variables between Sub-Saharan Africa and developing countries as a whole. The figures are also useful in showing the impact of agriculture not only on direct emissions, but also on the indirect emissions associated with land clearing and the conversion of other land uses to agriculture.

Figure 27 shows that, in relative terms (compared to developing countries as a whole), the expansion of agricultural area and, in particular, land clearing (the new land component in the chart) has been important in Africa's agricultural output growth. Although the intensity of input use (input/area) has increased by more than in developing countries as a whole, the growth in yield and output has been lower. The combined effect of these changes is reflected in the low growth rate of TFP relative to other regions in Table 3.

Figure 28 compares relative changes in various inputs in SSA to developing countries as a whole. While the growth in labor use has been higher and the growth in machinery use has been lower (i.e. mechanization has played a smaller role in the growth of output than in other regions), increased use of fertilizer and feed, and expansion in livestock numbers have played a larger role than in developing countries as a whole. The implication of these figures is that the growth in agricultural output in Sub-Saharan Africa has been skewed towards a pattern of input use (e.g. the clearance of land for agricultural purposes and the higher use of fertilizer) that has likely contributed to the increase in the carbon footprint of agricultural production. Increasing productivity, that could help to moderate that carbon footprint, has been lacking in the region (Table 3). As high growth rates in population and per capita income are expected to lead to increases in the demand for food and agricultural products, continued disparity between output and productivity growth in Sub-Saharan Africa would not bode well for the region's ability to reduce the carbon footprint of its agriculture in the future.

The relationship between productivity growth and input use in Sub-Saharan Africa is not the only cause for concern. The data in Table 3 suggest that productivity growth in Latin America and the Caribbean and in Asia (excluding West Asia) has also been inferior to the growth in output.

Table 3. Comparison of growth in agricultural production and total factor productivity among regions (2001-2012)

Region/country	Annual growth (2001-12)	
	Agricultural production	Total factor productivity
	%	
Sub-Saharan Africa (excluding South Africa)	3.3	0.6
South Africa	2.6	2.8
Latin America/Caribbean	3.4	2.3
North America	1.2	2.2
Asia (excluding West Asia)	3.6	2.6
Europe (excluding former USSR°)	-0.4	1.3
West Asia and North Africa	2.5	2.5
Oceania	0.2	1.2
Former USSR	2.6	2.5
World	2.6	1.7

Source: Adapted from Fuglie (2016).

Figure 27. Sub-Saharan Africa's agricultural productivity growth (excluding South Africa) compared to developing countries as a whole (2001-12)

Source: Calculated from Fuglie (2016).

Figure 28. Sub-Saharan Africa's changes in agricultural input use (excluding South Africa) compared to developing countries as a whole (2001-2012)

Source: Calculated from Fuglie (2016).

The data also suggest, however, that in these two regions the contribution of increased use of land (particularly new land) and increased use of fertilizer to the total growth in output has been smaller than in Sub-Saharan Africa. Increased use of machinery has an important source of output growth in Asia and Latin America, although higher usage of other inputs (fertilizer and feed) has also played a role.

Based on the data, we can conclude that, even in the absence of the adoption of specific mitigation efforts in agriculture, gains in efficiency have contributed to reductions in emissions intensity globally. This highlights the continued importance of technological progress and other contributors to improved production efficiency in restraining the growth in total direct emissions, irrespective of the magnitude of the growth in output. In addition, technological advancements and other developments that are land sparing lower agriculture's indirect emissions.

During the period 1961 to 2010, global annual agricultural emissions increased at a rate that was lower than the rate of growth in production of crops, milk and meat (Tubiello et al., 2013). The increase in crop production resulted from the combined effect of higher yields (i.e. output per unit area) and the expansion of land under cultivation, associated with the intensification of

management, and the use of agrichemicals and technical inputs that the green revolution introduced (Brown et al., 2015: 54).

In the more recent period of 2000-12, crop yields increased globally by about 1.8% per year, resulting in a roughly 20% increase in global cereal production (Tubiello et al., 2014), without a corresponding increase in the use of land (i.e. are land sparing).

Since 2000, food production in countries such as Brazil and China has been stimulated by the adoption of genetically modified crops (Brown et al., 2015: 54). The yield improvements in the crop sector of the past 50 years lowered real commodity prices, led to 86% savings in cropland expansion and avoided significant additional emissions. The livestock sector has also seen productivity increases, which in some cases led to land savings (Havlík et al., 2014: 3709).

Projections on the future role of agriculture in emissions growth

Agriculture will continue to be a major contributor to the accumulation of atmospheric GHGs as long as food for human consumption is produced on the Earth. The growth of the agricultural sector is essential for food security and for the reduction of poverty and hunger. This is particularly important in the least developed countries (e.g. in Sub-Saharan Africa), where agricultural productivity is low or stagnant, and population growth is expected to place further pressure on water and on stressed agricultural systems with limited adaptive capacity to climate change (Smith et al., 2007a; Brown et al., 2015: 22).

Most of the population growth, estimated to add more than 2 billion persons to current world population by 2050, is expected to take place in poor developing countries, where the income elasticity of demand for food is high. According to Wik, Pingali and Broca (2008: 1), under such conditions, even moderately high income growth could result in a more than 70% increase in demand for food and other agricultural products by the middle of this century. By 2030, demand for ruminant meat and milk is projected to be 44% and 55% higher, respectively, than the corresponding levels in 2000 (Havlík et al., 2014: 3710).

Currently, beef and cattle milk production contribute 41% and 20% of livestock emissions (Gerber et al., 2013: xii). The projected move towards an animal-based diet implies increases in crop and livestock production of 48% and 80%, respectively, by 2050 (Bennetzen, Smith and Porter, 2016: 763). As a result, emissions from livestock production and associated feed production and processing are projected to grow (Gerber et al., 2013: xii, 83), causing potential agricultural non-CO₂ emissions by 2050 to be 76% higher than the 1995 level (Bennetzen, Smith and Porter, 2016: 763). Using FAOStat data, this implies direct emissions of roughly 8 GtCO₂e/yr in 2050. That represents an increase of roughly 55% from average direct emissions in 2012-14.

Increased food demand is expected to lead to intensification, expansion of agricultural land to new areas, and pressure on natural resources, leading to increased AFOLU emissions (Smith et al., 2007a), especially since crop yield increases have been slowing down, reflecting the difficulty of achieving further improvements (Brown et al., 2015: 54).

East Asia is projected to show large increases in GHGs from animal sources, whereas South Asia's main contribution to increased emissions is expected to be from the use of nitrogen fertilizers and manure (Smith et al., 2007a: 16). Projected urbanization is likely to cause an expansion of food processing and an increase in food waste, which in turn will imply higher emissions and increased use of natural resources. Increases in the distance between the farm and the markets are likely to raise the use of energy for transportation and cold chain storage, and hence emissions in the food chain.

According to FAOStat projections, among the agricultural sources of direct emissions, those that are sole emitters of N₂O (i.e. the category identified as agricultural soils, which comprises not only synthetic fertilizers, crop residues, and cultivated organic soils, but also manure on pasture and manure applied to soils) are expected to grow faster than the sole sources of CH₄ emissions (i.e. enteric fermentation and rice cultivation) or the sources of combined CH₄ and N₂O emissions (i.e. manure management, and burning of crop residues and savanna). Thus, in 2050, global emissions from enteric fermentation are projected to be only 7% higher than emissions from agricultural soils. This will constitute a dramatic change from 1970, when emissions from enteric fermentation were 60% higher than emissions from agricultural soils.

The increasing role of agricultural soils in direct emissions growth points to the growing importance of land-use practices related to both crop and livestock production. It also shows the necessity of including N₂O in global mitigation efforts, since this is a GHG that is a lot more potent than CO₂. Over 100 years, an emission of 1 kg of N₂O traps 310 times more heat in the atmosphere than the emissions of 1 kg of CO₂ and also stays for a long time in the atmosphere (about 120 years) before decaying (Marchal et al., 2011: 12). The latter means that even small emissions of N₂O will accumulate over time, thus worsening climate change.

To summarize, continued increases in the demand for food and agricultural raw materials as world population and consumer incomes grow will stimulate increases in agricultural output. Without substantial reductions in the emissions intensity of agricultural production (i.e. emissions per unit of output), the growth in output will lead to an increase in global AFOLU emissions, particularly if this results in expansion of agricultural land. GHG mitigation in AFOLU will be essential if the increasing concentration of anthropogenic GHGs is to be halted.

2. Why must AFOLU in both developed and developing countries be included in global GHG emissions mitigation efforts?

There are several reasons for including AFOLU in global efforts to reduce total GHG emissions. These relate to the importance of the sector in creating and aggravating the problem (see previous section), the seriousness and universal urgency of dealing with the problem of climate change, the relative advantages of AFOLU in reducing global emissions, and the implications that the sector's exemption from mitigation efforts would have for other sectors, and for achieving the globally accepted mitigation goal. The following issues may be noted:

a. Emissions from AFOLU are a significant share of total GHG emissions

Currently, emissions from agriculture and land clearing induced by agriculture are larger than emissions from all of the world's cars, planes, and trains combined. They are three times greater than emissions from the global building sector and equal to all industrial emissions. In fact, energy production is the only sector that has a higher share of emissions (Retrieved February 2017 from www.environmentreports.com/how-does-agriculture-change/). The scale of emissions from AFOLU mandate that the sector be included in mitigation efforts.

b. Additional effort is needed to constrain emissions that continue to increase, despite expanding mitigation efforts

Climate-related hazards are expected to intensify as emissions continue to grow. Without additional efforts to constrain global GHG emissions, global average temperature (median climate response) is expected to increase in 2100 by between 3.7°C (6.7°F) to 4.8°C (8.6°F), compared to pre-industrial levels (IPCC, 2014).

The world community has been trying to address the challenge of climate change (e.g. Kyoto and Paris agreements). It has been conceded internationally that in order to avoid irreversible climate-related impacts, total global average warming should be stabilized below 2°C (3.5°F) above pre-industrial levels. Many national efforts have been undertaken to reduce GHG emissions.

Despite a growing number of climate-change mitigation policies, total annual GHG emissions, during 2000-10 grew on average by 1.0 GtCO₂e (2.2%) per year, compared to 0.4 GtCO₂e (1.3%) per year, from 1970 to 2000 (IPCC, 2014: 45). As the second largest contributor to emissions of CO₂ and the main contributor of other GHGs, AFOLU must be included in global mitigation efforts.

c. Nitrous oxide is a major contributor to global warming and agriculture is the major source of emissions

Climate-change impacts depend on cumulative emission levels. Even if emissions were stopped, many aspects of climate change will continue for centuries (Hollis et al., 2016: 18), since many greenhouse gases stay in the atmosphere for long periods of time (e.g. CO₂ and N₂O). Thus, even if the level of emissions was stabilized, over time the concentration of GHGs would continue to increase.

Even though N₂O has a shorter lifetime in the atmosphere than CO₂, it still lasts a long time (120 years) and is about 310 times more potent than CO₂. These characteristics make N₂O a gas with a “large global warming potential” (Marchal et al., 2011: 12; Blanco et al., 2014: 358). Since persistent changes in temperature induce enormous changes in the environment (NASA, 2016) and N₂O is a potential contributor to these effects, it must be targeted in mitigation efforts. Being the main source of N₂O, agriculture must be included in global mitigation efforts.

d. Agriculture is the largest source of emissions of methane, another potent GHG

Increasing accumulation of GHGs in the atmosphere can lead to irreversible effects. Intensification of global warming raises the risks of abrupt or irreversible climate change (IPCC, 2014). “Some risks are considerable even at 1°C global mean temperature above pre-industrial levels,” (IPCC, 2014: 65). An increase in global temperature of 4°C or more above 20th century levels would pose large risks to food availability, both globally and regionally. Without additional mitigation efforts beyond those in place today, even with adaptation, warming by the end of the 21st century will lead to a high or a very high risk of severe, widespread and irreversible impacts globally (high confidence) (IPCC, 2014).

CH₄, being a relatively short-lived GHG (12 years), does not accumulate as easily in the atmosphere. Nevertheless it is 25 times more potent than CO₂ over a 100-year period, which makes its contribution to global warming more than double its share in global GHGs (Marchal et al., 2011: 12). The combination of potency and duration makes reduction of CH₄ emissions “a critical strategy for reducing the near-term rate of global warming and avoiding climatic tipping points” (Marchal et al., 2011: 12), which could cause irreversible environmental damage. Because agriculture is the largest source of CH₄ emissions, it must be included in global mitigation efforts.

e. The characteristics of AFOLU are crucial for fighting climate change, due to its potential to contribute to the removal of carbon dioxide from the atmosphere and to supply bioenergy

The importance of agriculture in reducing global anthropogenic emissions is even greater than its current and projected future contribution to global emissions suggests.

Since agricultural production, by definition, cannot take place with zero GHG emissions, AFOLU needs to minimize emissions from agricultural activities and to make the maximum possible contribution to mitigation by enhancing carbon sinks and uptakes.

In addition, AFOLU could produce the biomass needed to substitute CO₂-emitting fossil fuels in generating energy, even though this approach should be treated with caution (see next section), given food security and water availability concerns, land restrictions and technological limitations (IPCC, 2014). AFOLU must be included in a comprehensive approach to mitigation.

f. Implication of exemptions

Exemptions for agriculture in global or national mitigation efforts should be viewed with great caution. Regardless of their justification, exemptions legalize a free rider problem at sectoral and regional levels, perpetuating a weak and ineffective approach to mitigation and magnifying the problem of climate change.

Exemptions not only imply that other sectors and the rest of the world bear the cost of inaction by exempted sectors and countries; they also introduce the need to impose additional adjustments on included sectors and countries to counterbalance the effect of exemptions on cumulative anthropogenic emissions.

“Scenarios indicate that direct and indirect agricultural emissions will constitute the largest sector of net emissions in the future, as other sectors are projected to reduce their emissions to the maximal extent by 2030” (Wollenberg et al., 2016: 3860). According to the same source, exclusion of agriculture from mitigation targets will either increase the mitigation cost in other sectors or reduce the feasibility of meeting the 2°C limit.

g. Agriculture has a high potential to mitigate

Agriculture has a high potential to mitigate not only by exploiting its technical (biophysical) potential in production, but also by taking advantage both of the soil's capacity to sequester carbon and the potential of other agriculture-related mitigation options, including the mitigation potential of forests and other land uses.

h. Agriculture, being one of the most exposed and vulnerable sectors to climate-related risks, has a major interest in limiting climate change

3. What potential contribution of the agricultural sector to GHG reduction targets (directly and indirectly through land-use change) might be envisaged?

As noted earlier, agriculture contributes to climate change directly through emissions of N₂O and CH₄. It also contributes, positively or negatively to carbon dioxide emissions through its impact on land use and land-use change. In addition to emissions of N₂O and CH₄, agricultural activities affect the capacity of soils to absorb and store carbon (soil carbon sequestration). Land-use changes induced by the expansion of agricultural area affect non-agricultural biomass and carbon sequestration (e.g. through forests, organic soils, savanna).

The capacity of soil and non-agricultural biomass to sequester carbon is limited and can vary over time as climate-change impacts on these limits. Mitigation from soil carbon sequestration also involves substantial uncertainty, as the outcome may be reversible. Nevertheless, agriculture's potential contribution to GHG mitigation should not be limited to the potential in reducing direct emissions but should also account for the potential mitigation from carbon sequestration in the soils used in agriculture, as well as the potential of other land uses for carbon removal and sequestration (e.g. forests, organic soils).

In considering the contribution of agriculture to mitigation, it is necessary to account for the combined potential of reducing all-GHG emissions in AFOLU and the food system, taking into account production, consumption and trade interlinkages.

A comprehensive approach to mitigation in AFOLU

A comprehensive approach to achieve the highest contribution of AFOLU to mitigation would require actions to exploit effectively the following:

- A. The supply-side mitigation potential in agriculture (i.e. in agricultural production and in the use of agricultural land). This comprises:
 - the technical (biophysical) potential of reducing emissions per unit of land or per animal by adopting appropriately tailored farming practices and land management
 - the potential from reducing emissions intensity in crop and livestock production (reductions in emissions per unit of output).
- B. The potential for mitigation in *Forests and Other Land uses (FOLU)* through:
 - reduction of emissions from land-use change (e.g. deforestation) associated with expansion of the area under agriculture
 - conservation of existing carbon stocks (e.g. peatlands, forest biomass, savanna)
 - enhancement of CO₂ uptake and carbon sequestration in forestry and other land uses (e.g. afforestation, reforestation, enhancement of carbon density in forest biomass)
 - protection from fires in forests and peatland.
- C. Exploiting options relating to the demand-side of the food system, i.e.:
 - reduction of food loss and wastage at all stages in the food chain
 - shifting dietary patterns to the benefit of less emitting agricultural and food products (e.g. substitution of non-ruminant meat for ruminant meat; substitution of crop protein for meat protein).
- D. Exploiting mitigation potential from reallocating agricultural production through international trade from countries with relatively emissions-intensive production to countries with lower emissions intensity.

In addition, the food system can make further contributions to mitigation through reduction of emissions in the production of agricultural inputs.

The supply-side potential for mitigation in agriculture: Technical potential and reducing emissions intensity

With respect to the supply side, equation (2) presented earlier suggests that total emissions in agricultural production can be reduced by decreasing: i) output; ii) emissions per unit of input (e.g. land or animals); or iii) the emissions intensity of output. Since food security is a major concern, any reduction in global food production caused by supply-side initiatives is not a desirable option. Nevertheless, reductions in total agricultural production or in the production of certain products may be an option for an individual country in meeting a national emissions reduction target.

Part of the supply-side mitigation potential lies in the technical potential of farming practices and management (Smith et al., 2007b; Smith et al., 2014) to:

1. Reduce N_2O and CH_4 emissions *per unit of area* under crop production or grazing.⁸ The contribution of each source (Figure 10) to agriculture's direct emissions suggests that priority in farming practices should be given to reducing emissions from:
 - enteric fermentation (CH_4), by improving grass varieties/sward composition and stocking densities (grazing land management), reducing ruminant stocks, increasing productivity in ruminants
 - manure on pasture (N_2O), by reducing the area of grazing land and stocking density, and by improving the ability to manage animal waste through the use of confinement
 - synthetic fertilizers (N_2O), by improving N use efficiency through N fertilizer application rates, fertilizer type, timing, precision application, inhibitors and drainage management
 - rice cultivation (CH_4), by improving water management and draining paddy at mid-season
 - manure management (CH_4 , N_2O), by reducing CH_4 emissions from manure stored in lagoons or tanks through cooling, the use of solid covers and separation of solids from slurry and by using anaerobic digestion to maximize CH_4 retrieval as a renewable energy source
 - burning of savanna (N_2O , CH_4), by preventing fires and improving management of prescribed burning
 - crop residues (N_2O), by using them as biomass to substitute for fossil-fuel use in energy production
 - manure applied to soils (N_2O), through better timing of applications and the use of nitrification inhibitors
 - cultivation of organic soils (N_2O), by refraining from converting organic soils to agricultural land and minimizing soil intervention
 - burning of crop residues (N_2O , CH_4) through fire prevention and improved prescribed burning.
2. Reduce CH_4 and N_2O emissions *per animal* under livestock management by targeting emissions from:
 - a. enteric fermentation (CH_4), by improving breeds and feeding practices (replacing forage by feed concentrates, improved forage), and by using CH_4 inhibitors

8. Emissions per unit of area and emissions per animal both measure emissions per unit of input in livestock production. Nevertheless, they should still be evaluated and assessed separately for mitigation purposes because management changes that directly target one of the two inputs (land, animals) can have indirect mitigating effects on the other. Specific mitigation alternatives under different categories (e.g. enteric fermentation or manure management) do not exclude the use of different options. For example, replacing forage by feed concentrates (an animal input focus) might be a less viable option for reducing emissions from enteric fermentation than improving grass varieties and changing stocking density (a land input focus).

- b. manure management (CH_4 , N_2O), by using dietary additives to reduce CH_4 emissions and by using soil applied and animal fed nitrification inhibitors and tailored diets and grazing management to reduce N_2O emissions.
3. Reduce CO_2 emissions and enhance CO_2 uptake and storage in soils under cropland management, grazing land management or other land uses (e.g. forestry, wetlands). Examples of practices that could enhance carbon sequestration in agricultural land (i.e. soil carbon sequestration) include:
- in cropland management: crop varieties and practices that increase carbon biomass above or below ground through crop rotation, use of cover crops, perennial trees, agroforestry, use of measures to increase yields and residue inputs, reducing tillage intensity and increasing residue retention, improving water availability (in humid regions, drainage of croplands is a way to promote productivity), and application of carbon additives (biochar)
 - in grazing management: appropriate intensity and timing of grazing under local conditions, improved grass varieties, fodder diversification and production; fire prevention and improved prescribed burning
 - restoration of degraded soils (revegetation for erosion control, improving soil fertility with organic and nutrient amendments, water conservation, improved fallow)
 - restoration of organic soils, usually classified as a mitigation option in agriculture, implies that the land that will be re-converted (by rewetting) to the native wetland ecosystems would be no longer used as cropland or grassland in agricultural activities.⁹

Implementation of technical mitigation options often involves trade-offs between emissions of different gases. In this case, the mitigation potential depends on the combined effect (see Smith et al., 2008). Examples of trade-offs include N_2O emissions, enhanced by soil carbon concentration; increased CO_2 and N_2O emissions when paddy-drying is used to reduce CH_4 emissions in rice production; enhanced CH_4 emissions when peatland fires are suppressed and organic soils are rewetted to reduce CO_2 and N_2O emissions; increased indirect emissions from biofuel production (Tian et al., 2016: 228). Annex 2 elaborates on the mitigation options and the trade-offs involved, using a classification based on Smith et al. (2008).

Another challenge associated with technical mitigation options in agriculture relates to risks to food security. This is because the technical mitigation options, focusing on reducing emissions per unit of land or animal, most of the time do not have a significant positive effect on output. In some cases they may even reduce output level (e.g. reduced tillage or rewetting of organic soils) in the absence of compensating changes in productivity. Thus, the required increases in output to meet the anticipated future growth in demand may not be achievable with technical mitigation options under current land use.

The effectiveness of technical mitigation options depends on their adoption rate, that is on how easily, how soon, and how fast they can be implemented (Smith et al., 2008). Differences in the criteria that underline the adoption rates are associated with economic, socio-cultural or institutional constraints.

IPCC's fourth assessment report (Smith et al., 2007b: 515) estimated the supply-side technical potential for mitigation in agriculture by 2030 to be within the range of approximately 4.5 Gt CO_2e per year to 5.5-6.0 Gt CO_2e per year. These estimates were obtained under the assumption that there are no barriers beyond the biophysical, and without accounting for any supplementary mitigating potential from the demand-side or from other land uses (e.g. forestry).

According to these estimates, the largest mitigation potential (89%) lies in soil carbon sequestration, i.e. in reducing net CO_2 emissions from farming practices and management, including cropland management, grazing land management, restoration of cultivated organic soils and restoration of degraded lands. In comparison, the mitigation potential in agriculture's direct emissions is modest. The mitigation potential for CH_4 is estimated to be around 9% of the total and is mostly concentrated in rice management and livestock management. Finally the mitigation potential of N_2O is estimated to be about 2% and lies in cropland management (Figure 29).

9. The restoration of organic soils is included by Smith et al. (2007b and 2014) under agriculture's mitigation potential but some other authors consider this option under mitigation from other land uses.

Figure 29. Global technical mitigation potential by 2030 by management practice (all gases)

Source: Smith et al. (2007b).

If the criteria of easy, fast, and immediate implementation are also taken into account, then two technical mitigation options qualify as effective options with high mitigation potential (Smith et al., 2014: Table 11.2). These are:

- reduction of tillage intensity (reduction of CO₂ emissions) and crop residue retention in the soil (reduction of N₂O and CH₄ emissions) and
- restoration of degraded soils.

The adoption of these two options faces economic challenges (e.g. average annual costs per hectare associated with the practices). Smith et al. (2008: 801) estimated the cost of tillage and residue management to be USD 5 per hectare, while that of degraded land restoration is estimated to be USD 50 per hectare, making it the second most expensive option after restoration of organic soils (USD 340 per hectare). Thus, the most cost-effective, easy and immediately implementable option with the highest mitigation potential at zero level of carbon pricing is the reduction of tillage and enhancement of crop residue retention in the soil.

Another challenge for some technical options relates to the duration and the reversibility of their mitigation effects. Some technical mitigation options cause permanent emission reductions, while others give temporary and reversible results (e.g. soil carbon sequestration). The selection of the appropriate mitigation options should be particular to the characteristics of a country and the relevant production systems.

Figure 30 shows estimates of the technical mitigation potential by region. These indicate significant differences both in biophysical mitigation potential and the uncertainty associated with the impact on emissions. In general, however, regions identified as high emitters in section one of this report (e.g. Southeast Asia, South America, East Asia, South Asia and Eastern Africa) are also identified as the regions with the highest biophysical mitigation potential.

Figure 30. Total technical mitigation potentials in agriculture (all practices, all GHGs) by region by 2030

Note: Boxes show one standard deviation above and below the mean estimate for per-area mitigation potential, and the bars show the 90% confidence interval around the mean.

Source: Smith et al. (2007b: 516).

The other supply-side potential for mitigation in agriculture lies in reducing emissions intensity (i.e. emissions per unit of output)¹⁰. This can be achieved through the following ways:

- gains in total factor productivity – i.e. gains in output are obtained through technological change, without increases in input use
- sustainable intensification – i.e. increases in output through enhanced managerial and technical efficiency in the use of existing inputs or through increased use of emitting inputs with high marginal productivity. Both of these intensification approaches lead to a reduction in the emissions intensity of total output, primarily because higher productivity in the use of existing agricultural land reduces the need for land clearing.¹¹

Both pathways may involve trade-offs with other environmental or social goals, but are compatible with food security (food availability) objectives, since they can be implemented without reducing food production. A challenge is posed by the possibility that gains in total factor productivity may result in higher total emissions due to “the rebound effect” (Herrero et al., 2016). This can occur if gains in productivity lead to lower consumer prices, stimulating food demand and leading to further expansion of agricultural production. Still, if the reduction in emissions intensity outweighs the effect of the increase in production, there would be an overall reduction in emissions.

Improved emissions intensity has been identified by Herrero et al. (2016) as a highly cost-effective mitigation option, particularly in the case of fertilizer use, cattle breeding, and (potentially) farm machinery adapted to local conditions and farm types.

As discussed in part 1 of this report, livestock production is a major source of direct emissions in agriculture. According to Herrero et al. (2016) and Gerber et al. (2013), livestock production has a high mitigation potential through improvements in emissions intensity. Gerber et al. (2013: xiii)

10. Mitigation options in this category may also qualify as technical mitigation options, since measures that lead to increases in productivity enhance soil carbon sequestration by raising yields and organic residues (Smith et al., 2007b). Nevertheless, the primary emphasis in the category of measures for reducing emissions intensity is on emissions per unit of output rather than emissions per unit of input.
11. Tilman et al. (2011: 20262) found that the avoidance of emissions from land clearance is roughly three times as much as the additional emissions generated by higher fertilizer use in under-yielding nations.

estimate that a 30% reduction of GHG emissions is possible (keeping output constant) if producers in existing production systems adopt the technologies and practices with the lowest emissions intensity, currently used by the top 10% of producers. Such a reduction would not compromise food security. Herrero et al. (2016) suggest that there is an even higher mitigation potential in livestock production.

These studies, however, stress the challenges associated with low adoption rates of technical practices and with reducing the supply of livestock products in food insecure regions. Adoption limitations could be addressed by implementing appropriate incentives (policies and market signals) and through investment in developing countries to facilitate greater market orientation in the livestock sector.

Both of the studies referenced indicate that the rebound effect is likely to be a challenge, both within the livestock sector and between the livestock and other sectors. Successful farmers, exploiting opportunities to increase profits, could expand output, thereby contributing to an increase in total emissions. Together with carbon leakage (discussed further below), potential rebound effects need to be addressed.

Mitigation potential in other land uses and the interaction with the demand-side

Agriculture is just one of the AFOLU sub-sectors and interacts with the other sub-sectors through the use of land. Differences in the use of land determine differences in the rate of carbon dioxide emissions and removals and define a land-use activity as either a source of carbon emissions or a sink (carbon removals).

As noted earlier (section one), agriculture reduces the soil's capacity to act as a sink. It is also a key factor in making global AFOLU a net emitter. Forests and organic soils in wetland ecosystems are sinks. When forests or organic soils are converted to agricultural land (cropland, grassland), this generates emissions through deforestation and drainage of organic soils. Additional emissions will follow from cultivation of the converted organic soils or the cleared forest land.

The mitigation potential in uses other than agriculture (i.e. FOLU) lies in:

- protecting forest land and organic soils from conversion to agriculture (i.e. deforestation and drainage of organic soils) and fires (wildfires or intentional burning)
- preventing forest degradation and restoring degraded forests
- increasing the forest carbon stock through forest management, reforestation, and afforestation of non-forested agricultural lands.

Prevention of biomass fires (forest, peat) requires proactive plans adapted to local conditions, focused on the most fire-prone biomass and regions.

A high mitigation potential lies in reducing the conversion of other land uses (e.g. forests, organic soils) to agricultural land. These conversions (i.e. deforestation and drainage of organic soils) are driven by increases in demand for agricultural land. Reductions in demand for land can be achieved through the following:

- technological advancements (leading to increased total factor productivity in agriculture)
- changes in production systems to increase the productivity of existing agricultural land (e.g. shift from extensive to intensive systems of production)
- shifts in human diets toward consumption of less meat or towards non-ruminant meat to take advantage of the fact that non-ruminants are more efficient converters of feed to edible products and their production systems are less land-intensive
- reduction in food waste across the food system.

Thus, land-sparing developments driven by either the supply or the demand-side of agriculture and the food system raise the mitigation potential in:

- agriculture, by reducing emissions per unit of output and enhancing soil carbon sequestration
- other land uses (FOLU), by avoiding emissions from the conversion of land under other land uses to agriculture

- other land uses (FOLU), by maintaining their capacity as sinks.

In addition, land-sparing developments such as the above are compatible with food security.

As noted, an important potential dimension of GHG mitigation relates to the demand-side of the food equation, including dietary preferences and waste. Reductions in demand for agricultural products due to changes in dietary preferences are beneficial because they typically decrease the use of emissions-generating inputs (particularly land), lower competition for water use (Smith et al., 2014: 837) and do not pose a threat to food security.

The Fifth IPCC Assessment Report (Smith et al., 2014) provides estimates of the GHG reduction potential in 2050 through changes in global land use considering different drivers for these changes, including yield improvements in crop and livestock production, human dietary changes, waste reduction and the combination of these factors (Table 4).

The estimates in the table indicate the contribution of the factors to GHG mitigation and their impact on the use of land in crop and livestock production. The reference scenario assumes continuation of on-going trends towards richer diets (particularly, higher consumption of animal protein), substantial gains in cropland yields (+54%) and a moderate expansion of cropland area (+9%). The dietary change case assumes a move to a lower animal product diet (8% of food calories from animal products). The yield growth scenario assumes additional yield growth of 9%. The feeding efficiency scenario corresponds to 17% higher feeding efficiency, and the waste reduction scenario assumes a 25% reduction in food losses throughout the supply chain.

Table 4. Changes in global land use and GHG reduction potentials in 2050 under various assumptions about mitigation options

Cases	Food crop area	Livestock grazing area	C sink on farmland	Afforestation of spare land	Biomass for energy on spare land	Total mitigation potential	Difference from reference case
Gha			GtCO ₂ e/year				
Reference	1.60	4.07	3.5	6.1	1.2-9.4	4.6-12.9	0
Diet change	1.38	3.87	3.2	11.0	2.1-17.0	5.3-20.2	0.7-7.3
Yield growth	1.49	4.06	3.4	7.3	1.4-11.4	4.8-14.8	0.2-1.9
Feeding efficiency	1.53	4.04	3.4	7.2	1.4-11.1	4.8-14.5	0.2-1.6
Waste reduction	1.50	3.82	3.3	10.1	1.9-15.6	5.2-18.9	0.6-6.0
Combined	1.21	3.58	2.9	16.5	3.2-25.6	6.1-28.5	1.5-15.6

Note: see source for details on assumptions and data sources.

Source: Smith et al. (2014: 840).

The highest total mitigation potential (6.1-28.5 GtCO₂e per year) is achieved through the combination of these factors, which also result in significant land savings (roughly 16% in the use of land for crop and livestock production) relative to the base scenario. The largest individual contributors to both potential emissions reductions and land saving are dietary change and waste reduction. Achieving such changes, however, is likely to be more challenging than increasing emissions efficiency through the adoption of supply-side mitigation options in agriculture (see section four of this report).

Estimates of the annual mitigation potential on the demand side by 2050 from studies that do not take into account carbon pricing or socio-cultural and institutional limitations, range between 0.76-8.55 GtCO₂e (Smith et al., 2014: 851) (Table 5).

Table 5. Estimated ranges of global mitigation potential (in GtCO₂e per year) in 2030

	Up to 20 USD/tCO ₂ e	Up to 50 USD/tCO ₂ e	Up to 100 USD/tCO ₂ e	Technical potential only
Agriculture only	0-1.59	0.03-2.6	0.26-4.6	-
Forestry only	00.01-1.45	0.11-9.5	0.2-13.8	-
AFOLU total	0.12-3.03	0.5-5.06	0.49-10.6	-
Demand-side options	-			0.76-8.55

Note: All demand side options are for 2050 approximately, see original source for additional notes on methodology.

Source: Smith et al. (2014: 851).

The economic potential: Mitigation potential under carbon pricing

As indicated earlier, estimates of the supply-side mitigation potential in agriculture are based on the exploitation of full biophysical potential and do not account for economic, socio-cultural or institutional constraints. Once economic constraints are taken into account, estimates of the achievable mitigation potential are reduced relative to their biophysical potential. The economic potential for mitigation takes into account likely adoption of mitigation practices, given their costs in relation to assumed prices for carbon. Carbon prices (and costs) have an impact on mitigation potential. The use of carbon pricing encourages mitigation activity (see section 4 for a discussion of carbon pricing and its effects in AFOLU).

The market potential, which reflects additional social and institutional constraints, is lower than the economic potential.

Figure 31. Economic mitigation potential by sectors in 2030

Source: IPCC (2007).

A comparison of the economic mitigation potential of technical options across sectors (Figure 31) shows that even with low carbon prices (i.e. <USD 20/tCO₂e), AFOLU (i.e. agriculture and forestry combined) has the second largest mitigation potential after buildings.¹² At high prices (i.e. <USD 100/tCO₂e), AFOLU is the sector with the highest potential, while the mitigation potential in agriculture expands more than in any other sector with increasing carbon prices.

At all prices, the highest potential in agriculture and forestry, considered both individually and combined, lies in developing countries, where, at low prices, agriculture also exhibits the second highest mitigation potential after buildings.

In Figure 32, mitigation potential in agriculture includes increased soil carbon sequestration through improved management of crop and grazing land and restoration of cultivated organic soils and degraded lands; reductions in CH₄ emissions (i.e. through improved rice cultivation techniques, and improved livestock and manure management); reductions in N₂O emissions (i.e. through improved N fertilizer application techniques); the use of dedicated energy crops to replace fossil

12. Although the base period for carbon prices is not defined in IPCC publications, it appears to correspond to currency values during the early part of the current century.

fuels; improved on-farm energy efficiency; and improvements in crop yields by applying key mitigation technologies and practices projected to be commercialized before 2030 (Smith, 2007a). The mitigation potential in forestry reflects: afforestation; reforestation; forest management; reduced deforestation; harvested wood product management; use of forestry products for bioenergy; and adoption of technologies, expected to be available by 2030, that enhance vegetation/soil carbon sequestration (directly or indirectly).

The Fifth Assessment Report of IPCC (Smith et al., 2014) estimates total annual AFOLU mitigation potential in 2030 to be approximately 3.0 GtCO₂e and 7.2 GtCO₂e at carbon prices of USD 20/tCO₂e and USD 100/tCO₂e, respectively, including only supply-side options in agriculture, but a combination of supply and demand-side options for forestry (Figure 32).

Figure 32. Mitigation potential for AFOLU by 2030

Note: Whiskers show the range of available estimates for agricultural options.

Source: Smith et al. (2014: Fig. 11.13).

Mitigation potential in AFOLU increases with higher carbon prices (Figures 31 and 32). At low and moderate prices agriculture exhibits similar potential to that of forestry. At high prices, however, its potential (and the uncertainty involved) increases relatively more than that of forestry. Under the scenarios examined, agriculture's global economic potential for mitigation is estimated to be 1.5-1.6 GtCO₂e, 2.5-2.7 GtCO₂e, and 4.0-4.3 GtCO₂e per year at carbon prices of up to USD 20, USD 50 and USD 100 per tCO₂e, respectively (Smith et al., 2008: 802).

Higher carbon prices change the relative rankings of mitigation options since they induce land-use changes that displace existing agricultural production (e.g. biofuels and afforestation) and allow the use of more costly mitigation options, such as improved animal feeding (Smith et al., 2008: 800).

Cropland management presents the highest mitigation potential in agriculture, except at high prices, where restoration of cultivated organic soils becomes the most promising option. At low carbon prices, only cropland management presents a high mitigation potential.

The restoration of cultivated organic soils, grazing-land management and the restoration of degraded lands exhibit relatively low mitigation potential at low carbon prices. This potential, however, is very responsive to carbon price increases, as conversion of marginal agricultural land to forestry or investment in low productivity land (e.g. grazing land or degraded agricultural land) becomes more attractive. Nevertheless, these options exhibit high mitigation uncertainty, associated with soil carbon sequestration.

Rice management (CH₄) and livestock (CH₄) show a relatively low mitigation potential, but with insignificant uncertainty. Mitigation potential in livestock is more responsive to carbon price increases. The mitigation potential from manure management and agroforestry seems to be relatively insignificant at all prices.

Regional mitigation potential under carbon pricing

The Fifth Assessment Report of IPCC (Smith et al., 2014) presented AFOLU's economic mitigation potential in 2030 by region and by source/sink of emissions under various carbon prices (Figure 33).

At all prices, Asia is the region with the highest mitigation potential both in AFOLU and in agriculture considered separately. It is the only geographical region that exhibits a clear mitigation advantage in agriculture relative to forestry. Developed countries (OECD-1990) show the second largest mitigation potential in agriculture at all prices.¹³ Latin America has a large mitigation potential in forestry (reduced deforestation), which increases with higher carbon prices.

At low prices, cropland management in Asia and OECD-1990, and rice management in Asia offer the highest global mitigation potential. At higher carbon prices, the mitigation potential of options that relate to land-use change and land-use improvement become increasingly important globally. The highest potential lies in restoration of cultivated organic soils in both Asia and developed countries; restoration of degraded lands in both developed countries and Asia; and grazing land management in both Africa and Asia. Livestock is more responsive to carbon pricing in developed countries and, to a lesser extent, in Asia and Latin America.

The potential of forestry mitigation options differs regionally. Within each region, the composition of forestry's mitigation potential is relatively unresponsive to increasing carbon prices (Figure 34).

Figure 33. Economic mitigation potential in AFOLU by region by 2030

Source: Smith et al. (2014: 852).

13. See the footnote 1 in Table 13 for the countries included in OECD-1990.

Figure 34. Mitigation potential from forestry options by region at different carbon prices.

Source: IPCC (2014 : graph 11.18).

In developed countries (OECD-1990 and Economies In Transition-EIT), nearly two thirds of the mitigation potential in forestry lies in forest management, followed by afforestation.¹⁴ As prices rise, the potential of forest management grows modestly relative to that of afforestation.

In Latin America (LAM), more than half of the mitigation potential lies in reducing deforestation. At high prices, afforestation's potential increases slightly at the expense of reduced deforestation. In the Middle East and Africa (MAF), reduced deforestation exhibits the highest and practically unchanged mitigation potential at all carbon prices.

In Asia, almost half of the potential lies in forest management, which is unresponsive to carbon prices. Higher carbon prices increase slightly the mitigation potential of afforestation relative to reduced deforestation.

In Africa and to a lesser extent in Latin America, the highest mitigation potential in forestry lies in reduced deforestation. Carbon pricing leaves the composition of forestry's mitigation potential virtually unchanged, at least at prices up to USD100/GtCO₂e. This suggests that there is a high and effective mitigation potential in reducing deforestation in these two regions.

The mitigation potential that could actually be realized, if socio-cultural and institutional challenges were taken into account, is unknown. Many of these challenges are extremely important for the choice and implementation of policies to achieve emissions reductions (see section five of this report for examples). Higher carbon prices will be needed to induce adoption of mitigation options that involve higher economic cost, and confront socio-economic and institutional challenges.

Agriculture's contribution under the Paris agreement: Needs and potential

Under the Paris Agreement, the vast majority of countries presented proposals for agricultural mitigation as part of their Intended Nationally Determined Contributions (INDCs). Of the parties that included mitigation in their INDCs, 103 included targets related to agriculture and 128 included targets related to other land uses (most commonly forests). Nevertheless, only nine provided specific percentage goals for reducing agriculture's direct and indirect emissions (e.g. Ethiopia) relative to business-as-usual levels. Moreover, pledges were usually limited to targeting improvements in efficiency and productivity in the livestock sector, without specifying how these targets will be achieved (Richards et al., 2015). Finally, the largest emitters (China, India, and the United States) did not provide sector-specific targets. Thus, the national pledges under the Paris Agreement are not sufficient to achieve, on AFOLU's part, the global target of keeping global warming below 2°C by the end of the century (Richards et al., 2015).

14. Economies in transition include countries that were part of the Soviet Union and associated states, such as Bulgaria, Hungary and Poland.

Linking mitigation efforts in agriculture and agriculture-related options to the 2°C goal is crucial for contributing in a realistic way to the objective of avoiding irreversible climate change and for keeping the focus on what is required (Wollenberg et al., 2016). Current pledges concentrate only on what is technically and politically feasible. The challenges involved are considerable. Adhya et al. (2014: 3) state that “if agriculture were to reduce its emissions in the same proportion as other sources to meet the generally recognized target of limiting global warming to just 2°C, agricultural emissions would have to decline by two-thirds from present levels, even as agriculture produces 70% more food.”¹⁵ That means that 70% more food will have to be produced with a third of current emission levels.

Wollenberg et al. (2016) used a low-emissions IPCC scenario (RCP2.6) and three different integrated assessment models (IAM) to derive target levels for reductions in agriculture’s direct emissions, consistent with the 2°C limit in 2100. All the models assumed significantly higher carbon prices than current prices, no changes (positive or negative) in food security relative to current levels, and accounted for increases in food production to meet the needs of a larger population and shifts in consumer demand. The gases and emission sources used to determine agriculture’s share in emissions reduction were limited to non-CO₂ gases (i.e. only direct emissions from crop and livestock production). Soil carbon sequestration and the related CO₂ fluxes associated with crop and livestock production and with agroforestry, were not taken into account. Carbon sequestration from other land uses, as well as a combination of bioenergy and carbon capture and storage technology needed to offset expected demand-driven increases in food emissions, were included in the models but were not accounted for under agriculture.

The analysis showed that the reduction in global direct (non-CO₂) agricultural emissions needed in the near term (2030) to be consistent with the 2°C limit in 2100 is roughly 1 GtCO₂e per year and would need to be increased gradually to 4.3 GtCO₂e per year over the long term (by 2100).

The total reduction in emissions across all sectors in 2030 from business-as-usual levels (approximately 68 GtCO₂e per year globally in 2030) to be in line with the 2°C goal, is 26 GtCO₂e per year or almost 62% of the business-as-usual (BAU) level. The annual reduction needed in agriculture’s direct emissions in 2030 corresponds to 11-18% fewer emissions relative to BAU levels. This would contribute 4-5% to the total annual mitigation needed across sectors in 2030 to achieve the 2°C goal. Thus, the required share of agriculture’s direct emissions in global annual mitigation is less than half the current contribution of agriculture’s direct emissions to total GHG emissions.

Nevertheless, Wollenberg et al. (2016) showed that under current technologies and at low carbon prices (<USD 20/tCO₂e) even this relatively modest contribution cannot be achieved by relying solely on agriculture’s technical mitigation potential. Current agronomic and policy interventions targeted to non-CO₂ emissions in agriculture and compatible with food security were estimated to be capable of achieving only 21-40% of the needed mitigation, even if global dissemination and nearly universal adoption of improved technologies were realized, and large-scale transformation of crop and livestock production systems took place at low cost (up to USD 20/tCO₂e).

Widespread dissemination and adoption of improved technologies and technical agronomic practices in livestock, cropland and rice management were shown to have the potential to reduce agricultural direct emissions by up to 0.40 GtCO₂e per year in 2030 (i.e. the 40% reduction stated above). Sustainable intensification of crop and livestock production achieved by increasing economic efficiency (i.e. transitioning from extensive grassland systems to more efficient and sustainable livestock production with improvements in feeding, breeding, reproduction, health and grass management, as well as re-allocating production to GHG-efficient regions) was shown to have the potential to contribute 0.21 GtCO₂e per year in 2030 to the total (i.e. the 21% reduction stated above).

Wollenberg et al. (2016) suggest that to increase mitigation potential in agriculture, either more transformative technologies and policies are required, or mitigation targets should be expanded to agriculture-related sectors. Their analysis suggests the following actions:

15. According to the Food and Agriculture Organisation (FAO), the world agricultural production needed to satisfy the increase in food demand due to population growth in 2050 is 60% higher than that in 2005/07 (Alexandratos and Bruinsma, 2012), but figures of 70%-100% are often cited in the literature.

- development and dissemination of more transformative technologies, especially in developing countries. Such solutions are not likely to be widely available soon, even though developments in CH₄ inhibitors and low emitting cattle breeds and crop varieties are considered to be potentially promising. Strong technical assistance to farmers and co-ordination in research and investment are needed to develop high-impact, quickly implementable, and easily accessible technical options, especially in developing countries. Incentives are needed to improve information systems and to promote large scale adoption of productive and new agricultural practices by farmers.
- design and implementation of more transformative policies to expand the availability of options with higher mitigation potential in sectors related to agriculture in production (e.g. carbon sequestration, forestry and other land uses), as well as in the post-production stages (e.g. food loss and waste and dietary preferences) of the food system. Financing of low emissions agricultural development will be crucial, especially in developing countries.
- internalizing the cost of carbon by setting carbon prices at higher levels to expand the range of mitigation options and increase mitigation potential. According to World Bank, Ecofys and Vivid Economics (2016: 23) currently “about three quarters of the emissions covered [under policies] are priced at less than USD 10/tCO₂e,..., thus well below the level required to effectively support at least a 2°C goal”.
- coordination of global institutions concerned with agriculture and food security to set sectoral targets compatible with the 2°C limit and to enable countries to establish plausible mitigation goals for the food system.

In the absence of agreed targets for carbon sequestration and agriculture-related emission sources linked to the 2°C limit, Wollenberg et al. (2016: 3863) estimated targets compatible with the 2°C limits “based on what is achievable globally at low costs”.

The expansion of options was found to increase the mitigation potential of AFOLU and related emissions to approximately 5-9 GtCO₂e/year or about 27% of the mitigation needed across all sectors, a larger share than AFOLU’s contribution to global emissions. It comprises the following:

- soil carbon sequestration (1.2 GtCO₂e/yr in 2030 at USD 20/tCO₂e), which is considered the largest potential sink compatible with food security, although it has easily reversible effects (e.g. through tillage)
- reducing land-use conversions associated with expansion of agricultural land (1.7-4.31 GtCO₂e/yr in 2030 at USD 20/tCO₂e)
- reducing food loss and waste, which currently corresponds to 30-50% of global food production, by 15% of the total global waste level (0.79-2.00 GtCO₂e/yr in 2030)
- changing diets according to recommendations by the World Health Organisation (0.31-1.37 GtCO₂e/yr in 2030) or in response to increases in carbon prices (see also Briggs et al., 2016).

Thus, agriculture has a great and achievable mitigation potential at low costs under the condition that mitigation options are not restricted to the potential offered by reductions in direct agricultural emissions, but are expanded to cover: the entire AFOLU sector (i.e. including CO₂ fluxes from soil sequestration in agricultural production); food loss and waste; and changing diets. More mitigation could be achieved by targeting the energy sector (e.g. manufacturing of inputs), but that would not be counted under AFOLU.

The work of Wollenberg et al. (2016) highlights the urgency of maximizing all potential options for mitigation compatible with the 2°C limit, by using a comprehensive approach that would include all sectors, all gases, and all aspects of markets across the economy, including in agriculture and the food system.

To summarize:

- Agriculture could contribute effectively to meeting the necessary reduction in global GHG emissions by 2030 and beyond, providing that in addition to direct emissions of N₂O and CH₄, soil carbon sequestration from the use of land in agriculture is addressed.
- The reduction required in agriculture's direct emissions relative to the required global mitigation in 2030 to be in line with the 2°C goal is less than half the current contribution of agriculture's direct emissions to total GHG emissions.
- Significant mitigation potential in AFOLU lies in avoiding emissions from conversion of other land uses to agriculture and in maintaining/increasing carbon sinks.
- Realistic carbon prices are needed in order to stimulate the adoption of mitigation options. Effective mitigation requires the use of supportive policies.
- AFOLU mitigation requires a comprehensive approach, including: changes in dietary preferences; waste and food loss; as well as the use of non-food land and agricultural biomass in the production of bioenergy (substitute for fossil-fuel energy).
- Transformative approaches to mitigation require addressing social, cultural and institutional barriers, in addition to overcoming technical and economic constraints.

4. How would such mitigation targets affect the sector's productivity, competitiveness, and food security?

As noted in section three above, achieving desired mitigation in agriculture requires changes in production, consumption, land use, and waste. These can be facilitated by changes in relative prices and in producer and consumer behavior, induced naturally, in response to mitigation policies targeting AFOLU, or by other sectoral and non-sectoral policies.

Mitigation options have different implications for productivity, competitiveness and food security, depending on whether:

- production costs increase or decrease
- output increases or declines
- differentiated markets for products of low-emissions intensity exist.

Additional implications result from the differences in distributional effects across sectors, farmers and regions. Land-use mitigation options can also have an impact through reallocation of agricultural land to other uses (e.g. bioenergy, peatland restoration, forestry).

The absence of any additional mitigation efforts, however, will also have implications for productivity, competitiveness and food security, due to the effects of climate change on yields, productivity and output.

Impact of climate change on agricultural productivity, competitiveness and food security

Higher temperatures associated with increased concentration of anthropogenic greenhouse gases in the atmosphere lead to climate-change intensification. The continuation of AFOLU activities in a business-as-usual framework will increase the accumulation of GHGs in the atmosphere and enhance the impact of climate change and related events on yields and productivity. Food security, productivity, and competitiveness will be affected to various degrees, depending on the intensity of climate change, the relative exposure of farmers, sectors, and regions to the phenomenon, and their capacity to adapt.

The following paragraphs summarize some of the key conclusions from the assessment of IPCC (2014) and other studies of the impact of climate change on agriculture.

Increased concentration of CO₂ in the atmosphere can contribute to higher crop yields, improved efficiency in water-use, and increases in soil organic matter caused by easier penetration of plant residue into soils. The latter effect may be offset by increased soil-erosion due to intense

precipitation and nutrient deficiency associated with global warming. The impact of elevated CO₂ levels varies according to plant variety, temperature, the availability of water and nutrients and interactions among these factors.

In the twentieth century, higher average global temperatures resulted in an earlier start to the growing season and its lengthening by a global average of 10–20 days. Longer growing seasons can increase yields and permit double-cropping, particularly in temperate latitudes, providing that sufficient water and nutrients are available and higher temperatures do not interfere with crop germination.

Warmer temperatures also increase the rate of biomass decomposition. As this may lead to greater availability of soil-nutrients, it can also increase yields. On the other hand, higher average temperatures associated with longer growing seasons result in reductions in soil moisture and higher crop-moisture stress, even under unchanged precipitation.

The effects of CO₂ fertilization tend to be greater for temperate or cool season plants (such as wheat, rice, cotton, soybeans, sugar beets and potatoes) but less for tropical or warm-season plants (such as maize, sorghum and sugarcane).

Studies suggest that yields of maize and wheat in the tropics begin to decline when global average temperatures rise by 1–2°C. Yields of maize in temperate regions and rice in tropical regions are less clearly negatively affected but decline significantly with warming of 3–5°C. Yields in northern latitude regions may be positively affected by climate change. Even after accounting for CO₂ fertilization benefits, however, yields of all crops will be negatively affected with temperature increases greater than 3°C. Negative impacts become more likely from 2030 onwards (see Annex 1, Table A1.1).

Climate change also impacts crop production by affecting the range and the intensity of infestations by crop pests and pathogens. Weather is the primary driver of the emergence of 25% of crop-pathogen species.

Livestock production is likely to be affected by climate change. The major impacts are through changes in forage, feed and water availability; the impact of higher temperatures on animal health; and the incidence of pests and disease. Heat stress from higher temperatures diminishes food intake and physical activity for livestock, leading to lower growth, survival and reproductive rates, and lower production of meat, milk and eggs. For grazing livestock, changes in precipitation and warmer temperatures can lead to increased availability of forage but also to lower nutrient content, thus resulting in decreased digestibility and poorer livestock performance. The climate effects on these factors vary by location and types of outdoor livestock operations. Livestock production, like crops, is projected to be negatively affected in all continents. Dairy, meat and wool production systems are likely to be most affected due to their reliance on fodder. Even in indoor livestock production systems (primarily poultry and swine operations) which provide greater potential for temperature control, the absence of additional measures to manage higher temperatures could raise heat stress and associated mortality.

The overall effects of climate change on yields are expected to differ by region. In the absence of adaptation, South Asia and Southern Africa are projected to be most negatively affected by climate change (estimated yield declines of up to 8% for both regions by 2050). Annex 1, Table A1.1 summarizes projected impacts of various climate-change scenarios on crops and livestock per region, as examined in the IPCC Fifth Assessment Report (see the table for details).

Adaptation, having the capacity to reduce the impact of climate change, is an objective that complements mitigation. The productivity and competitiveness of regions and farmers with greater capacity to adapt will be less affected by climate change. Large farmers and farmers in countries and regions where access to capital, technology and information is easier, and infrastructure for adaptation can be well-developed, will be better able to adapt and maintain their competitive position in the face of climate change.

In conclusion, the absence of mitigation will affect productivity, competitiveness and food security through the impact of climate change on yields, output and costs of production. The negative effects of climate change on productivity and competitiveness will increase with global warming and will expand geographically from tropical to temperate and northern regions. With higher increases in temperature, both crop and livestock will be affected in all continents.

Policy approaches to promote mitigation

Mitigation can be effected by changes in relative prices (input to input, input to output, output to output) to which producers and consumers respond in making production and consumption decisions or by dissemination of information, knowledge and new socio-cultural values that influence decision-making. Changes in relative prices and in behavior can be naturally induced or result from targeted mitigation policies and other policies.

Targeted mitigation policies can be directed to all stages of the food system (Table 1), as well as to non-agricultural activities in AFOLU. Approaches identified below, are conceptually possible, although their feasibility may vary across sub-sectors and regions:

- Carbon pricing. This can be achieved explicitly through carbon taxes, implicitly through regulation or through a mixed approach, such as emissions trading. The implementation of carbon pricing in the food system includes the following:
 - Pre-production stage (supply of inputs): carbon pricing, applied indirectly on energy used in the production of agricultural inputs or directly on the inputs themselves (e.g. fertilizer taxes and taxes on fossil-fuel energy)
 - Production stage: direct or indirect taxes, applied to agricultural outputs (crops and livestock) according to emissions intensity or to AFOLU practices (e.g. deforestation)
 - Post-production stage: direct or indirect taxes on energy use (processing, storage, packaging and transportation, refrigeration, retail activities); direct regulation of energy use (e.g. energy efficiency requirements in the cold chain); taxes on waste; consumer taxes on emissions-intensive foods.
- 2. Inducement policies. These involve the creation of economic incentives for the use of low-emission inputs or adoption of low-emission AFOLU practices; promotion of the production or consumption of low-emission products; or promotion of the production and use of biomass as an alternative to fossil energy. This category of policies includes:
 - Pre-production stage: subsidization of the development and use of emissions-reducing inputs (e.g. nitrogen inhibiting fertilizers, and inputs, such as natural pesticides; the production of which does not rely on fossil fuels)
 - Production stage: use of environmental programs (subsidies and regulations) to promote the adoption of emissions-reducing AFOLU practices (e.g. minimum tillage, restoration of degraded soils, retirement of carbon-rich soils from agricultural production, sustainable forest management)
 - Post-production stage: subsidization of the development and use of emissions-reducing technologies and practices (e.g. energy-efficient appliances).
- 3. Behavioral change policies. These involve the use of information, education and knowledge transfer to effect emissions-reducing behavior by producers, consumers and land managers in AFOLU. Implementation could include the following:
 - Pre-production stage: diffusion of information on the implications of production practices for emissions
 - Production stage: increasing managerial efficiency and enhancing the understanding of the implications of production practices and decisions on emissions
 - Post-production stage: promotion of voluntary schemes for energy conservation and waste reduction in post-production activities (e.g. reduction of packaging, changes in date labelling of food); promotion of emissions-reducing food choices and reduction of waste at the consumer level (e.g. through labelling of carbon footprint on food, consumer education on the emissions implications of food choices).

To the extent that low-emission products can be differentiated from high-emissions products, a market could be created for low-emission food products. This could help consumers to express their preferences for low-emitting foods. Product standards and labelling could help to achieve

differentiation in the same way as they have helped to create a market for foods produced using “organic” methods in some countries.

Economic incentives and disincentives (i.e. inducement policies and carbon pricing) affect both the level of output and its composition, and the cost of production. The latter is also affected by the reallocation of land to different uses. Behavioral change policies pose a minimal risk to food security and have no direct effect on productivity and competitiveness associated with production costs at the national level. They do, however, lead to redistribution of resources among different uses within the agricultural sector; therefore, their effect on agricultural sub-sectors and among farmers will differ.

In addition to deliberate changes in relative prices induced by policy actions, changes in relative prices can also result from systematic developments affecting agricultural and food markets (e.g. changes in technology, demographics, consumer preferences) and random factors (e.g. weather and political events). Climate change and related hazards will have significant impacts on price volatility and food security globally, even though effects on sub-sectors and regions will vary.

Changes in relative prices caused by systematic developments may create “natural incentives” for economic agents to contribute to mitigation. In production, natural incentives can generate shifts in the output mix (to lower-emitting products), in the input-output mix (reduced emissions intensity of output) or in the input mix (substitution of a lower-emitting inputs for higher-emitting inputs). In many countries, for example, increases in total factor productivity (TFP) have contributed to large increases in agricultural output, while at the same time economizing on the use of inputs, some of which were significant sources of emissions (e.g. fertilizer and land). Market-oriented producers (i.e. those who respond to output and input price signals), having an economic incentive to succeed in the market place, adopt technologies and practices that reduce the cost of production. In so doing, producers involuntarily contribute to GHG mitigation.¹⁶

Similarly, “natural incentives” for consumers may induce a shift in consumption from higher-emitting products (e.g. beef) to lower-emitting products (e.g. poultry). This has occurred in some developed countries (e.g. the United States) as a result of substantial declines in the relative price of poultry to that of other protein sources, driven largely by efficiency gains in poultry production.

“Natural” changes in relative prices that result in involuntary mitigation (“natural incentives” to mitigation) are almost always associated with improvements in productivity and competitiveness and with no loss of food security since they occur through voluntary adjustments by producers or consumers in optimizing their economic welfare.

Even though the pursuit of aggressive mitigation targets in AFOLU, such as those needed to keep global warming below the 2°C limit, requires the implementation of targeted mitigation policies, the capacity of “natural incentives” to promote mitigation could be suggestive of directing public and private investment into the development of technological advancements that would create favorable market conditions for promoting mitigation. This can be an effective strategy to follow, especially in regions where targeted mitigation policy approaches face socio-cultural and institutional limitations.

Implications of mitigation options in AFOLU for productivity, competitiveness and food security

As noted in section three, estimates suggest that the amount of GHG mitigation in agriculture required to limit the increase in global warming to below 2°C is proportionately less than that for other sectors (e.g. energy). This implies that the pursuit of mitigation target in agriculture should not cause its competitive position to deteriorate relative to other sectors. In other words, the sector should be able to attract resources needed to meet food security objectives.

Nevertheless, the implications of mitigation targets for productivity, competitiveness and food security depend on the types of policies (approaches and options) used, and their effect on production costs and output. Other policies (sectoral or economy-wide, mitigation or non-

16. One example relating to changing the mix of inputs was observed in the 2000s, when in response to the increase in the price of fossil-fuel energy, US farmers sought to economize on the use of energy-intensive inputs in order to maintain profitability (Harris et al., 2008).

mitigation) also influence the outcome through their impact on production, consumption, land use and international trade.

The following can be identified as general implications of mitigation policies for productivity, competitiveness and food security:

- Productivity increases as a result of:
 - output-increasing or input-decreasing technological advances (e.g. agricultural biotechnology)
 - changes in practices and managerial skills that enhance efficiency (e.g. sustainable intensification)
 - improvements in the quality of inputs (e.g. use of feed in ruminant production, restoration of degraded land)
 - infrastructural improvements in the post-production stages of the food chain leading to less waste
 - increased availability of scarce, productivity improving inputs (e.g. fertilizer).
- Productivity decreases as a result of:
 - climate change (as discussed earlier)
 - restoration of organic soils if the land removed from agriculture is highly productive
 - expansion of agriculture to marginal land with low productivity
 - conversion of existing agricultural land to lower productivity uses (i.e. extensification).
- Competitiveness may increase as a result of:
 - reductions in production costs
 - increases in output for a given volume of inputs
 - reductions in land use induced by lower demand or by technological advancements that raise TFP. Land sparing (release of land from agriculture) lowers the cost of land and reduces the cost of production in agriculture. Imposed reductions in agricultural land use or the control of agricultural land expansion (e.g. through regulation to control deforestation) raise the cost of agricultural land and lower competitiveness
 - product differentiation on the basis of carbon footprint, if consumers adjust their purchases in response to carbon labelling
 - a change the relative international competitiveness of regions. In the absence of a universal application of carbon pricing in AFOLU, countries that do not mitigate may gain competitiveness over countries that mitigate and thereby increase the cost of production of emissions-intensive products. This leads to the problem of carbon-leakage, discussed later in this section. Even with the universal application of a carbon price, differences in emissions efficiency (emissions per unit of output) will mean that the relative competitiveness of regions and agricultural sub-sectors is likely to change.
- Competitiveness may decrease as a result of:
 - imposing a high national carbon price if carbon pricing is not implemented internationally.
- Food security:
 - may be enhanced as a result of increases in food output
 - may be unaffected by mitigation policies that do not have a significant impact on output¹⁷ or that substitute nutritionally equivalent (calories or protein) lower-emitting food for higher-emitting food

17. This holds under the assumption that the output level would be adequate to maintain the current level of food security or if we consider the impact on food security at a specific point of time. If time and

- may be put at a disadvantage by mitigation policies that promote the use of land in non-food activities (i.e. bioenergy based on food or feed crops, regulation that limits deforestation); reduce consumption of protein- or calorie-rich products, indiscriminately, without allowing for substitution by products of equivalent nutrient value.

We now turn to examining likely effects of specific mitigation options, according to a classification under the supply- or demand-side of the food system.

Supply-side mitigation options

As seen in section three, supply-side mitigation options, excluding output reduction, comprise farming practices and land management that target emissions per unit of input (land or animal), as well as changes in technical and managerial efficiency and technology that lower emissions per unit of output.

Reducing emissions per unit of input

Many options among those that target emissions per unit of input may have a modest positive or even a negative effect on productivity and output. For example, the use of no-till may reduce crop yields and output, but can be profitable and cost-effective for (and therefore adopted by) farmers, if the reduction in production costs is greater than the reduction in the value of output. However, the reduction in output may lead to a decline in national competitiveness and to deterioration in food security.

Other options in this category, for example the use of improved feed rations in livestock production or improvements in pastureland, although cost-increasing, may be profitable and cost-effective for farmers, because they increase output and productivity, thereby improving national competitiveness and food security. In general, mitigation options in this category can be more easily and quickly adopted, but have uncertain effects on productivity and food security.

Some practices in crop and livestock production reduce emissions by improving efficiency, without increasing the use of inputs (e.g. optimized rotation, crop-livestock system integration, precision farming). This type of sustainable intensification is compatible with environmental goals but has limited output-enhancing effects, thus doing little to enhance food security in the face of increasing demand due to population and income growth.

Reducing emissions per unit of output

Mitigation options targeting emissions per unit of output involve increases in agricultural productivity. The effects on mitigation and the implications for competitiveness and food security differ according to the pathway followed.

Total factor productivity gains, in which gains in output are obtained through technological change without increases in input use, can make a major contribution to meeting the increasing global demand for food and therefore to global food security. Many analysts have emphasized the benefits generated by technological change for consumers in advocating for the public funding of research that supports technological change and innovation in agriculture. Rapid productivity growth also contributes to gains for consumers by constraining increases in the real price of food. Although food security, particularly at the level of individuals or households, is not guaranteed by the availability of ample supplies of food at affordable prices, keeping food prices low (or at least avoiding sharp increases) has been seen as desirable in many countries, particularly in the developing world where a large proportion of household disposable income is often spent on food. Total factor productivity gains also improve competitiveness. Total emissions may increase as a result of increased output (the “rebound effect”). According to some estimates, total factor productivity gains are only half as efficient in saving emissions as they are on the food supply side due to the rebound effect (Valin et al., 2013). Nevertheless, TFP gains are probably the most effective way to contain emissions in food production as food demand grows.

In conventional intensification practices, increased yields result from increased variable input usage (e.g. additional fertilizers, pesticides, irrigation and machinery). This is likely to produce higher total emissions and possibly create other environmental stresses (e.g. on water quality and quantity). Even if total emissions increase, however, emissions intensity can be reduced if the effect of intensification on

anticipated demographic changes were taken into account, stagnant levels of output would increase food insecurity in the future in the absence of offsetting developments (e.g. a reduction in food waste).

output expansion is larger than the direct effect on emissions. In some cases where intensification results in land sparing, total emissions might even decrease if saved emissions from a reduction in land clearing outweigh additional emissions from the intensive use of fertilizer. This is particularly relevant to many developing countries that have yields below the global average due to, for example, farmers' lack of access to inputs or technology, non-optimal conditions of applying fertilizer or soil erosion. Parts of Asia and Africa are underutilizing fertilizers and could benefit significantly from better access to these.

The importance of land sparing in mitigation is crucial in determining the optimal allocation of land to food, feed and bioenergy crops.

Improved technical and managerial efficiency in production can also lead to correction of nutrient overload. According to the University of Minnesota's *Environment Reports* (www.environmentreports.com/foodmatters/), roughly 45% of the nitrogen added to fields globally each year is not taken up by crops. For crops such as sugar beets, sugarcane, potatoes and cotton the percentage can be as high as 65% to 93%. Correcting for surpluses in fertilization would decrease emissions while increasing productivity, output and environmental quality, and possibly profits.

Environment Reports states that in countries with high yields, nitrogen and phosphorus applied to maize, wheat and rice could be reduced by an estimated 20%-24% and 13%-22% respectively, without compromising crop yields. Such a reduction in input use would reduce N₂O emissions, which have a high warming effect, while raising productivity and competitiveness.

The recent performance of the OECD countries shows the effect of a continuing focus on increasing technical efficiency and productivity in agriculture. During the period 2000-10, OECD countries reduced their agricultural emissions intensity by 1.6% per year by adopting improved technology and farm management practices. GHG emissions decreased at an annual rate of 0.4%, while agricultural production increased at 1.6% per year as a result higher productivity and value added (MacLeod et al., 2015: 7-9) (Figure 35). Such developments promote both the objective of food security through higher output, while constraining the growth in emissions.

Figure 35. Trends in GHG emissions, agriculture GDP and productivity in OECD countries

Note: Excluding LULUCF (land use, land use-change and forestry). Source: OECD (2014) based on UNFCCC Greenhouse Gas Inventory Data, http://unfccc.int/ghg_data/items/3800.php; FAO, FAOSTAT (database), <http://faostat.fao.org/>.

Source: MacLeod et al. (2015).

The overall effect of mitigation options that are based on efficiency and productivity improvements depends not only on the type of technological improvement but also on the factor that benefits from productivity gains. Sustainable land intensification has been estimated to increase GHG savings by one-third when compared to a fertilizer intensive pathway (Valin et al., 2013).

Productivity improvements have different impacts on crop and livestock production. Crop yield increases benefit mostly production growth and food security, whereas livestock productivity gains allow the greatest GHG emissions reductions by allowing reductions in livestock numbers and land

saving. In order to exploit fully mitigation and food security co-benefits, a combination of productivity increases in both crop and livestock sectors is required (Valin et al., 2013).

Soil carbon sequestration

As noted in section three, the highest mitigation potential for achieving the desired global warming limit lies in improvements in cropland management, in the restoration of degraded lands, and in the restoration of organic soils. These mitigation options, with the possible exception of crop management, increase the cost of production by more than the increase in output and can only become attractive options for farmers under carbon pricing or the use of targeted subsidies. Restoration of cultivated organic soils will reduce agricultural output and thus increase food insecurity, unless the output effect is offset by TFP gains in the land that remains in agriculture.

Mitigation options in forestry and other land uses (FOLU)

Mitigation in other land uses comprises:

- Reductions in CO₂ emissions from the conversion of forests and organic soils to agricultural uses (i.e. deforestation and drainage of organic soils for conversion to cropland and grassland). Land-sparing mitigation options in agriculture compatible with food security, would contribute to this goal. Such options include technological advancements (total factor productivity gains), practices that increase the productivity of land while reducing emissions per unit of output (i.e. a shift from extensive to intensive systems of production), inducement of shifts in human diets to consume less ruminant meat, inducement of reduction in food waste across the food system, and reduction in the establishment of plantations of oil palms on cleared forest land
- Reductions in CH₄, N₂O, and additional CO₂ emissions from forest fires and peat fires. This would require proactive plans to control intentionally-set fires and wildfires
- Increases in the sequestration capacity of forests through forest management to avoid forest degradation and forest restoration. Reforestation and afforestation also have additional socioeconomic and environmental benefits.

Demand-side mitigation options

Reducing food loss and waste

Mitigation options reducing consumer waste and food loss across the food system increase food availability and competitiveness of the food sector. In the developing countries, this option implies significant cost for improving the infrastructure of the food system and improving the operation of markets. In the developed countries, mitigation options should target behavioral changes.

Changing diets

Mitigation options that shift human diets to less emission-intensive products as a result of inducements and behavioral change do not pose a threat to food security, although they may have implications for the competitiveness of higher-emitting sub-sectors and for the livelihood of the farmers involved (e.g. livestock production and, in particular, ruminant livestock production will become less profitable). Reductions in consumption through consumption taxes can increase food insecurity, especially in certain regions and among poorer populations.

In developed countries (e.g. the European Union), consumption taxes based on GHG emissions per food unit could be a cost-effective mitigating policy, even though taxes may be difficult to implement for political reasons. Health concerns relating to the increase in obesity and the consumption of red meat (e.g. diabetes and heart disease) could facilitate the imposition of taxes on high-emitting animal products in developed countries.^{18, 19}

18. Taxes on emissions, while preferable for addressing directly the divergence between private and social costs, may be more costly to administer than taxes on inputs or outputs. Output taxes are a better alternative when there are limited mitigation options apart from output reduction and there is high substitution between outputs (e.g. in food production). Higher cost savings could be realized

In developing countries, where the income and price elasticities for food are higher than in developed countries, the use of consumption taxes is more problematic since the impact on consumers is likely to be larger. Nevertheless, selective consumption taxes could be used to steer food consumption preferences in a desirable direction (Springmann et al. 2016).

In many developing countries, there is a need to improve diets by increasing the proportion of animal protein in the diet. Figure 36 shows the global emissions intensity associated with meat, milk and eggs. It can be seen that poultry products, particularly eggs, are a more emissions-efficient source of protein than many other products. Beef, which has already been identified in section one of this report as a major source of emissions, performs particularly poorly. Even among the ruminant products, cow's milk is less emission-intensive, primarily due to the joint production of meat and milk in many dairy systems (there are limitations of this system in some regions due to cultural factors, as identified in section five of this report). These differences in emissions intensities suggest that selective consumption taxes could be used to discourage the consumption of high-emitting livestock products to the advantage of lower-emitting livestock products. In part five of this report, we examine methods that could be used more generally to identify products and production systems to be targeted for mitigation at the national level.

Figure 36. Global emissions intensities of sources of animal protein

Source: Robinson et al. (2011).

Impact of other policies (non-mitigation sectoral and non-sectoral) on mitigation, productivity, competitiveness and food security

In addition to policies targeting mitigation in AFOLU and the food system, a range of other policies, such as agricultural support policies, can affect AFOLU emissions. Policies most likely to influence emissions are those that are directly linked to agricultural output or those that lower the cost or increase the availability of agricultural inputs.

The actual magnitude of subsidies (total value and value relative to the value of production) varies widely. In the OECD's estimates for support to agriculture (for 2015), producer support varies from less than 1% of the gross value of production at the farm level in New Zealand to 62% in Norway and Switzerland. In most countries for which data are available (see Figure 37), the dominant type of support is that most likely to influence production decisions (i.e. support linked to current output and input use). Although one cannot draw any conclusions from Figure 37 about the impact of support on

with a tax imposed on “emissions per unit of food” differentiated by category of food, with the differentiation based on average emissions levels across a region (e.g. the European Union).

19. Thus, for example, a Commission appointed by the Norwegian government to examine options for meeting Norway's commitment to a 40% reduction in emissions has suggested that a tax be imposed on ruminant meat in order to reduce meat consumption and emissions from ruminants.

agricultural emissions, the data point to the importance of examining domestic support policies and the extent to which these may either promote or discourage emissions-intensive agricultural production.

In section five of this report we discuss an approach recently applied by Josling et al. (2017), linking commodity support to emissions from individual commodities. Such a linkage is important for identifying products that are targets for mitigation and for determining how changes in existing agricultural policies might contribute to mitigation objectives. This issue is discussed further in section five of this report.

Figure 37. Percentage of support that is most likely to affect production decisions in selected countries (2015)

Note: These percentages are the sum of the shares of the total PSE (Producer Support Estimate) provided through: support directly linked to output; to area or the number of animals; receipts or income for which current production is required; and support based on input use. The Percentage Producer Support Estimate (%PSE) represents policy transfers to agricultural producers, measured at the farm gate and expressed as a share of gross farm receipts.

Source: OECD PSE/CSE database (2016).

Elimination or weakening of policies that currently stimulate output and the use of inputs would reduce emissions at the expense of competitiveness and output. Nevertheless, reduction of support policies could remove distortions that pose a barrier to technological advancements and improvements in practices.

Policies that affect energy prices can affect emissions in the food system and resource allocation in AFOLU. The International Energy Agency, for example, estimates that fossil-fuel consumption subsidies amounted to USD 493 billion (2013 dollars) globally in 2014. These subsidies may lower production costs for farmers and stimulate the use of fossil fuels. Subsidies specific to agriculture (e.g. lower taxes on fuel used for agricultural purposes) may be reflected in the OECD estimates, but those not specific to farmers may not be included (e.g. general reductions in the price of liquid fuels). In addition, consumption subsidies for fossil fuels may affect the pre-production and post-production parts of the food system through their impact on energy costs. Subsidies provided to fossil-fuel producers may also influence energy and energy-related costs. Estimates of the global magnitude of such subsidies are limited, but the International Institute for Sustainable Development (a non-profit organization located in Canada) reports that they may currently be of the order of USD 100 billion per year (www.iisd.org/).

The prevalence of subsidies for the production and consumption of fossil fuels has important implications for renewable energy and the sustainable development of AFOLU. Subsidies for fossil fuels place renewable energy, including energy produced from biomass, at a disadvantage. The contribution of so-called first-generation biofuels (such as maize and sugarcane for ethanol production, and rapeseed and oil palm for biodiesel) to the reduction in GHG emissions from energy use has been questioned due to trade-offs relating to the emissions generated in the production of these fuels. Policies used to promote the use of first-generation fuels (e.g. blending mandates) can be criticized for their impact on land use (expansion of agricultural land and increases in the cost of land). Nevertheless, fossil-fuel subsidies also disadvantage the potential future expansion of sustainable sources of renewable energy in AFOLU, such as fuels based on crop and livestock waste and non-food crops.

The use of first-generation biofuels has a direct impact on food markets, as fuel production competes with food and feed production for the same raw products and inputs. Biofuel demand induces additional pressure on agricultural markets. Reduced competition with food production could be offered by feedstocks for lingo-cellulosic bioenergy, crop and forest residues, waste and purpose-grown grasses (e.g. miscanthus and switch grass) or fast-growing trees (e.g. poplar, willow and eucalyptus). Energy yields per hectare of lingo-cellulosic bioenergy crops are potentially much higher than those of current agricultural crops with the exception of sugar cane. Despite the uncertainty involved, it is clear that cellulosic bioenergy crops could provide a considerable share of total energy use by 2050 and beyond (Lotze-Campen et al., 2014). The production of such crops is more likely to be compatible with food security.

The overall impact of second-generation bioenergy on global food prices is estimated to be modest. Ambitious climate-change mitigation through the expansion of bioenergy demand need not drive up global food prices if the extra land and water required for bioenergy production is accessible or if the feedstock, for example from forests, does not directly compete for agricultural land and water. Agricultural price effects across models by 2050 from high bioenergy demand in an ambitious mitigation scenario appear to be much smaller (+5% average across models) than those from direct climate impacts on crop yields in a high-emission scenario (+25% average across models). Nevertheless, the potential scarcity of water and nutrients, stronger policy-based restrictions on agricultural land expansion (e.g. for tropical forest protection), and overall welfare effects have not been examined. Price effects might be considerably stronger if agricultural land expansion is restricted and the supply of residues for energy use is limited (Lotze-Campen et al., 2014).

The international implications of mitigation: Carbon leakage and carbon reallocation

As noted earlier, mitigation can be achieved by internalizing the external costs of emissions (the costs of the damage created by climate change) through taxes, regulation and mixed approaches, such as emissions trading. Mitigation can also be promoted through the use of inducements, such as abatement subsidies. It is difficult to link either taxes or subsidies directly to the volume of emissions in agriculture due to the challenge of monitoring emissions at their source. However, in many developed countries subsidies are already used to promote the adoption of agricultural practices that contribute to the supply of environmental goods, such as wildlife habitat, and this approach could also be used to promote the adoption of practices that reduce GHG emissions. The provision of financial support for agriculture (directly through subsidies and indirectly through measures such as trade restrictions) has been widespread in OECD countries. The OECD has estimated that total support for agriculture in OECD countries in 2016 was roughly USD 317 billion (EUR 287 billion) ([OECD PSE/CSE database](#) accessed on 28 August, 2017). The provision of subsidies can be politically attractive, since it is likely to be supported by farmers, whereas the imposition of taxes can be politically challenging.

From the perspective of GHG mitigation, the provision of an abatement subsidy may have an impact similar to that of an equivalent carbon tax on the volume of emissions (at least in the short run). However, exclusive reliance on subsidies to address mitigation in agriculture has a number of weaknesses. Among these are the following:

- The linkage of subsidies to specific practices or technologies may reduce the incentive for innovation and for the adoption of unsubsidized mitigation options. Subsidy schemes need to be sufficiently flexible to encourage innovation and self-induced changes in production practices, and this can be difficult to achieve.
- If subsidies are only provided for agriculture they can attract resources to the sector and create an incentive for expansion. While higher output could contribute to food security if the demand for food is increasing due to population and income growth, it could also result in an overall expansion of emissions (similar to the rebound effect in the context of technological change discussed in Section 3).
- Unlike a carbon tax, which will ultimately be reflected in higher consumer prices and hence contribute to adjustments in both production and consumption, an abatement subsidy will not change the relative cost of high-carbon products for consumers and will not contribute to emissions-reducing changes in diets.

- The option for using subsidies is limited to countries that can afford them. As for all types of budgetary support for agriculture, the way in which the funds for subsidization are obtained can introduce distortions into the economy.

For these reasons, while financial incentives for the adoption of mitigation practices can play a part in the pursuit of GHG reduction goals in agriculture, the internalization of the costs of emissions has a central role to play in achieving necessary adjustments in both production and consumption in the sector.

Apart from the difficulties posed by technical considerations and political constraints, one of the challenges of internalizing the costs of carbon emissions in agriculture relates to potential interactions among consumption, production and international trade. In a closed economy, a carbon tax imposed on food will have the same effects on prices and quantities in the market, regardless of whether the tax is imposed on producers or on consumers as long as they both respond to price changes. A production tax will cause changes in the pattern of production to reflect emissions intensity. The impact of adjustments in output will be reflected in consumer prices. Similarly, the imposition of a tax at the consumer level will cause adjustments in production, in response to the change in the pattern of consumption. However, when international trade comes into the picture, the situation is much more complicated.

The imposition of a tax at the production level will, as before, cause changes in the pattern of production, with a shift away from emissions-intensive products to less emissions-intensive products. In a small open economy (one whose changes in production and consumption do not affect international prices), consumers will see little change in relative prices of products. As a result, while the domestic production of emission-intensive products will fall, consumers may simply substitute imported products for their domestic equivalents. The replacement of emissions-intensive domestic products by emissions-intensive imports has typically been categorized as “carbon leakage”.²⁰

This is clearly an issue. Domestic producers who are subject to the carbon tax will probably object to being disadvantaged against competing sources of imports that are not subject to the tax²¹. But the implications are potentially more significant if there are differences in emissions intensities in production between trading countries. While a country’s domestic emissions at the production level will be assessed as being reduced as a result of the tax, its contribution to global emissions measured at the level of consumption will not necessarily fall. The outcome depends on whether the emissions intensity of imported products is higher or lower than that of the domestic product.

The potential implications of this can be seen by considering emission-intensity data for major livestock products.

Consider beef, for example. The emissions intensity of beef in Latin America and the Caribbean is more than three times higher than in Europe (Figure 38). It is also significantly higher than the intensity in Oceania and North America. These regions contain some significant exporters and importers of beef (e.g. Australia, Brazil, the European Union and the United States). If, for example, mitigation efforts in Europe resulted in a fall in beef production, and consumers replaced the food gap with increased imports of beef from Brazil, there would clearly be carbon leakage. To the extent that the export price of Brazilian beef increased as a result of Brazil’s mitigation efforts, this would reduce the leakage effect by discouraging an increase in imports. There would be no leakage if the rise in the import price due to mitigation effort in Brazil matched the rise in the European supply price of beef, due to its own mitigation effort. Imports from Brazil could actually fall if its mitigation efforts resulted in a larger increase in its supply price than in the European supply price.

If mitigation efforts were price-neutral across countries, relative competitiveness internationally and trade flows would not be affected. But the relative competitiveness of beef among importing and exporting countries would be affected by mitigation efforts that result in differential increases in beef

20. Carbon leakage may still occur if mitigation is pursued through the use of abatement subsidies, if abatement leads to a reduction in domestic output. There may be less opposition to increases in imports from domestic producers who are receiving abatement subsidies, but failure to internalize the external costs of emissions will still lead to international distortions in production, consumption and trade.

21. If the country is an exporter of the product concerned, the effect will be felt through a reduction in exports rather than an increase in imports.

prices. Indeed, if mitigation resulted in higher productivity in the global beef sector, world prices could fall and consumption could expand, resulting in a rebound effect. In contrast, mitigation efforts that resulted in an overall increase in global beef prices would have a reinforcing impact on global emissions by the beef sector, by causing global beef consumption to fall.

Figure 38. Emissions intensity of beef production by region

Source: FAOStat data.

Emission reduction efforts that resulted in differential changes in beef prices among countries would cause changes in the pattern of trade. The net impact on emissions would depend on: the total magnitude of reductions in emissions intensity in individual countries; the magnitude of relative reductions in beef emissions intensity across countries; and how mitigation efforts affected output costs and prices in individual countries and the prices that consumers face. It would be necessary to take all these factors into account to determine the total effect of specific mitigation efforts for beef production in individual importing and exporting countries (in addition to impacts in countries where beef trade is insignificant) both on the pattern of trade and on the resulting change in global emissions associated with beef production and consumption.

Viewed from the perspective of an individual country, carbon leakage will certainly occur if domestic mitigation efforts for a particular production activity result in an increase in imports. Nevertheless, viewed from a global perspective, there will only be leakage if the resulting change in the pattern of trade results in a replacement of lower-emitting beef production by higher-emitting beef production globally, i.e. global emissions increase because global production and consumption of the product generates more total emissions than before. If the opposite occurs, then carbon reallocation rather than carbon leakage takes place. Global emissions are reduced as result of a shift in production from high-emitting production locations to low-emitting locations, and changes in the pattern of trade facilitate that reallocation.

The concept of carbon reallocation is extremely important. Since food production by its very nature cannot be decarbonized, and global demand for food is likely to increase due to population and income growth, in order to minimize agriculture's contribution to global GHG emissions, future production increases should take place in locations that can produce food with a lower carbon footprint²². To return to the beef example, unless significant reductions can be achieved in the emissions intensity of beef production in the three regions with the highest intensities in Figure 38 (South Asia, Latin America and the Caribbean, and East and South East Asia), from a global perspective it would be desirable that any increase in global demand for beef should be met through higher production in lower-emitting regions, such as Europe and Oceania, rather than significant beef production increases in these three regions.

22. The concept of carbon footprint has sometimes been equated with simplistic measures such as “food miles”, i.e. the energy consumed in transporting traded agricultural products. But a true carbon footprint takes into account all the direct and indirect energy used in the supply of imports and their domestically produced equivalents.

Similarly the emissions intensity data in Figure 39 (and Annex 1, Figure A1.16 on trends in milk yields) suggest that it would be preferable from a global perspective to meet future increases in demand for dairy products from Oceania, Europe and North America. In particular, without a major reduction in emissions intensity in Sub-Saharan Africa, increased demand for dairy products in that region would seem to call for an increase in imports rather than increased domestic production. However, it is important to note that a cross-country or cross-regional comparison of current emissions intensities, measured in terms of physical emissions intensity, cannot provide a definitive guide to priorities for emissions reduction targets across countries or regions, or for the desirability from a global emissions perspective of meeting expanding food needs from domestic sources or from imports. Nevertheless, Figures 38 and 39 can provide some pointers to addressing these issues. The identification of emissions reduction priorities is discussed further in section five of this report.

Consistency between national mitigation policies and global GHG mitigation: Implications for production, consumption and trade

If there were no barriers to international trade, the adoption and implementation of a globally agreed price for carbon would result in a global adjustment in production, consumption and trade that would reduce global emissions in line with the carbon price, even though the net impact could be reduced through a rebound effect (discussed earlier). But we do not live in a free-trade world and there is no globally agreed carbon price. Consequently, there is a high potential for substantial distortions in production, consumption and international trade if countries pursue unilateral, uncoordinated mitigation policies that have differential national impacts. Some of the potential distortions could be offset by trade policies, although this is not straightforward (Blandford et al., 2015). Countries pursuing unilateral mitigation may face trade policy limitations in addressing perceived carbon leakage due to commitments through bilateral, regional and multilateral trade agreements. Unilateral pursuit of trade policies in an attempt to remedy the perceived carbon leakage carries high risk both for the global effectiveness of mitigation efforts in agriculture and for the international trading system.

Climate change and differential adaptation capacity to climate change will affect comparative advantage across countries. If the same mitigation policies were to be implemented in agriculture throughout the world (i.e. if patterns of production and trade reflected “emissions comparative advantage”) trade and trade flows would be redefined by the differences in emissions intensity among countries and regions. Nevertheless, a simple comparison of emissions intensity would fail to capture the role of different climate and non-climate policies in increasing AFOLU’s potential contribution to reducing global emissions and thus would have limited practical effect. It would also fail to address other economic and environmental objectives, such as economic development with sustainable use of natural resources (sustainable development). The bottom line is that in the absence of a globally homogeneous policy for mitigation across sectors and countries (i.e. a uniform carbon tax), national approaches could result in distortions, ineffectiveness of national mitigation efforts, and inefficiencies with respect to emissions-intensity in production and in trade flows, possibly resulting in higher global emissions (Wirsénus, Hedenus and Mohlin, 2011; Golub et al., 2013). Carbon would be reallocated in an inefficient way, since emissions-based comparative advantage would not operate.

The complexity of interactions likely to occur in production, consumption, and international trade as a result of differences in national or regional mitigation approaches poses considerable challenges for determining the relative effectiveness of approaches to reducing emissions at the national, regional or global level. It was argued earlier that changing food consumption towards lower-emitting products can be a powerful force for achieving mitigation in AFOLU. A carbon tax at the consumer level is preferred to one at the producer level in order to avoid carbon leakage while permitting carbon reallocation. Even with a consumer tax, however, secondary international impacts of reduced domestic consumption cannot be avoided if the mitigating country has a large enough share in world markets to cause a reduction in world prices. In that case, increased consumption of the high-emitting product could be induced in the rest of the world. There are clearly complex and significant trade-offs in pursuing mitigation policies in agriculture once international trade is taken into account.

Differences in emissions intensity among products in individual countries and among similar products internationally are of major importance for the pursuit of climate-change policies. In agriculture, considerations for national mitigation policies range from the substitution of lower-emitting products for higher emitting products to reductions in emissions intensity per unit of output. By adding the trade dimension to the analysis, proposed solutions extend beyond inter-sectoral and inter-product substitutions to include the potential presented by differing emissions elasticities among countries

(i.e. the percentage change in emissions associated with a 1% change in output). From a global perspective, GHG mitigation cannot be achieved solely by enforcing policies that appear to be appropriate from a domestic perspective; rather it should be ensured that the net effect of both domestic and international actions is lower global emissions.

Figure 39. Emissions intensity of cow's milk production by region

Source: FAOStat data.

5. How would countries differ in terms of their national options for mitigation and their potential consequences?

Defining mitigation and mitigation priorities from a global perspective

Mitigation in AFOLU requires a comprehensive approach that will minimize emissions in agriculture, agriculture-related sectors, deforestation and other land-use sources, and maximize removals (sinks). For the latter, the protection and enhancement of sinks, such as forests, organic soils and soil used in agriculture (soil carbon sequestration) is crucial.

From a global perspective, mitigation also necessitates the prevention of carbon leakage associated with national initiatives and facilitates the reallocation of production from emissions intensive to less emissions intensive countries, without compromising global access to food.

In order for mitigation efforts to be globally effective, national mitigation goals should be coordinated internationally and should be consistent with the global warming upper limit of 2°C for 2100.

An effective approach to global mitigation requires that regions, countries and activities with the highest potential for global GHG mitigation (i.e. priorities) in AFOLU and agriculture-related sectors be identified, allowing for mitigation options to be tailored to each country's conditions.

AFOLU emissions in some regions come mainly from agriculture and in others from deforestation mostly aiming at bringing land into agricultural use. Net emissions from AFOLU in developing countries have been increasing (Figure 13). While deforestation has been decreasing globally, it still generates a high level of emissions in Sub-Saharan Africa where it also shows no tendency to decrease significantly, Southern and South-East Asia (e.g. Indonesia, for expansion of oil palm and wood plantations), and Latin America and the Caribbean (e.g. Brazil, for producing timber, cattle and soybeans) (see *Environment Reports* www.environmentreports.com). On the other hand, agriculture's direct emissions have been increasing globally mainly as a result of increases in South and South East Asia, Sub-Saharan Africa, and Latin America and the Caribbean.

The strong increase in agricultural emissions (Figure 14), in combination with food security concerns, suggests that reducing the emissions intensity of agricultural production in developing countries is a high priority. Net emissions from land-use change remain significant, indicating that land-use change is a target for both reducing emissions and increasing carbon sequestration (Figure 10). Given the large

contribution to global emissions from AFOLU of roughly 92% (Figure A1.2) in developing countries compared to their share of the world's population of around 84% in 2015 (World Bank, *Development Indicators Database*), reducing emissions intensity in agriculture and reducing emissions from other land uses (AFOLU) in developing countries is clearly a priority.

Net emissions in developed countries have tended to decline but have been relatively flat in recent years (Figure 13). Net emissions from land use and land-use change in developed countries are negative, indicating net carbon sequestration from AFOLU activities, but that contribution has declined in recent years (Figure 14). Taken together, these figures indicate that effort needs to be directed to reducing emissions intensity in agriculture in developed countries and to strengthening carbon sequestration activities in AFOLU.

The remainder of this section first presents aspects of identifying mitigation priorities (potential) and then focuses on identifying the appropriate mitigation options at the country level.

Mitigation priorities in agriculture (direct emissions) from a global perspective²³

In part three of this report, a target for the reduction of direct emissions from agriculture needed to keep the increase in global average temperature below 2°C was discussed. This was identified as 1 GtCO₂e per year and corresponds to a needed global reduction in emissions of roughly 19%, applied to all regions and sub-regions. Table 6 shows the regional allocation of that reduction on the assumption that this is distributed equally across regions based on their average emissions in 2012-14.

Given its major share in total direct emissions, Asia would be required to contribute the largest share (44%) of the global emissions reduction. Southern and Eastern Asia would be the largest contributors to the emissions reduction at roughly 18% and 15%, respectively of the global total. However, South America would also have a reduction share equivalent to 15% of the global total. These three sub-regions would collectively account for 48% of the total reduction. South-East Asia (9%), North America (8%) and Eastern Africa (7%) would collectively account for another 26%.

Table 6 also summarizes the leading sources of direct emissions (those accounting for at least 10% of the total in each geographical sub-region). Shares of global emissions by source indicate that livestock activities, particularly ruminant livestock, are a major global target for global reductions in emissions intensity. In 17 of the 22 sub-regions, and 6 of the 7 sub-regions that would require the highest emissions reductions, enteric fermentation is the leading source of direct emissions. This, and manure left on pasture, which is the second leading source of emissions in 9 of the sub-regions, is largely associated with ruminant livestock production. The only major emitting sub-region in which ruminant livestock production is not the principal target for emissions reduction is South-East Asia, where rice production presents the largest target.

Table 7 provides an additional pointer to sources of emissions that are potential targets for mitigation. It highlights regions and sub-regions in which the contribution of various sources of direct emissions to the regional (sub-regional) total is in excess of the global average.

The first row of Table 7 summarizes the contribution of various sources to total global direct emissions from agriculture. The share of global emissions that can be directly attributed to livestock (63% from enteric fermentation plus manure management and manure left on pasture), as well as the contribution of livestock to other emissions sources, through the use of fertilizer in animal feed production (the total of 16% from synthetic fertilizer and manure applied to soils) or through the contribution of livestock to the burning of savanna (4%), also strengthen the case for making livestock a target for emissions reductions. The large share of direct emissions attributable to enteric fermentation (40%) and the fact that this emissions source combined with manure left on pasture collectively accounted for almost 60% of the increase in global direct emissions from agriculture in recent years (Figures 10 and 11), highlights the urgency of addressing livestock emissions, particularly in ruminant systems.

23. We use global averages as the basis for comparison since the focus of this report is on the global reduction in emissions needed to limit the increase in global average temperature. However, mitigation options are often locally specific. Some of that specificity is reflected in the numbers presented here. Later in this section we analyse the characteristics of emissions for major products in selected countries in order to provide a more detailed assessment of mitigation potential.

Table 6. Equi-proportional regional reductions in direct emissions consistent with the 1 GtCO₂e emissions reduction target (with respect to average emissions for 2012-14)

Region	Reduction MtCO ₂ e	% of world total	Leading sources of emissions (percentage of total):			
Africa	158.3	15.8%				
Northern	25.9	2.6%	EF 46%	MP 32%		
Western	36.6	3.7%	EF 41%	MP 31%		
Middle	19.0	1.9%	BS 56%	EF 22%	MP 16%	
Eastern	67.8	6.8%	EF 42%	MP 29%	BS 18%	
Southern	9.0	0.9%	EF 38%	MP 29%	BS 20%	
Americas	252.5	25.3%				
Northern	79.3	7.9%	EF 33%	SF 24%	MM 12%	MP 11%
Central	22.2	2.2%	EF 55%	MP 23%	SF 10%	
Caribbean	4.6	0.5%	EF 53%	MP 24%		
South	146.4	14.6%	EF 59%	MP 23%		
Asia	440.4	44.0%				
Southern	177.6	17.8%	EF 46%	RC 15%	SF 15%	MP 12%
Western	17.5	1.8%	EF 39%	MP 33%	SF 17%	
Eastern	146.4	14.6%	EF 29%	SF 21%	RC 16%	MP 12% MM 10%
Central	12.4	1.2%	EF 51%	MP 16%	MM 10%	
South-Eastern	86.5	8.6%	RC 44%	EF 16%	SF 10%	
Europe	110.8	11.1%				
Eastern	40.3	4.0%	EF 34%	SF 17%	COS 13%	MM 12%
Northern	19.5	1.9%	EF 41%	SF 14%	MM 13%	COS 12%
Southern	18.7	1.9%	EF 38%	MM 18%	SF 17%	
Western	32.4	3.2%	EF 41%	MM 17%	SF17%	
Oceania	38.0	3.8%				
Aust./NZ	36.6	3.7%	EF 37%	BS 28%	MP 22%	
Melanesia	1.4	0.1%	COS 62%	EF 14%	MM 12%	
Micronesia	0.0	0.0%	MM 44%	EF 29%	MP 14%	MS 11%
Polynesia	0.1	0.0%	MM 46%	EF 28%	MP 13%	

Notes: BS = burning of savanna; COS = cultivation of organic soils; EF = enteric fermentation; MM = manure management; MP = manure left of pasture; MS = manure applied to soils; RC = rice cultivation; SF = synthetic fertilizers.

Source: Based on FAOStat data.

Table 7. Regional composition of emissions from agricultural production (average 2012-14)

Region	EF	MM	MS	MP	SF	CR	RC	OS	CRB	SB
World	40	7	4	16	12	4	10	3	1	4
Africa	40	2	1	28	3	2	3	1	0	19
Americas	50	6	3	19	12	4	2	2	1	1
Asia	34	7	4	12	16	4	20	2	1	0
Europe	38	15	9	6	16	6	1	8	1	0
Oceania	37	5	1	21	5	2	0	3	0	27
N. Africa	46	2	1	32	9	3	3	0	0	4
W. Africa	41	3	1	31	2	2	7	0	1	10
Mid. Africa	22	2	1	16	0	1	1	0	0	56
E. Africa	42	2	1	29	1	1	3	2	0	18
S. Africa	38	2	1	29	6	2	0	0	1	20
N. America	33	12	4	11	24	8	2	5	1	1
Cen. America	55	4	4	23	10	2	0	0	1	1
Caribbean	53	4	5	24	3	1	9	0	0	0
S. America	59	2	3	23	6	3	2	0	0	2
S. Asia	46	5	3	12	15	4	15	1	1	0
W. Asia	39	2	1	33	17	4	1	0	1	0
E. Asia	29	10	5	12	21	5	16	1	1	0
Cen. Asia	51	10	6	16	8	4	2	0	1	3
S.E. Asia	16	7	3	6	10	4	44	9	1	1
E. Europe	34	12	8	5	17	8	1	13	1	1
N. Europe	41	13	8	9	14	4	0	12	0	0
S. Europe	38	18	9	9	17	4	4	0	0	0
W. Europe	41	17	9	6	17	5	0	4	0	0
Aust. NZ	38	4	1	22	5	2	0	0	0	28
Melanesia	14	12	2	7	2	0	0	62	0	1
Micronesia	29	44	11	14	0	0	1	0	0	0
Polynesia	28	46	7	13	6	0	0	0	0	0

Notes: EF = enteric fermentation; MM = manure management; MS = manure applied to soils; MP = manure left on pasture; SF = synthetic fertilizers; CR = crop residues; RC = rice cultivation; OS = cultivation of organic soils; CB = burning of crop residues; SB = burning of savanna. Highlighted figures denote percentages in excess of the world average.

Source: FAOSTat data.

Major geographical regions differ with respect to the emissions sources that are relatively more important. Thus in Africa, both the shares of manure left on pasture and of savanna burning are significantly higher than the global average. In the Americas, this also applies to manure left on pasture and to enteric fermentation, reflecting the importance of ruminants in that region. In Europe, emissions associated with livestock production make an above average contribution in the areas of manure management and manure applied to soils, but the contributions of emissions from the use of synthetic fertilizers, crop residues, and the cultivation of organic soils are also above the global average. In Oceania the contributions of manure left of pasture and the burning of savanna are higher than the global average.²⁴

Table 7 also highlights cases where the contributions of the various sources of agricultural emissions are higher than the global average for geographical sub-regions. It should be noted that even when the emissions ratio for a major geographical region is not above the global average, the ratios for individual sub-regions can be above average. This is particularly noticeable in the case of enteric fermentation. Even though the Americas is the only major geographical region to display an above-average emissions percentage for that source, sub-regions in all geographical regions (with the exception of Oceania) are revealed as having higher than average emissions from that source. Also, while the Americas as a whole have an emissions share that is substantially higher than the global average (50% compared to the global figure of 30%), the North American sub-region's percentage is below the global average.

The table helps to identify differences in potential targets for emissions reduction by sub-region. For example, in North America, emissions from manure management, synthetic fertilizers, crop residues and the cultivation of organic soils are highlighted. In Europe, emissions relating to livestock production, particularly manure management and manure left on pasture, appear as issues in all sub-regions, as do emissions from synthetic fertilizers. It is also noteworthy that emissions from cultivation of organic soils are an issue, particularly in Northern and Eastern Europe. In Africa, the importance of manure left on pasture in all sub-regions, except Middle Africa, and of the burning of savanna, with the exception of North Africa, are highlighted by the table, but it also suggests that enteric fermentation is significant, particularly in North Africa.

In Asia, the importance of emissions from the use of synthetic fertilizers and rice production identified in the aggregate regional figures is emphasized, although there are significant differences across Asian sub-regions. Enteric fermentation is particularly important in Central and South Asia, due to ruminant livestock production. Manure management and manure applied to soils are more significant in Central and East Asia than in other Asian sub-regions. Manure left on pasture is a more significant source of emissions in Western Asia than in the other Asian sub-regions. The intensification of crop production, particularly rice production, is apparent in the figures for rice cultivation in South, South-East and East Asia, and for the synthetic fertilizer figures for West, East and South Asia.

Although aggregate data for Oceania are dominated by the Australia-New Zealand sub-region, data for the other sub-regions point to other areas of focus for emissions reductions. In both Micronesia and Polynesia, emissions from manure management and manure applied to soil are higher than the global averages. In Melanesia the contribution of the cultivation of organic soils to emissions is also noticeable.

While the data in the table provide some insight into potential areas of focus for mitigation activities, the nature of the challenge (or opportunity) involved for each of the sources of emissions can be brought into focus by a series of charts that graphs an index of the difference in the percentage contribution of each emissions source at the sub-regional level and the global level.²⁵ The index provides a picture of the relative magnitude of this difference across countries. The ordering of the graphs reflects the contribution of each of the sources of direct emissions to the global total in 2012-14, in other words the ordering indicated by the magnitude of the percentages in the top row of Table 7.

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24. The burning of savanna may not be directly associated with agricultural activity. It is notable that the contribution of this emissions component is highly variable in Australia, where drought plays an important role in the incidence and severity of brush fires.
 25. The distance index in these charts is calculated as the difference between the percentage of total emissions for each source of emissions in the region and the global percentage of that category of emissions, relative to the global percentage, multiplied by 100.

Emission sources and regions where emissions reductions could be potentially targeted are as follows:

- Enteric fermentation (Figure 40): is a particularly important area of emphasis for mitigation in South and Central America, the Caribbean, and Central Asia, and to a lesser extent in North Africa and South Asia.

Figure 40. Enteric fermentation: Distance from global average contribution to direct emissions

- Manure left on pasture (Figure 41): could be a particular target for mitigation activity in West Asia, all of Africa, with the exception of Middle Africa, and to some extent in the Caribbean, Central and South America and in Australia/New Zealand.

Figure 41. Manure left on pasture: Distance from global average contribution to direct emissions

- Synthetic fertilizers (Figure 42): stand out in importance for North America, in most of Asia and Europe.

Figure 42. Synthetic fertilizers: Distance from global average contribution to direct emissions

Source: Based on FAOStat data (averages for 2012-14).

- Manure management (Figure 43): Polynesia and Micronesia stand out in the graph, but so does Europe, Melanesia, North America, and Central and Eastern Asia.

Figure 43. Manure management: Distance from global average contribution to direct emissions

Source: Based on FAOStat data (averages for 2012-14).

- Burning of savanna (Figure 44): stands out in Africa, particularly Middle Africa, as well as in Australia/New Zealand.

Figure 44. Burning of savanna – distance from global average contribution to direct emissions

Source: Based on FAOStat data (averages for 2012-14).

- Crop residues (Figure 45): Eastern Europe and North America are highlighted by the graph for this emissions source.

Figure 45. Crop residues – distance from global average contribution to direct emissions

Source: Based on FAOStat data (averages for 2012-14).

- Manure applied to soils (Figure 46): Micronesia, Europe, Polynesia, Central and Eastern Asia as well as the Caribbean are highlighted for this source.

Figure 46. Manure applied to soils – distance from global average contribution to direct emissions

Source: Based on FAOSTat data (averages for 2012-14).

- Cultivation of organic soils (Figure 47): Melanesia is highlighted but the above average contributions to direct emissions in Northern and Eastern Europe, Southeast Asia, and to a lesser extent North America also makes this a potential target for emissions reduction.

Figure 47. Cultivation of organic soils – distance from global average contribution to total direct emissions

Source: Based on FAOSTat data (averages for 2012-14).

Graphs for rice are not shown, due to the dominance of Asia in the production of that crop. Nevertheless, as can be seen from Table 6, the importance of rice production in Southeast Asia and its large contribution to total direct emissions in that sub-region (44%) make the crop a major target for emissions reduction. A graph for emissions from crop burning is also not shown, since this contributes similar percentages to total direct agricultural emissions at the global level in regions where the practice is employed.

The picture of the potential mitigation targets provided by these graphs indicates some of the complementarities that can exist in targeting emissions reductions in production systems. For example, regions with above average emissions in manure management also have above average emissions from manure applied to soils (Figures 43 and 46). This suggests that the targeting of livestock waste (e.g. use for the production of bioenergy) could have multiple effects in terms of emissions reduction. Some

regions that have above average emissions associated with the use of synthetic fertilizer also have above average emissions from crop residues (Figures 42 and 45). This suggests that a joint focus on improving the use of nutrients in crop production and the use of crop residues could have substantial benefits in terms of emissions reduction.

The figures also point to some challenges that regions might face in targeting areas for emissions reduction. Clearly, Asia (particularly Southeast Asia) must direct some effort on reducing emissions from rice production. Given the importance of that crop in rural communities and for food consumption, this may present challenges.

Regions that have relatively undiversified agriculture (do not have a wide variety of products) and consequently have a high proportion of their total emissions in certain activities (e.g. emissions associated with livestock production in small island states in Micronesia, Polynesia and the Caribbean) may face challenges in reducing emissions, since there is a limited portfolio of production activities that can be targeted for emissions reduction. On the other hand, the implementation of viable (technically feasible and cost-effective) emission-reducing options for the production systems that are the dominant sources of emissions in such regions could have a major impact in meeting emissions reduction targets.

Mitigation priorities in agriculture, accounting for economic contribution

Countries with different production systems, resource endowments, levels of productivity and the like will have different degrees of freedom in targeting emission reductions. Inter-country comparisons of emissions intensity (e.g. kg of emissions per kg of production) have been the basis for discussing mitigation priorities across products and regions, for example, in the livestock sector (e.g. Gerber et al., 2013). However, focusing on a physical emissions comparison has severe limitations for policymaking. The use of physical emissions criteria alone in identifying national mitigation priorities in products or production systems does not take into account the relative economic importance of different products and their contribution to national well-being. In setting mitigation priorities at the national level, it is important to weigh mitigation potential against the domestic economic cost of mitigation.

Differences in output value

One way to cast light on this issue is to examine the ratio of emissions from agricultural production to the total value of production. Figure 48 shows this for geographical sub-regions and for the world as a whole. The calculations are based on average total agricultural emissions for 2011-13 and the corresponding average value for total agricultural output in constant US dollars.²⁶ The world emissions ratio averaged 2.11; in other words global average emissions for each dollar of global agricultural output were 2.11 kg of CO₂e.

Regional emissions ratios demonstrate substantial variability around the global average. The lowest ratio (1.13) applied to production in Southern Europe. The ratios for Micronesia, Eastern and Western Asia, Western and Eastern Europe and Northern America were all below the global average. At the opposite end of the scale, the highest ratios (of around 6) corresponded to Middle and Eastern Africa.

The emissions ratios reflect regional differences in the structure of agricultural production (mix of commodities produced and their market values) and in production systems. For example, Middle Africa has high emissions from the burning of savanna; roughly 56% of the average emissions for the most recent three years for which data are available (2012-14) came from this source in the region. Table 8 shows that while Middle Africa accounted for roughly 12% of Africa's total emissions from agricultural production in 2011-13, it only accounted for 8% of the total value of agricultural output for Africa. The high emissions from savanna burning translate into high total emissions relative to the value of agricultural production in the region.²⁷

26. Indicative world prices in US dollars are used to value commodities, hence the valuations are referred to as international dollars (I\$) in the FAOStat database.

27. The high emissions ratio for Australia/New Zealand is strongly influenced by climatic variability, which through the effect of periodic droughts, impacts on crop and livestock production and the number, size and intensity of fires in Australia. Emissions from the burning of savanna contributed to an average of 22% of the total emissions attributed to agricultural activities during 2012-14. Year-to-year variability in fire-related emissions is substantial. The area burned between 2000 and 2014, for

Figure 48. Ratio of total direct agricultural emissions to the total value of agricultural output

Source: FAOStat data.

Eastern Africa also has a high emissions ratio (over 6 kg of emissions in CO₂e per dollar of output in 2011-13). In this case, however, both ruminant production, with 78% of the region's emissions in 2012-14, and the burning of savanna (18% of total emissions) contribute to the high emissions ratio. Ruminant production generates a relatively low value for agricultural production in this region. The region's share of the total value of agricultural production in Africa at around 25% is significantly lower than its share of Africa's total emissions.

In contrast, the low emissions ratio in Southern Europe is associated with a higher share of Europe's total value of agricultural production. Agriculture in Southern Europe generates a range of high value crops, particularly fruit and vegetables. As a result, emissions from typically high-emitting activities, such as ruminant production, are relatively low in comparison to total agricultural emissions in this region. Other regions in Asia and Europe, as well as North America, which have high output value in agriculture, also have emissions ratios that are less than the global average.

In addition to the composition of output, another factor affecting the ratios of emissions to the value of production is efficiency.²⁸ This is particularly relevant to the production of livestock, which (as noted earlier) is a major contributor to total emissions from agricultural production. For example, the high emissions ratio for Eastern Africa is partly due to the importance of ruminant meat production in the region's agriculture. But productivity in the meat sector is relatively low in comparison to many other regions. According to FAO figures (FAOStat database), the average beef yield (yield relative to carcass weight) in 2013 in Eastern Africa was roughly 134 kg. That is below the all-Africa average of 155 kg and substantially below the yield of roughly 256 kg in the Americas, Europe and Australia/New Zealand. Relatively low productivity in the meat sector in Africa means that emissions per unit of marketed output are high. The importance of productivity, which has already been identified earlier, is further discussed in relation to mitigation possibilities below.

example, ranged from a low of roughly 20 million hectares to over 80 million hectares. The coefficient of variation for the area burned over this period was 46%.

28. Potential differences in emissions due to differences in local values of products across countries and regions are not reflected in the numbers since indicative world prices are used to value output. Local price differences could increase or decrease the ratio of emissions to value from the figures used here.

Table 8. Emissions ratios by sub-region and sub-regional shares of regional agricultural emissions and value of production (averages 2011-13)

	Emissions ratio	Shares of regional	
	kgCO ₂ e per USD of output	Emissions	VOP
Eastern Africa	6.19	40.8%	25.5%
Middle Africa	5.80	12.3%	8.2%
Northern Africa	2.59	17.7%	26.4%
Southern Africa	3.56	6.4%	6.9%
Western Africa	2.68	22.8%	32.9%
Northern America	1.55	31.5%	45.9%
Central America	2.24	8.8%	8.9%
Caribbean	2.81	1.8%	1.5%
South America	3.00	57.9%	43.7%
Central Asia	2.20	2.8%	2.3%
Eastern Asia	1.24	33.2%	48.7%
Southern Asia	2.62	40.6%	28.1%
South-Eastern Asia	2.29	19.6%	15.6%
Western Asia	1.30	3.9%	5.4%
Eastern Europe	1.50	36.4%	37.3%
Northern Europe	2.50	17.6%	10.8%
Southern Europe	1.13	16.9%	23.0%
Western Europe	1.56	29.2%	28.8%
Australia & New Zealand	5.37	96.5%	91.8%
Melanesia	2.23	3.4%	7.7%
Micronesia	1.21	0.0%	0.1%
Polynesia	2.32	0.1%	0.3%

Note: VOP = value of production expressed in constant (2004-06) international dollars.

Source: FAOStat data.

One way to assess the importance of defining emissions efficiency in terms of the ratio of emissions per dollar of output is to examine the consequences of an emissions ratio reduction to the global average level (2.11 kg of CO₂e per dollar of output) for countries that have high emissions.

Table 9 summarizes the results of these calculations. It shows that increases in emissions efficiency (i.e. a reduction in the emissions ratio to the global average in the 14 sub-regions for which the ratio was above the global average in 2011-13) would translate into a reduction of global emissions of over 0.9 GtCO₂e per year. This almost equals the estimated required reduction in direct emissions from agriculture identified in section three of this report if the global warming limit of 2°C is to be achievable.

Table 9. Reduction in emissions if emissions efficiency is increased to the global average for 2011-13

Region	Emissions/Value of Production	% reduction to achieve global average ratio	Emission reduction MtCO ₂ e at the world ratio
Eastern Africa	6.19	66%	233
Middle Africa	5.80	64%	63
Australia/New Zealand	5.37	61%	116
Southern Africa	3.56	41%	19
South America	3.00	30%	226
Caribbean	2.81	25%	6
Southern Asia	2.62	19%	180
Northern Africa	2.59	18%	25
Northern Europe	2.50	15%	16
Polynesia	2.32	9%	0
South-Eastern Asia	2.29	8%	35
Central America	2.24	6%	6
Melanesia	2.23	5%	0
Central Asia	2.20	4%	3
WORLD	2.11		
Western Europe	1.56		
Northern America	1.55		
Eastern Europe	1.50		
Western Asia	1.30		
Eastern Asia	1.24		
Micronesia	1.21		
Southern	1.13		
Total of regions with emissions ratio above the global average			928

Source: Based on FAOStat data.

Implications of government support

As discussed in section four of this report, governments of many countries provide financial support to agriculture. To estimate the impact of this support on emissions and to assess the potential for mitigation requires an analysis of how the support affects the volume of production and inputs used, and the emissions associated with the observed output/input mix. Such analysis is beyond the scope of this report. However, we can gain some insight into the potential importance of government support for the volume of output and (by extension) for the potential volume of emissions by considering how support affects calculations of the ratio of the volume of emissions from agriculture relative to the value of agricultural output. Table 10 illustrates the implications of adjusting the value of output for government support for a selection of countries, for which the OECD derives the Producer Support Estimate (PSE).

The first ratio in the table is computed by dividing total emissions from agriculture over the period 2012-14 by the value of total agricultural output over the same period, converted to US dollars at the applicable annual exchange rate. The next ratio is the one derived when the PSE is subtracted from the value of production. The final ratio is derived by adjusting the value of production for elements of the PSE that are most closely related to farmers' decisions about what to produce. These comprise the components that are based on commodity outputs, variable input use and current area (A), animal numbers (An), receipts (R) or income (I) that require production.

Adjusting the value of production downwards by subtracting the value of support increases the emissions ratios. The increases in three cases – China, the European Union and Indonesia – where the PSE adjustment is made are quite large. The emissions ratio increases by roughly 25-30% in these cases.

The comparison of the impact of only adjusting for support that is most closely related to production decisions is also illuminating. Since a large proportion of the support provided by the European Union is not directly linked to production, the emissions ratio after adjusting for output-linked support is around 11%, rather than 29% without that adjustment. The corresponding reduction from 10% to less than 6% for the United States may also be noted. In contrast, since a much larger proportion of support is linked to production in China and particularly in Indonesia, the emissions ratio for these countries under the second adjustment is much closer to the ratio under the first adjustment.

Although these estimates are broadly suggestive of the potential importance of government support for total output and – other things being equal – for potential emissions associated with production, a direct correspondence between support policies and emissions cannot be made using data at this level of aggregation. For example, if support is skewed towards higher-emitting production systems (e.g. ruminant meat), it will presumably have a greater overall impact than support directed towards lower-emitting products. Nevertheless, the aggregate figures provide a pointer to the potential role that support can play in stimulating emissions by increasing the overall volume of agricultural production.

Table 10. Emissions relative to the value of production adjusted for support in selected countries

	Emissions ratio (kg per USD)			Percentage increase in ratio	
	Averages 2012-14				
	VOP	VOP – PSE	VOP less output and input linked support (1)	VOP-PSE	VOP less output and input-linked support
Brazil	2.280	2.363	2.333	3.6%	2.3%
China	0.552	0.688	0.672	24.7%	21.9%
European Union	0.819	1.058	0.910	29.2%	11.1%
Indonesia	1.255	1.591	1.584	26.7%	26.2%
United States	0.884	0.972	0.933	10.0%	5.5%

VOP = total value of production at the farm gate

PSE = total PSE

(1) Sum of PSE components for support based on commodity outputs, payments based on input use (variable input use) and payments based on current A/An/R/I with production required

Source: Based on FAOStat emissions data and data from the OECD PSE/CSE database for 2016.

To obtain greater insight into the role that individual commodities play in the overall level of a country's emissions from agriculture and, by extension, into the role that the structure of support can play in stimulating or suppressing emissions, it is necessary to generate emissions estimates on a commodity by commodity basis.

In a recent report prepared for the Inter-American Development Bank (IADB) referenced in section four of this report, Josling et al. (2017) combine commodity level estimates of emissions with PSE estimates for Jamaica to examine the relationship between support policies and emission. The focus is on whether policy transfers are structured in such a way as to encourage GHG emissions. The approach relies on adjusting the value of agricultural output for each of the major commodities in Jamaica by the value of support (measured by single commodity transfers) and an emissions cost estimate, calculated as total emissions per commodity (in CO₂ equivalent), multiplied by an assumed price for carbon. The resulting numbers are interpreted as the net value of output and a partial estimate of the net social value of output associated with each commodity.

The study is an interesting example of using available data to examine the linkage between support and emissions at an individual commodity level. The analysis shows that commodities that benefit from high levels of support and generate significant emissions (e.g. poultry) contribute less to the Jamaican economy than many types of fruit and vegetables, which receive little support and generate fewer emissions relative to output value.

There are two major limitations, however, to the approach used by Josling et al. (2017). The first is that the assumption made about the price of carbon has a major impact on the results. The higher the absolute price of carbon, the lower the apparent social value of commodities that are high emitters and vice versa. Since it is difficult to know what price of carbon should be applied in calculations, sensitivity to the choice of carbon price is a disadvantage. The second limitation is that the gross value

of output is not an accurate indicator of a commodity's contribution to the economy, and hence the commodity's social value. That contribution would be more accurately captured by using value added rather than gross value of output.

In Annex three we discuss the derivation and potential uses of a measure that expresses the ratio of emissions to value added (the emissions to value added ratio or EVAR) for agriculture, forestry and other land use (AFOLU) activities. The measure captures the relative contribution of different commodities or land-use activities to the national economy through the value added that they create, and compares this contribution to the emissions generated by each activity. A carbon price is not needed to compute the measure and the value-added decomposition facilitates a more comprehensive assessment of the economic implications of mitigation options. In addition, EVAR provides a basis for capturing the importance of other regional or national policy priorities (e.g. values placed on non-market outputs) in identifying the most appropriate mitigation options given a country's specific conditions.

Given available data, estimates for EVAR were derived for the United States for the following commodities: barley, maize, rice, sorghum, soybeans, beef, milk and pork. The principal sources of information used are emissions data from FAOStat; costs and returns data by product (to impute value added) from the Economic Research Service of the US Department of Agriculture (USDA), and the OECD's 2016 PSE/CSE database (see Annex 3 for additional details).

Table 11 summarizes the results obtained for the three alternative indicators (ratios) using data for 2014. The first column of numbers contains the physical emissions ratio in tons of CO₂e per ton of production. The next two columns show the calculations of emissions in kg per dollar of gross output; the final two columns give the ratio of emissions to value added (EVAR). For both the gross output and the value-added measures, the first of the two columns uses data that are not adjusted for government support. The second of the two columns has estimates that are adjusted for support. These adjustments reduce both the total value of output and the estimated value added.

The rankings of the products, from least to most polluting, are given in Table 12. The rankings on the basis of relative emissions intensity are virtually identical across the gross output and value-added measures, but different in comparison to the physical emissions ratio. Maize, for example, that appears to be most emissions efficient on the basis of the physical emissions ratio, appears to be less so when total value or value added is taken into account. This is also the case for sorghum. In contrast, soybeans and pork move up the rankings in terms of emissions intensity in the value measures. Milk and beef appear to be the most emissions-intensive products on the basis of all three measures.

Table 11. Estimates of emissions ratios for selected US products (2014)

Product	Physical emissions ratio	Emissions per USD of gross output		Ration of emissions to value added (EVAR)	
		Including support	Excluding support	Including	Excluding
Barley	0.523	2.1475	2.2489	4.44253	4.65232
Maize	0.191	1.3080	1.3653	3.20367	3.34415
Rice	1.088	3.6819	3.7594	7.70130	7.86340
Sorghum	0.482	3.0384	3.2963	11.91993	12.93152
Soybeans	0.158	0.4262	0.4417	0.66895	0.69337
Beef	12.588	2.1591	2.2802	5.62740	5.94296
Milk	0.430	0.8136	0.9401	2.88863	3.33779
Pork	2.058	0.8831	0.8831	1.63210	1.63210

Note: All emissions ratios are per kg of product.

Source: Based on data from FAOStat, OECD and USDA.

Table 12. Rankings of US products from least to most emissions intensive

	Physical emissions ratio	Gross output ratio	Ratio to value added
1	Soybeans	Soybeans	Soybeans
2	Maize	Pork	Pork
3	Milk	Milk	Milk
4	Sorghum	Maize	Maize
5	Barley	Barley	Barley
6	Rice	Beef	Beef
7	Pork	Sorghum	Rice
8	Beef	Rice	Sorghum

Source: Based on data from FAOStat, OECD and USDA.

Some of the added information that is provided by the EVAR relative to the total output measure can be seen from Figure 49. In this figure, the calculated emissions ratios using total value and value added are expressed as indices by using the estimated emissions intensity for the least emitting commodity as a base. For the total output measure this is rice and for the EVAR, it is soybeans. Figure 49 shows that the relative emissions intensity of the various products changes significantly when their contribution to value added is considered. The relative emissions intensity of all products rises and the magnitude of the increase differs substantially across products. The emissions intensity ratios for beef, milk, sorghum and maize increase substantially when their respective value-added contributions are taken into account.

Figure 49. Indices of relative emissions intensity for US products, based on total output and value added

Note: Support is netted out in calculating both the gross output ratio and the EVAR used in constructing this graph.

Source: Based on data from FAOStat, OECD and USDA.

Figure 50. US EVAR, when agricultural support is included and excluded from value added

Source: Based on data from FAOStat, OECD and USDA.

As demonstrated by Josling et al. (2017), taking government support for commodities into account can affect the assessment of the relative emissions intensity of commodities. Figure 50 compares EVAR with and without adjustment to value added for government support for the various commodities. We can see that since pork received no government support transfers in the United States in 2014, the EVAR is unaffected when adjusting for support. For most commodities, the change in the EVAR is modest, but the reduction in value-added for supported commodities does affect the results. The percentage increases in the emissions ratios after adjusting for support are largest for milk (16%) and sorghum (9%).²⁹

There are several conclusions that can be drawn from this analysis:

- Taking into consideration how the level of emissions generated in a product's production process compares to that product's contribution in value added (i.e., a product's EVAR) can help countries identify priorities in targeting commodities for mitigation efforts.
- Commodities that may appear to be of lower priority on the basis of physical emissions ratios can be identified as more important in terms of relative mitigation potential when emissions are compared to value added, and vice versa.
- Taking into account the impact of existing agricultural policies on emissions by adjusting value added for policy transfers can serve as a potential detector of increases in emissions associated with these policies and provide a more accurate indicator of the economic contribution of commodities.
- Comparing across commodities, each commodity's ratio of the absolute magnitude of emissions to its value added is an important indicator of the relative benefits that could be obtained by reducing emissions for individual commodities, and could be used in conjunction

²⁹ Blandford and Hassapoyannes (2017) have expanded the commodity coverage to include cotton and sugar, two commodities that received high levels of support in 2014 (PSE of roughly 15% and 27%, respectively). The impact of adjusting for government transfers (EVAR, excluding support) is significant for these commodities, resulting in increases in emissions ratios of roughly 80% and 20%, respectively.

with estimates of the costs of various emission reduction measures to establish emission reduction priorities.

Feasibility of AFOLU's potential to contribute its share in reaching the global mitigation goal

In part three, estimates of mitigation potential in AFOLU by 2030 under various carbon prices were discussed. Analysis by the IPCC (Smith et al., 2014) suggests that with a carbon price of USD 20/tCO₂e substantial mitigation in direct emissions from agriculture would be possible and additional mitigation in FOLU would also be feasible. Table 13 summarizes estimates of the regional distribution of mitigation potential implied by that analysis.

As has been stressed above, much of the potential for reductions of direct emissions exists in Asia. Roughly 55% of the total regional contribution to reducing direct emissions lies in that region. In other regions, mitigation through FOLU can play a major role in mitigation. This is particularly so in Latin America and in the developed countries (represented by the OECD-90 in the table). The IPPC estimates suggest that it would be possible to meet the 1GtCO₂e reduction target for direct emissions, if carbon was priced appropriately and FOLU could play a major role in mitigation.

Table 13. Estimated mitigation potential for AFOLU by 2020 with a carbon price of USD 20 per tCO₂eq

Region	Mitigation potential				Regional contributions		
	Agriculture		FOLU		Total		
	GtCO ₂ eq/yr	% of total regional reduction	GtCO ₂ eq/yr	% of total regional reduction	GtCO ₂ eq/yr	Ag.	FOLU
OECD-90	0.3	28%	0.7	72%	0.9	20%	29%
EIT	0.1	40%	0.2	60%	0.3	9%	8%
LAM	0.1	20%	0.6	80%	0.7	11%	25%
MAF	0.1	31%	0.3	69%	0.5	11%	14%
Asia	0.7	55%	0.5	45%	1.2	50%	24%
World	1.3	37%	2.3	63%	3.6	100%	100%

Notes: 1. OECD-90 = members of the OECD as of 1990, i.e. Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States; EIT = economies in transition; LAM = Latin America; MAF = Middle East and Africa.

2. Agriculture (Ag.) = direct emissions from agriculture through: cropland management; rice management; grazing-land management; restoration of degraded lands; and livestock and manure management.

3. FOLU = restoration of cultivated organic soils and forestry; reduced deforestation; avoidance of biomass fires; and drainage of organic soils.

4. Emissions figures may not add due to rounding.

Source: Based on Figure 11.17 in Smith (2014).

Determining cost-effective mitigation options

Given that countries have made commitments under the Paris agreement to reduce national GHG emissions, there is a need to determine which technical mitigation options are likely to be most effective in achieving mitigation at the national level. Feasible options must take into account the potential cost effectiveness of technical mitigation options as well as constraints in their use.

Considerable analysis has been conducted on mitigation options at global level (e.g. IPCC Fourth and Fifth assessment studies in Smith et al. (2007b; 2014); Havlík et al. (2014) assessment of mitigation options in global livestock systems). There are fewer examples of applications at a national level.

Although the complete representation of national mitigation options through a quantitative or modelling framework may not be possible, the use of a quantitative approach can provide significant insights to guide policy choice. Three principal approaches have been employed: 1. Simulations of national mitigation options; 2. Construction of national marginal abatement cost curves; and 3. Optimization analysis of national mitigation policy options. A selection of results is presented here:

- Simulations of national mitigation options were used to examine the effects of changes in technology and consumer preferences on future emission levels by Bryngelsson et al. (2016). The authors sought to identify options for achieving the EU's targeted reduction of 80% in GHG emissions in Sweden by 2050, among supply-side approaches (i.e. increases in productivity and efficiency gains in agriculture and adoption of specific emissions-reducing options, such as nitrification inhibitors and manure management) and demand-side approaches (i.e. dietary shifts to less meat consumption and to non-ruminant meat, and waste reduction). The authors conclude

that even under optimistic assumptions, supply-side mitigation options would be insufficient to reduce GHG emissions from agriculture in Sweden by more than 50% by 2050, and that significant reductions in ruminant meat consumption would also be needed. Waste reduction was found to have a minor mitigation potential in Sweden. Enhancement of carbon sequestration through conversion of agricultural land to forest or natural vegetation was found to play a significant role.

- Marginal abatement cost curves have been used to identify the cost effectiveness (cost per ton of GHG abatement) of GHG-reduction measures at the farm level (Macleod et al., 2010). Applied to China (Wang et al., 2014) this approach suggests that some mitigation options can be cost-saving and a significant amount of abatement (roughly 44% of the maximum potential) can be achieved at low carbon prices (less than EUR 12 per ton of CO₂e). The most cost effective abatement measures were found to be increased efficiency through reduced application of fertilizer, improved use of irrigation, improved livestock feeding practices and manure management. An application to livestock production in Brazilian savanna (Cerrado) showed the cost effectiveness of mitigation potential through pasture restoration and protein supplementation in increasing efficiency in beef production (de Oliveira Silva et al., 2015).
- An optimization approach to national mitigation (McCarl and Schneider, 2001) showed that at low carbon prices (USD 10 per ton of CO₂e), there would be only modest changes in agricultural practices, but that significant changes would be generated at higher carbon prices (up to USD 500 per ton of CO₂e). The work also showed significant environmental co-benefits from reductions in soil erosion and leakage of nutrients to water supplies, at all carbon prices. A similar approach applied to Norway (Blandford, Gaasland and Vårdal, 2014a) showed that a significant reduction in heavily-supported beef and sheepmeat production is needed to achieve a 30% reduction in emissions, but that changes in dairy policy (relaxation of production quotas) could facilitate mitigation in dairy production by increasing productivity. Mitigation would also be facilitated if farmers were rewarded for undertaking carbon sequestration activities (agroforestry) on marginal land, thereby avoiding significant contraction in agricultural output, in line with the government's policy objective of preserving agricultural activity in the country.
 - In a second optimization study by Blandford, Gaasland and Vårdal (2014b), the effect of trade liberalization on emissions was contrasted to the impact of a carbon tax. It was concluded that proposed changes in domestic and trade policies under the Doha Round of negotiations conducted through the WTO would have only a limited effect on emissions, due to a modest impact of trade liberalization under the proposed agreement on domestic production. More ambitious changes in the market access for imports could be used to mitigate. These, however, unlike the use of a carbon tax, would not necessarily shift the structure of production to less emissions-intensive products. In a more recent study, Blandford, Gaasland and Vårdal (2016) showed that restructuring domestic support away from emissions-intensive ruminant meat could mimic the effects of a carbon tax in achieving a 40% reduction in emissions, while at the same time achieving Norway's food security objective of maintaining a base level of calorie availability from domestically-produced food.
 - Finally, in Blandford, Gaasland and Vårdal (2015), the authors derive a marginal abatement cost curve for Norwegian agriculture. One important difference between this curve and those discussed earlier is that the curve takes into account costs incurred at the production level (farm and industry), costs to taxpayers (input and output subsidies in agriculture) and costs for Norwegian consumers due to higher product prices. Given the heavily subsidized structure of Norwegian agriculture, changes in production induced by the use of a carbon tax, resulted in net welfare gains for the country, even at higher costs for the consumers. The analysis suggested that the retirement of organically rich peatland from agriculture would be an efficient and cost-effective step in reducing emissions from Norwegian agriculture.

These papers illustrate the usefulness of the optimization approach in evaluating options for meeting targeted emissions reductions in both agriculture and FOLU. The Norwegian analysis demonstrates the following important aspects for policy choice:

- Where ruminant livestock production is important, this is a prime target for achieving emissions reductions.

- It is difficult to achieve significant reductions in emissions from ruminant production without inducing changes in consumption; in the Norwegian case, by a shift in consumption from ruminant to non-ruminant meat.
- Non-climate policies, such as trade liberalization and reform of domestic agricultural support policies, can make an important contribution to emissions reduction, as long as carbon leakage is clearly distinguished from carbon reallocation (see section four of this report).
- Changes in land use (e.g. retirement of organic soils) can play an important part in meeting GHG-reduction targets.
- Balancing other objectives, such as the preservation of economic activity in rural areas and food security, can be examined through this approach, and complementarities or trade-offs between various objectives can be identified.

Identifying appropriate mitigation options in AFOLU at a country level

Identifying mitigation options for a country or region requires examination of the largest emission sources or sinks, and of drivers underlying their contribution to emissions and to mitigation.

Regions and countries differ in their food production systems, the sources of generated emissions, and the drivers of these sources. Drivers of emission sources specify to a large extent potential biophysical mitigation at a regional or national level. The regional impact of climate change also affects the biophysical potential for mitigation. Lack of access to technology and information on efficient practices could limit significantly regional potential. Socio-cultural characteristics and the institutional environment can be significant factors influencing the feasibility and the cost effectiveness of mitigation options. Sectoral and non-sectoral policies affecting directly or indirectly the use of inputs in agriculture, agricultural and food production, and the operation of the food system are also determining factors of regional potential. Forestry and land uses other than in agriculture are important sinks and help reduce emissions from agriculture. Finally, the selection of mitigation options should be consistent with other regional priorities, such as food security and sustainable development.

Effective approaches will result from tailoring mitigation options to each country's conditions, and addressing potential implications for food security, productivity and competitiveness (Section 4).

This sub-section focuses on the nine countries/entities introduced in section 1 of this report to show how the appropriateness of mitigation options in AFOLU can vary according to differences in the drivers of emission sources and to specific conditions. The emphasis is on identifying appropriate mitigation options relating to both agriculture and land use. The analysis is based on data compiled from FAOStat and is based on the average values of the 2008-10 period, unless otherwise stated. Table 14 summarizes data that are important for identifying the relative importance of agriculture's direct (agriculture) and indirect (other land uses) emissions, as well as the potential associated with removals from forests.³⁰

Brazil is the largest global emitter among the countries examined, contributing 12% to global AFOLU emissions from agriculture and other land-use sources, followed by Indonesia (9%), China (7%) and India (6%).

Brazil's agriculture, forestry and fisheries contributes less than 5% to national income, but AFOLU emissions account for 70% of total national emissions. Brazil is the second largest emitter globally (average 1990-2014), taking into account removals from forests. Land-use changes contribute more to this total than direct emissions from agriculture. The main, if not the only source of the land-use emissions, is deforestation. Given that the country's main direct emissions from agriculture are CH₄ (64%), it can be seen that deforestation is induced to a large extent by ruminant livestock systems. If this connection were not taken into account and mitigation efforts only focused on reducing direct emissions from agriculture, available mitigation options would be much less effective.

30. Data on national emissions by sector are available only until 2010. Data for land-use sources in Australia for that period are likely to be inaccurate and in any case are non-representative of the situation since 2010. For an explanation of the FAOStat data for forest emissions and removals, see Federici et al. (2015).

Table 14. AFOLU contribution to GDP and decomposition of net emissions in selected countries (average 2008-10)

Averages 2008-10	World	AUS	BRA	CHN	ETH	EU	IND	IDN	NZD	USA
Share of Value Added Agriculture, Forestry, Fisheries in GDP	3.7%	2.3%	4.4%	10.3%	45.0%	1.4%	7.2%	13.7%	5.8%	1.0%
Emissions and removals from AFOLU sources and sinks: Absolute numbers and global shares										
Emissions from AFOLU (sources only) GtCO ₂ e/yr	10.716	0.340	1.280	0.699	0.114	0.581	0.628	0.952	0.044	0.494
% of AFOLU emissions in global AFOLU (sources only)	100%	3%	12%	7%	1%	5%	6%	9%	0%	5%
Net emissions (removals) from forests GtCO ₂ e/yr	-2.554	-0.223	-0.325	-0.397	-0.003	-0.513	-0.136	-0.606	-0.022	-0.494
Forest removals as % of global sinks	100%	9%	13%	16%	0%	20%	5%	24%	1%	19%
Forest removals as % of global AFOLU sources	24%	2%	3%	4%	0%	5%	1%	6%	0%	5%
Share of total national emissions (across all sectors)										
Agriculture- direct emissions	10%	14%	23%	7%	59%	8%	24%	10%	45%	5%
Land use sources (deforestation & other land uses)	12%	27%	47%	0%	20%	3%	0%	53%	7%	2%
AFOLU - sources only	22%	40%	70%	7%	80%	11%	24%	63%	52%	7%
Share of AFOLU emissions (sources only)										
Agriculture - direct emissions	47%	34%	33%	100%	74%	71%	98%	16%	86%	71%
Land use sources (deforestation and other land uses)	53%	66%	67%	0%	26%	29%	2%	84%	14%	29%
Share of agriculture's direct emissions										
Due to CH ₄	57%	54%	64%	49%	56%	51%	66%	51%	62%	48%
Due to N ₂ O	43%	46%	36%	51%	44%	49%	34%	49%	38%	52%
Share of emissions from land use sources (i.e. deforestation and other land uses)										
Deforestation	66%	98%	98%	0%	33%	49%	0%	49%	52%	0%
Burning biomass (peat & forest fires)	21%	1%	2%	60%	25%	0%	20%	14%	0%	48%
Drainage of organic soils (cropland)	13%	1%	0%	35%	41%	49%	80%	36%	47%	50%
Drainage of organic soils (grassland)	0%	0%	0%	5%	1%	1%	0%	1%	1%	1%

Source: Based on FAOStat data.

Brazil is a typical case where mitigation efforts should focus on land-sparing options in agriculture, including restoring degraded pasturelands that would increase pasture productivity (de Olivera Silva et al., 2015). In addition to the need to limit emissions from deforestation, the country's forests contributed more to the global removals of carbon dioxide (13%) than the country did to global AFOLU emissions. This suggests that Brazil's large potential to mitigate lies in enhancing its sink base and increasing global carbon removals, once deforestation is eliminated. As was observed in section one, reducing deforestation is an option that offers high mitigation potential even at low carbon prices and could be exploited relatively easily. In addition to promoting the reduction of deforestation, mitigation options that are restricted to practices that reduce emissions per ruminant (e.g. breeds, CH₄ inhibitors, etc.) would not be as effective as land-sparing options, such as increasing productivity in ruminant production or substituting ruminants by non-ruminants. If these options were not available, it would be better from a global perspective to promote reallocation of Brazil's emissions-intensive livestock (ruminant) production to less emissions-intensive ruminant production systems elsewhere in the world and to support the concentration of Brazil's mitigation efforts on afforestation.

Indonesia's AFOLU is another major global emitter (9% of global emissions), the single main contributor to national emissions (63%) and an important sector of the economy (13.7% of GDP). It is the top emitter globally in land uses (average 1990-2014), taking into account removals from forests (FAOStat). Even more than Brazil, Indonesia's AFOLU emissions are overwhelmingly due to land-use changes (84%) rather than to the agricultural sector (16%). The latter generates equally emissions from N₂O (49%) and CH₄ (51%), mostly from cultivation of organic soils and rice, respectively. Agriculture's impact on the country's sinks is seen partly in the dominance of emissions from the cultivation of organic soils (N₂O emissions in agriculture) and in CO₂ emissions from the drainage of organic soils for conversion to cropland (36% of land-use sources). Deforestation, being the main land-use source (49%), is another indicator of agriculture's impact on indirect emissions. Fires of organic soils and tropical forests (almost 14%) were also related to the conversion of land to agricultural uses.

Clearly, mitigation efforts in Indonesia need to focus on reducing deforestation and the drainage of organic soils. In Indonesia's case, however, deforestation is induced by the establishment of palm oil plantations for use in bioenergy production, which is also a major source of national income. It is also important to note that Indonesia's forests account for nearly a quarter of the world's pool of removals, but under the current agricultural structure, the country cannot offset even its own AFOLU emissions.

India's AFOLU accounts for 6% of global AFOLU sources and a quarter of its national emissions. In India's case, all AFOLU emissions are generated by agricultural sources (98%), and are mostly CH₄ (66%). The main sub-sector emitting this gas is cattle, followed by rice. The largest emitting sources are enteric fermentation and manure on pasture. Since most cattle in India are not used for meat production, it would be more effective to concentrate efforts on reducing emissions per animal (e.g. improving forage, feed, animal breeds), as well as reducing emissions in rice production. It is also interesting to note that India's production system, in which cattle are integrated with crop production on existing cultivated land, has not led to deforestation. The country accounted for 5% of the global forest sink for the period 2008-10 and currently is one of the largest net sinks in the world (fourth largest in the period 1990-2014) due to a large extent to the absence of deforestation.

The rest of the countries presented in Table 14 generate mostly direct emissions from agriculture. They show significant differences which suggest different mitigation options. The criteria for selecting mitigation options for the supply-side of agriculture will be further examined in the next sub-section.

Direct emissions of agriculture in **Ethiopia** and **New Zealand** account for 59% and 45% of their total national emissions, respectively. Agriculture accounts for nearly half of Ethiopia's GDP and it contributes a large percentage of New Zealand's GDP, especially for the standards of a developed country. Both countries generate mostly CH₄ emissions from enteric fermentation and manure left on pasture by ruminants. Here is where the similarities end. New Zealand is a practically insignificant emitter at the world level, whereas Ethiopia contributes 1% of global AFOLU emissions. Moreover, New Zealand's emissions are generated by an agricultural production that is only marginally smaller in terms of value (USD 10.8 billion in 2013), compared to that in Ethiopia (USD 11 billion), even though Ethiopia's population is about twenty times larger than that of New Zealand. This is an indicator of differences in productivity. The selection of mitigation options targeting direct emissions will be examined in more detail in the next sub-section. New Zealand has a small margin for reducing global emissions, because it produces agricultural products efficiently, without putting a globally serious burden on land-use sources. New Zealand's mitigation efforts should be focusing on enhancing the country's sinks. From a global perspective, New Zealand is an efficient – in terms of agriculture and land use – supplier of relatively high-emitting products.

Ethiopia's agriculture, on the other hand, emits heavily direct emissions associated with ruminant production and is responsible for another 20% of the national emissions from drainage of organic soils, deforestation and fires. Land-sparing improvements in livestock production, such as increases in productivity, would qualify as mitigation options for Ethiopia, while raising the country's agricultural output and reducing its emissions intensity.

China is a major contributor to global AFOLU emissions (7%), but also contributes a large pool of removals from forests, which actually makes the country the second largest net sink in the world after the United States (average 1990-2014). China's AFOLU emissions are generated almost entirely in agriculture and make China the top emitter of agricultural direct emissions in the world (average 1990-2014). A small amount of land-use sources comes from biomass fires and drainage of organic soils. Agricultural emissions come mainly from CH₄ and N₂O, but the sub-sectors generating CH₄ are ruminants as well as rice production. It follows that China's mitigation potential lies in agriculture and in preserving its forests and enhancing their carbon density (forest management). In agriculture, improvements in rice management will be needed. While emissions reduction in ruminant production should be a focus area, the current absence of deforestation allows for that reduction to be pursued either by decreasing emissions per animal or by increasing productivity. Land-sparing productivity, in particular, could provide opportunities for afforestation.

The **United States** and the **European Union** present great similarities relating to their AFOLU sectors. In each case, AFOLU contributes 5% to global AFOLU emissions (sources only), about 20% to the pool of global removals from forests, and accounts for less than 2% of GDP. Agriculture also contributes 8% to EU emissions and 5% to US emissions. Half of the land-use emissions in the European Union are generated by deforestation and the other half by drainage of organic soils for use in

crop production. In the United States, for the period 2008-10, half of the land-use emissions were due to drainage of organic soils for conversion to cropland, but the other half came from peat fires. In the European Union, CH₄ emissions (ruminant production) account for slightly more than N₂O emissions (mainly from synthetic fertilizers), whereas in the United States, as seen earlier, the opposite holds, and this is largely due to the more intensive use of organic fertilizer in the European Union (manure applied to soils). Both the European Union and the United States have further scope to intensify their mitigation efforts in agricultural production and enhance their capacity to act as the top global sinks (e.g. through forest management).

Australia's AFOLU performance is not accurately represented in the period 2008-10, where data show a discontinuity in deforestation.³¹ As of 2011, data show that Australia turned from a net source of land-use emissions to a net sink. Emissions associated with uses other than agriculture are generated by the burning of non-tropical forests and the drainage of organic soils. Data also show that agriculture's direct emissions are the main source of AFOLU emissions for the period that preceded 2001 (FAOStat). In agriculture, most emissions come from the burning of savanna and ruminant production. Fires, associated either with agricultural activities and land use, constitute a major weakness for the country's efforts to contain emissions. While Australia forest management and fire prevention will continue to be important, a significant driver for future emissions in this case will be climate change (future incidence of droughts and natural fires).

The next sub-section will focus on identifying mitigation options relating to the supply side of agriculture.

Identifying appropriate mitigation options in the supply side of agriculture at a country level

In Section 1, we introduced two simple equations to show basic linkages between emissions in agriculture and efficiency in production. In this sub-section, we expand these equations, to demonstrate the importance of examining emissions drivers in identifying appropriate mitigation options on the supply side of agriculture at the country level. Such decomposition allows for better understanding of the factors that can affect emissions intensity in agricultural production. Since a given intensity can result from different combinations of factors, such disaggregation can help identify mitigation challenges and priorities at regional/local levels.

As stated earlier, emissions from AFOLU comprise emissions of CH₄ and N₂O from agriculture (E_A) (crop and livestock production), net emissions from the soils used in agriculture³² (NE_S), and net emissions from forests and land uses other than forestry and agriculture (NE_{FOLU}) (Equation 3). Negative emissions (i.e. removals) from soils in agricultural production and FOLU denote carbon uptake and sequestration in the soils and in FOLU, respectively. Agriculture is a determining factor of the sign of net emissions from soils and FOLU. Minimization of agriculture's interference with land and soil is essential for the carbon sequestration needed to offset unavoidable emissions from food production.

$$E_{AFOLU} = E_A + NE_S + NE_{FOLU} \quad (3)$$

Direct emissions from agriculture can be further disaggregated into *emissions from crop production* (E_C) and *emissions from livestock production* (E_{LV}) (Equation 4):

-
31. In all but years 2001-10 deforestation has a zero value, which is more consistent with Australia's recent performance.
 32. *Net emissions from the soils used in agricultural production* (NE_S) are defined here as the sum in CO₂ equivalent of CO₂ net emissions associated with restoration of degraded soils and the use of cropland and grazing land in agricultural activities, as well as the N₂O and CH₄ emissions associated with the burning of savanna and the N₂O emissions from cultivation of organic soils. The definition of *net emissions from forests and land-uses other than forestry and agriculture* (i.e. including restored organic soils) (NE_{FOLU}) that we use here includes the sum in CO₂ equivalent of CO₂ net emissions associated with organic soils (both drainage and restoration), forests (removals net of forest degradation), deforestation and fires (forest and peat), as well as N₂O and CH₄ emissions associated with the burning of FOLU biomass (forests and peat). *Emissions in crop production* include emissions from the use of synthetic fertilizers, crop residues and the burning of crop residues, whereas *emissions attributed to livestock production* include enteric fermentation, manure on pasture, manure applied to soils and manure management.

$$E = (E_C + E_{LV}) + NE_S + NE_{FOLU} \quad (4)$$

In each of these sub-sectors, emissions are determined by the level of output (i.e. Q_C and Q_{LV}) and the emissions intensity per unit of output (i.e. $e_C = \frac{E_C}{Q_C}$ and $e_{LV} = \frac{E_{LV}}{Q_{LV}}$) in crop and livestock production, respectively (Equations 5-6):

$$E = [(e_C \cdot Q_C) + (e_{LV} \cdot Q_{LV})] + NE_S + NE_{FOLU} \quad (5)$$

$$E = \left[\left(\frac{E_C}{Q_C} \cdot Q_C \right) + \left(\frac{E_{LV}}{Q_{LV}} \cdot Q_{LV} \right) \right] + NE_S + NE_{FOLU} \quad (6)$$

In crop production, where the primary input is land (L_C), emissions intensity per unit of output can be seen as the outcome of emissions per unit of land in crop production ($\frac{E_C}{L_C}$) and crop yields ($\frac{Q_C}{L_C}$). The exact relationship can be seen in the first part of Equation (7) below.

In livestock production, where the main input is the animal stock (A), emissions intensity per unit of output can be viewed as the outcome of *emissions per animal head* ($\frac{E_{LV}}{A}$) and *yields in animal product* ($\frac{A}{Q_{LV}}$) as in the second part of Equation (7).

$$E = \left[\left(\frac{E_C}{L_C} \cdot \frac{L_C}{Q_C} \cdot Q_C \right) + \left(\frac{E_{LV}}{A} \cdot \frac{A}{Q_{LV}} \cdot Q_{LV} \right) \right] + NE_S + NE_{FOLU} \quad (7)$$

Equation (7) can be further decomposed into Equation (8) to show that in crop production, emissions per unit of land can be driven by *emissions per unit of fertilizer* ($\frac{E_C}{F}$) and *the intensity with which fertilizer is used per unit of land* ($\frac{F}{L_C}$). Equation (8) also shows that in livestock production systems that use grazing land (mainly ruminant systems), emissions per animal can be driven by *emissions per unit of pastureland used* ($\frac{E_{LV}}{L_{LV}}$) and *the intensity with which land is used per animal* ($\frac{L_{LV}}{A}$)

$$E = \left[\left(\frac{E_C}{F} \cdot \frac{F}{L_C} \cdot \frac{L_C}{Q_C} \cdot Q_C \right) + \left(\frac{E_{LV}}{L_{LV}} \cdot \frac{L_{LV}}{A} \cdot \frac{A}{Q_{LV}} \cdot Q_{LV} \right) \right] + NE_S + NE_{FOLU} \quad (8)$$

The following can be deduced from Equation 8. In crop production, high emissions can be the result of high emissions from the use of synthetic fertilizer or from crop residues or from residue burning (each of them reflected in $\frac{E_C}{L_C}$), and/or low crop yields. High emissions per unit of fertilizer can be due to the type of fertilizer used, the intensive use of synthetic fertilizer (emissions per unit of N fertilizer increase as N fertilizer levels increase) or to non-optimal application and poor conditions for absorbing fertilizer (e.g. reduced water availability, climatic constraints, soil erosion, low soil productivity), each of these reflected in $\frac{E_C}{F}$. The intensity of fertilization ($\frac{F}{L_C}$) also drives up emissions per unit of land. High emissions can also be the result of high levels of output driven by high demand.

At the country level, especially given concerns for food security, it is desirable to focus on products that have the lowest emissions intensity (i.e. lowest emissions per unit of land and the highest productivity of land). The potential to reduce emissions intensity by improving the absorption of nutrients in the soil (water management, precision farming, restoration of degraded soils), as well as the productivity of land (crop rotations and the application of better seeds, technologies, etc.) should be fully exploited wherever possible. Mitigation should also be examined in terms of possible substitution toward crops with lower emissions intensity. Finally, the focus should turn to the potential of carbon sequestration both in agriculture and in other land uses, especially by reducing land clearing (forestry, organic soils, etc.) and land use in agriculture. In developed countries, where emissions per unit of land are high but yields per unit of land and production are also high, the emphasis should be on minimizing emissions per unit of output or on enhancing the capacity to function as sinks. The potential for reallocating production spatially should be considered at a global level.

In livestock production, high emissions may be generated by high output levels or high emissions intensity. The latter may be due to high emissions per animal and low yields of livestock products. Emissions per animal may be high because of the type of animal (ruminant or non-ruminant, type of ruminant), the animal breed, feeding practices or livestock management. High emissions per animal,

however, may also be driven by emissions associated with grazing (manure left on pasture, poor grazing management, too high grazing density), reflected in $\frac{E_{LV}}{L_{LV}}$, or with extensive livestock systems per se (a large amount of land used per animal through grazing), reflected in $\frac{L_{LV}}{A}$. High emissions can also be the result of low animal productivity (i.e. high $\frac{A}{Q_{LV}}$) in Equation (8) due to various reasons, including the type of breed, feeding practices, forage of low nutrient value, and climatic conditions.

Equation (8) facilitates the observation of an interesting aspect of ruminant production (i.e. livestock production that uses land as an input through grazing) that distinguishes it from crop or non-ruminant production in mitigation approaches. In contrast to intensification in crop production, where increased use of fertilizer and intensive use of soil increase emissions per unit of land, the intensification of ruminant production (i.e. through confinement and/or substitution of grazing through the provision of animal feed) reflected in lower L/A ratios reduces emissions per animal, associated with the use of land (mainly manure left on pasture and grazing – enteric fermentation). Thus, emissions per unit of input (E/A) are reduced directly, not only as a result of improvements in livestock management but also as a result of improved feeding, manure management and most important through land sparing. The latter relieves pressures on land that induce conversion of FOLU land (sinks) to agriculture (emission sources).

Wherever possible, high-emitting livestock products should be substituted by low-emitting ones, which will also allow land to be freed and devoted to carbon sequestration. In developing countries, there might be some potential for mitigation by improving livestock management and grazing practices. As discussed in section four, developed countries should focus on changing consumer preferences away from high-emitting products to low-emitting products of equivalent nutritional value, fighting obesity (and overconsumption of products that cause health problems).

Identifying appropriate mitigation options in agriculture at a country level

The decomposition presented by Equation (8) facilitates the analysis of the linkage between sources of emissions (e.g. enteric fermentation, manure on pasture, etc. in livestock production and synthetic fertilizers etc. in crop production) and their drivers, and leads to conclusions about appropriate mitigation options for each country. This sub-section uses equation (8) estimates of these drivers calculated from FAOStat data, plus additional data from FAOStat to examine the implications of mitigation options available to selected countries and to identify appropriate mitigation options for each case.

To economize on space, the country tables on which the analysis is based are contained in Annex 4. Only the table for Australia is included here to illustrate the approach. Tables with cross-country comparisons, which are particularly important for drawing global implications, are also included in this sub-section.

Australia

Table 15 for Australia summarizes estimates of the components of Equation (8) and their changes (average 2012-14 with respect to the average for 1999-2001).

It can be seen that in 2014 the largest emitting activities in Australia's agriculture were the production of beef (39% of total direct emissions) and the burning of savanna (NE_S), which accounted for nearly a third of direct emissions. Sheepmeat production was also a major emitting activity (16%), but with significantly reduced emissions since the base period (35%), which was also the case with the burning of savanna. The activities that showed the largest increase in emissions since the beginning of this century were cereals (+17%) and chicken production (+12%).

In beef production, the 8% increase in total emissions experienced during the period covered was associated with a much larger increase in production. This caused emissions intensity (E/Q) to drop by 5%. The reduction was the result of an increase in animal productivity (6%). Unchanged emissions per animal over the period conceal a 4% increase in emissions per unit of land associated with an increase in grazing density (4% decrease in use of grazing land per animal). The increase in emissions per unit of land was generated by higher emissions from enteric fermentation (8%) and manure on pasture (8%) due to an 8% increase in the number of non-dairy cattle. Pasture land also expanded to accommodate larger cattle numbers, but by less (5%). Production rose by 15% during this period. Emissions per

dollar of beef increased (index E/V = 104), but by less than total emissions, indicating a partial offset of the increase in emissions by an increase in the unit value of beef.

Table 15. Australia: Drivers of direct emissions in agriculture

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	kg per hectare (E/L)	Index	Yield per hectare (kgs) (Q/L)	Index	Emissions per fertilizer use (E/F)	Index	Fertilizer per land (F/L)	Index	kg per dollar (E/V)	Index
Cereals	6.6%	9,403	117	0.25	108	525	110	2,100	102	6.7	97	78	132	2.6	97
Rice	0.4%	552	64	0.67	90	7,201	100	10,683	112	27.6	73	18,315	93	2.6	94
Burning - savanna	29.6%	42,022	64												
Cultivated organic soils	0.2%	348	100												
	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	Emis. per animal (E/A)	Index	Yield per animal (kgs)(Q/A)	Index	kg per hectare (E/L)	Index	Land per animal (L/A)	Index	kg per dollar (E/V)	Index
Cattle	43.2%	61,295	105			2,106	99			238	102	8.9	96	6.4	106
Beef	39.3%	55,749	108	21.6	95	2,033	100	94	106	230	104	8.9	96	8.4	104
Cow's milk	3.9%	5,546	78	0.6	86	3,306	100	5,688	116	373	104	8.9	96	1.9	86
Sheep	16.0%	22,709	65			313	100			235	104	1.3	96	9.1	93
Sheepmeat	16.0%	22,709	65	31.5	68	313	100	9.9	148	235	104	1.3	96	12.3	82
Ruminants	59.8%	84,888	90							236	103			7.0	98
Chicken	0.2%	319	112	0.3	63	3.9	100	13.4	159					0.2	63
Eggs	0.1%	83	106	0.4	67	5.4	98	15.1	147					0.4	67
Pork	0.7%	938	83	2.6	84	407	100	157	118					1.5	86
Non-ruminants	0.9%	1,339	90											0.6	62
Agriculture	100%	141,847	74												

Emissions are in gigagrams of CO₂e

Emissions for crops are calculated using the following crop sources: synthetic fertilizers, crop residues and burning of crop residues

Emissions per dollar (\$) are for 2013

Indices = average of 2012-14 relative to the average for 1999-2001

Yield per hectare is yield per hectare harvested

Fertilizer/land = total nitrogen fertilizer use/area of cereals or rice

Emissions/fertilizer use = emissions per crop/total fertilizer use

Value of production for cattle includes meat and milk; for sheep it includes meat and wool

Total ruminant emissions includes goats

Source: Based on FAOStat data.

In milk production, the pattern of change was different. Emissions showed a significant decrease (22%) due to higher productivity (index 116) but also lower production (index 90). Emissions relative to land use increased due to increased animal density. The change in grazing density was the result of a dramatic drop in dairy cattle numbers (index 75), which had a large land-sparing effect. Emissions from manure on pasture and enteric fermentation were also reduced accordingly. Emissions per dollar of value decreased in line with emissions per unit of product, denoting that prices remained relatively unchanged.

The development of these two sub-sectors in Australia suggests that there was a change in the composition of production away from lower-emitting dairy cattle to higher-emitting non-dairy cattle, possibly due to favorable increase in the price of beef relative to that of milk.

Control of the burning of savanna seems to have improved (emissions index of 64), even though, as noted earlier in this report, there is large variability from year to year in emissions from that source, due to climatic conditions.

With respect to sheepmeat production, a reduction in total emissions was associated with a slight reduction in production and a large reduction (32%) in emissions intensity (E/Q). The latter was induced by a dramatic increase in productivity (nearly 50%) that allowed for a reduction in numbers of sheep (index 65) and even larger savings in land (index 62). Grazing density increased and so did emissions per hectare of pastureland. The drop in emissions per dollar of sheepmeat (index 82) was smaller than the drop in emissions per unit of output, suggesting that there was an increase in the unit value of sheepmeat.³³

33. Note that in this and other tables in Annex 4 the emission ratio with respect to value for sheep, includes meat and wool, and (where relevant) milk. The figures for goats include both meat and milk, where relevant.

The trend away from the production of sheepmeat in Australia toward the production of beef shows a shift from higher-emitting to lower-emitting (in all E/Q, E/V, and E/L) ruminant production due to favorable prices for beef (“natural disincentives”) and large increases in animal productivity. Unfavorable market conditions have also moved production away from dairy cattle and toward beef production.

Decreases in sheepmeat and milk production and especially the increases in productivity are associated with large land savings that offset the effect of the expansion in non-dairy cattle on the demand for grazing land.³⁴ Land was more intensively used by the remaining stock (higher grazing density and emissions per unit of land). Higher productivity associated with more intensive use of grazing land suggests an improvement in feeding practices (better quality of forage and better feed to forage ratio).

Total emissions in chicken production showed the second largest increase among the major products, but production experienced the largest reduction in emissions intensity (index E/Q=63). This was associated with the largest increase in animal yield (index Q/A=159) across the products analyzed. Emissions per dollar of output decreased by the same percentage as emissions per unit of output indicating that unit values were relatively stable. The large increase in chicken production probably reflects (as in many other countries) a shift in dietary preferences toward chicken consumption as well as reductions in feed costs.

Total emissions from cereal production increased by more than any other activity during the period examined, due both to an increase in output and in emissions intensity. Cereal production was the only category of agricultural activity for which emissions intensity increased during the period. Emissions per unit of land area increased by 10%, as a result of higher fertilizer use per unit of land (index F/L = 132). This outstripped moderate savings from more efficient application (E/F = 98). Improvement in yield was 2%. Emissions per dollar of output increased, but by less than either total emissions or emissions per unit of output, reflecting an increase in cereal prices, which generated favorable market conditions for the expansion of cereal production.

Based on the above analysis, Australia could reduce emissions efficiently by continuing on the path of intensifying livestock production through land-sparing productivity increases and substitution in the product mix towards lower-emitting production systems. The extent to which the shifts already observed have been induced by market conditions that could be reversed may be a source of concern for the future, although the progress already made provides a pointer for the future focus for mitigation policies.

In order to examine Australia’s most efficient options for mitigation from a global perspective, it is useful to compare relative emissions efficiency and drivers across the countries examined in this report. Table 16 summarizes cross-country emissions per unit of output for major products and Table 17 summarizes the drivers for these major products across the countries. The analysis that follows in this section is based on these tables.

In comparison to the other countries examined in this study, Australia is not an emissions-efficient country in terms of cereals production. The disadvantage is mainly related to relatively low yields and high emissions with respect to fertilizer use, possibly reflecting unfavorable climatic conditions for the absorption of nutrients (e.g. availability of moisture). The relative underutilization of fertilizer (F/L) may also suggest that increased fertilizer application could lead to disproportionately high increases in emissions from this source. Given also the high growth rate of emissions generated by cereals, one mitigation option for Australia would appear to be to reduce the production of cereals in favor of production in lower-emitting countries. However, given that Australia is a significant exporter of wheat, this could pose problems politically and for global food security.

Australia is among the most emissions-efficient countries in terms of beef production, so it should not be a priority to reduce beef production, unless efforts are made globally to shift diets away from the consumption of ruminant meat.

34. FAOStat data suggest that the total area of land-used for pasture over the period examined decreased by roughly 13%.

Table 16. Comparative figures for emissions intensity across selected countries (2014)

	kgCO ₂ e per kg of product								
	AUS	BRA	CHN	ETH	EU	IND	IDN	NZD	USA
Cereals	0.25	0.18	0.22	0.10	0.20	0.30	0.19	0.20	0.20
Rice	0.67	0.49	0.79	1.40	2.60	0.70	1.10		1.10
Beef	21.60	32.50	24.50	140.50	16.20	106.80	44.50	17.70	11.70
Cow's milk	0.60	1.40	0.70	5.60	0.60	1.10	2.30	0.70	0.40
Buffalo meat			93.20		17.40	66.30	66.10		
Buffalo milk			3.20		2.30	0.80			
Goats meat		26.80	18.90	80.50	20.90	43.40	39.30		
Goats milk		7.00	1.10	3.90	0.80	1.30	5.70		
Sheepmeat	31.50	39.20	13.90	59.00	23.80	52.60	52.40	19.00	
Sheepmilk			5.90		2.70				
Chicken	0.30	0.30	0.70	3.40	0.30	0.60	3.60	0.20	0.30
Eggs	0.40	0.90	0.60	1.60	0.70	0.50	1.10	0.40	0.50
Pork	2.60	2.70	1.00	4.90	1.60	4.90	2.10	2.20	2.10

Source: Based on FAOStat data.

The trend that the country has followed in shifting away from cow's milk production is not on the right track globally in terms of E/Q, although it is desirable if the ratio of emissions per animal is the basis for comparison. Australia has the second largest emissions per animal in the cross-country comparison but one of the lowest emissions per unit of output across countries and among products.

Australia seems to have an advantage over other countries in chicken production. Despite having the fastest growth in emissions among products in the country, this is clearly a sub-sector with an emissions-efficiency advantage.

Sheepmeat production is not particularly inefficient in terms of emissions when compared to other countries. Therefore, unless there is a global reallocation of production to countries with lower emissions intensity for this product (e.g. the European Union) or demand for the product falls, there would be no particular need to reduce production further, especially given the recent trend towards emissions reduction.

Finally, the country should focus on preventing fires associated with its savanna, although this will be challenging given the likelihood of increasingly adverse climatic conditions (potential increase in the incidence and severity of drought).

Table 17. Comparison of drivers of direct emissions across countries for selected products (2014)

	AUS	BRA	CHN	ETH	EU	IND	IDN	NZD	USA
Cereals - E/Q	0.25	0.18	0.22	0.10	0.20	0.30	0.19	0.20	0.20
Cereals - E/L	525	816	1,218	217	1,026	675	945	1,472	1,558
Cereals - Q/L	2,100	4,573	5,449	2,323	5,715	2,401	4,954	8,026	7,620
Cereals - E/F	6.7	4.6	4.8	9.3	4.9	3.7	5.7	0.6	7.3
Cereals - F/L	78	177	253	23	211	184	165	29	214
Cereals - E/V	1.70	1.30	1.50	0.50	1.20	1.80	1.30	1.30	1.40
Rice - E/Q	0.7	0.5	0.8	1.4	2.6	0.7	1.1		1.1
Rice - E/L	7,201	2,559	5,384	3,996	21,421	3,390	5,631		9,237
Rice - Q/L	10,683	5,201	6,815	2,815	8,299	4,531	5,135		8,492
Rice - E/F	92	14	21	172	102	19	34		43
Rice - F/L	78	177	253	23	211	184	165		214
Rice - E/V	2.6	1.8	2.9	2.6	11.4	2.7	3.9		4.0
Beef - E/Q	21.6	32.5	24.5	140.5	16.2	106.8	44.5	17.7	11.7
Beef - E/A	2,033	1,669	1,532	1,134	1,830	717	1,532	2,012	1,683
Beef - Q/A	94	46	62.5	8	113	6.7	34.4	114	144
Beef - E/L	230	1,843	604	1,042	2,964	1,303	2,962	2,854	594
Beef - L/A	8.9	0.9	2.5	1.1	0.6	0.6	0.5	0.7	2.8
Beef - E/V	8.4	11.9	9.0	49.9	5.7	39.6	15.9	7.0	4.6
Cow's milk - E/Q	0.6	1.4	0.7	5.6	0.6	1.1	2.3	0.7	0.4
Cow's milk - E/A	3,306	2,093	2,095	1,644	3,690	1,674	2,479	3,188	4,437
Cow's milk - Q/A	5,688	1,526	2,979	292	6,683	1,495	1,088	4,376	10,319
Cow's milk - E/L	373	2,310	826	1,510	5,977	3,043	4,793	4,522	1,430
Cow's milk - L/A	8.9	0.9	2.5	1.1	0.6	0.6	0.5	0.7	3.2
Cow's milk - E/V	1.9	4.5	2.3	14.4	1.8	4.0	5.1	2.6	1.4
Sheepmeat - E/Q	32	39	14	59	24	53	52	19	
Sheepmeat - E/A	313	191	156	177	204	196	142	311	
Sheepmeat - Q/A	9.9	4.9	11.2	3.0	9.0	3.7	2.7	16.0	
Sheepmeat - E/L	235	1,407	764	1,086	2,204	2,378	1,832	2,940	
Sheepmeat - L/A	1.3	0.14	0.2	0.2	0.1	0.83	0.1	0.1	
Sheepmeat - E/V	12.3	14.1	5.1	18.9	8.2	19.4	17.1	7.8	
Chicken - E/Q	0.3	0.3	0.7	3.4	0.3	0.6	3.6	0.2	0.3
Chicken - E/A	3.9	4.2	1.8	4.0	4.0	4.0	5.0	4.0	4.0
Chicken - Q/A	13.4	13.0	2.7	1.3	13.0	7.0	1.0	16.0	11.0
Chicken - E/V	0.2	0.2	0.5	2.2	0.2	0.5	2.5	0.2	0.2
Eggs - E/Q	0.4	0.9	0.6	1.6	0.7	0.5	1.1	0.4	0.5
Eggs - E/A	5.4	6.0	5.4	7.2	10.0	6.0	6.0	6.0	8.0
Eggs - Q/A	15	7	9	4	14	12	6	16	16
Eggs - E/V	0.4	1.0	0.7	1.8	0.9	0.6	1.4	0.4	0.6
Pork - E/Q	2.6	2.7	1.0	4.9	1.6	4.9	2.1	2.2	2.1
Pork - E/A	407	226	116	276	246	173	204	360	315
Pork - Q/A	157	84	115	56	152	35	99	166	153
Pork - E/V	1.5	0.6	0.7	3.2	1.1	3.2	1.3	1.8	1.3

Source: Based on FAOStat data.

Brazil

Almost all of Brazil's emissions come from beef production (71.5%) and cow's milk (10.9%). Total emissions for each of these have increased by 24% during the period 1999-2001 to 2012-14, despite considerable improvements in emissions efficiency as measured per unit of output (E/Q) of beef (index E/Q = 86) and milk (index E/Q = 77). These efficiency gains were the result of substantial increases in yield per animal (16% in meat and 29% in milk) over the period. Production became more intensive (L/A index = 80, i.e. land grazed per animal dropped by 20%) and emissions per unit of land increased as a result of higher stock numbers (index A = 124) on an unchanged area (index L = 100).

Nevertheless, the country is still underperforming in terms of emissions efficiency for these products when compared to developed countries or even China for beef (China's E/Q for beef is 25, whereas Brazil's is 33) and India for milk (India's E/Q for milk is 1.1 and Brazil's is 1.4) (see Table 16).

Over the period analyzed, emissions per unit of output for milk showed the second largest reduction among the major agricultural activities in the country. The reduction in E/Q is not reflected in emissions per unit value (E/V) for milk, implying that a switch to milk production may not be a particularly attractive mitigation option for Brazilian cattle producers.

Overall, the country's beef and milk sub-sectors, which are dominant in their contributions to national direct emissions, are emissions inefficient both at the national and global levels, due mainly to low productivity.

Chicken production, on the other hand, is the agricultural activity that has had the largest reductions in emissions per unit of output (index E/Q = 76) in Brazil, due to a major increase in productivity (32%). The country's emissions intensity per unit of output is comparable to globally efficient producers in terms of emissions, denoting a potential to mitigate in the sector. The smallest emissions ratio in terms of unit value (E/V = 0.2) also advocates toward that path for future mitigation.

Cereals are the activity that experienced the highest increase in emissions (+116%) both within the country and across countries (compare indices for E across the summary tables for the countries). Nevertheless, production increased by relatively more than emissions and consequently emissions intensity fell slightly (2%). This was the result of increases in productivity, in response to a combination of intensified fertilizer use (F/L index = 174) and improved application (E/F index = 86).

In terms of emissions per unit of output, cereals have the lowest ratio among activities in the country, suggesting a potential focus activity for mitigation, although emissions per dollar do not compare as favorably with other options in the country (e.g. chicken). At a global level, Brazil could continue to produce cereals in consistency with global mitigation efforts.

The combination of the two emission-efficient activities for Brazil (chicken and cereals) that also operate in complementary terms (grains used as feed for non-ruminants) seems to be an advantage in emissions efficiency for Brazil even from a global perspective.³⁵

China

China's largest contributing activities to direct emissions are beef production (23%), rice (23%), cereals (11%) and pork (8%). Among these activities, rice production showed the smallest increase in emissions (2%) during the period examined; pork had the highest (22%). Beef and cereals also exhibited considerable increase in emissions (14% each).

Beef production experienced a large reduction in emissions intensity (index E/Q = 81) due to a significant increase in productivity (Q/A index = 63). This was caused by relative intensification of production (L/A index = 82), which resulted in higher emissions per unit of grazing land (E/L index = 121). Still, the sub-sector's emissions intensity is high at the global as well as the country level.

As noted, emissions from rice increased but by less than production; consequently emissions intensity dropped slightly (E/Q index = 94). Rice yields in China are the highest among the developing countries

35. Due to a lack of emissions data from the FAO, we are unable to examine the contribution of soybeans to emissions in Brazil. Since this is a major crop in the country and typically has lower emissions per unit of area (and, depending on yields, possibly per unit of output), its future contribution to mitigation in Brazil, both in terms of the production of the commodity per se and its use in livestock production, cannot be assessed.

examined in this study but still compare poorly in relation to developed countries, suggesting a large potential for further improvement in productivity and emissions efficiency. No attempt is made to interpret the fertilizer indicators, since FAOSTat does not provide data on fertilizer use per activity. Estimates presented in the summary tables were derived by allocating fertilizer usage between cereals and rice according to their share in arable land. Consequently, potential differences in application rates per hectare between cereals and rice are not reflected³⁶

Cereals production has the lowest emissions intensity in the country and shows a substantial reduction in emissions intensity and in emissions per dollar over the years (index $E/Q = 76$ and $E/V = 78$), due to a large increase in productivity (34%). While further productivity improvements can be made, cereals production is moving in the right direction with respect to emissions efficiency.

Pork production is a sector where China shows a global advantage in terms of emissions efficiency, having the lowest emissions per unit of output among all countries examined, due to high productivity but also to the lowest emissions per animal. This suggests potential advantages conferred by better breeds and feeding practices in a sector of Chinese agriculture that has seen considerable growth and modernization in recent years.

Cow's milk and sheepmeat production showed the highest increase in emissions (153% and 58% respectively). Nevertheless, cow's milk, which accounts for 3.7% of China's direct emissions, also showed the largest drop in emissions per unit of output (index $E/Q = 60$) and per dollar (index $E/V = 58$) in the country. The emissions intensity indicator is also comparable to that for developed countries, suggesting an activity in which China has a comparative advantage in terms of emissions.

Sheepmeat production, which also shows a relatively high emissions intensity among the activities in the country and increasing emissions per unit of output, has the lowest emissions intensity ratio ($E/Q=14$) across all the developing and developed countries examined. The country's emissions-related comparative advantage appears to derive from the combination of high productivity and low emissions per unit of grazing land for the sub-sector (i.e. a relatively intensive production system).

Ethiopia

Ethiopia has a poor performance in emissions, associated with low and diminishing productivity in most livestock products, especially cow's milk. This also points to the country's vulnerability in terms of food security. Improvements in productivity are essential for food security and will help mitigation.

The outlook for cereals production is relatively promising. Ethiopia's doubling of emissions over the period was associated with a much higher increase in production that resulted in a decrease in emissions intensity per unit of output of 24%. This was the outcome of an 80% increase in yields, in response to a 111% increase in the use of fertilizer per unit of land.

In comparison to the other countries under examination, Ethiopia's cereal production has the lowest emissions per unit of output due to the lowest emissions per unit of land. This is the result of yield per unit of fertilizer, even though yield per unit of land in Ethiopia is low in absolute terms. The use of fertilizer is still low, which suggests a large margin for further improving productivity and enhancing food security. A significant potential for mitigation lies in adopting better application techniques for fertilizer since the country lags considerably behind all other countries in emissions per unit of fertilizer ($E/F = 9.3$ in Ethiopia over 5.7 in Indonesia or 0.6 in New Zealand). Emissions per dollar for cereals are higher than emissions per unit of output but still lower than for all other activities in the country. The indicator's slightly larger reduction over the years relative to emissions intensity in physical output points to a relatively attractive option for producers in mitigating (prices increased).

European Union

In the European Union, the largest contributing activities to emissions are beef (29%) and cow's milk (21%) production, cereals (14%) and pork (9%). A significant contribution also comes from cultivation of organic soils (6%).

Among the agricultural sub-sectors in the European Union, beef was the only one that showed an increase in emissions intensity at the same time as productivity decreased by 6%. These developments

36. This limitation applies to all the countries examined in this report. The fertilizer usage ratios are indicative only of changes in the overall use of fertilizer in the crops concerned.

were probably associated with a shift away from the intensification of production due to changes in beef policies that partially decoupled support from output. The extensification of production is evident in all of the EU livestock products mentioned. The European Union and the United States are the only countries exhibiting this trend in the livestock sector for the period examined and are also the countries with the lowest emissions per unit of beef produced (E/Q is 16.2 for the European Union, 11.7 for the United States compared to 17.7 in New Zealand, which ranks next in emissions efficiency).

The European Union's low emissions intensity in beef is associated with one of the highest productivities across countries. This points to the potential for mitigation in EU beef production by moving back to more intensive production systems.

Unlike beef production, cow's milk production showed an 18% decrease in emissions intensity per unit of output, due to a 22% increase in yields. EU production of cow's milk has the second lowest emission intensity and the second highest productivity, following the United States. EU emissions per unit of grazing land in cow's milk production are the highest across countries (5 977 compared to 1 430 in the United States and 373 in Australia), suggesting that more intensive production could possibly lead to reduced emissions.

The increase in emissions in cereals production was accompanied by a 6% reduction in emissions intensity per unit of output and a 7% reduction per dollar of value. This is the result of increases in productivity (15%) associated with both more intensive and more precise use of fertilizer (both E/F and F/L increased by 3%).

Increase in productivity in EU pork production led to reduction in both emissions intensity and emissions. The European Union has the second lowest emissions intensity in pork production, following China. EU mitigation potential lies in the reduction of the conversion of organic soils to cropland (see land use source) and the cultivation of these soils, as well as the intensification of cattle production.

India

India's largest shares of its agricultural emissions are attributed to rice (19%), buffalo meat (17%), beef (16%) and cow's milk (12%). Cow's milk also showed the largest increase in total emissions during the period 1999-2001 to 2012-14.

There was a substantial increase in productivity (42%) in cow's milk production due to intensive use of land, which led to almost a 30% reduction in emissions per unit of output. Smaller increases were observed in the productivity of other livestock products, but in all cases the improvement was associated with intensification of production (L/A index for cow's milk, beef, and buffalo meat = 95). Beef production in India, however, remains highly inefficient at a global level, due to the country's cultural characteristics that limit slaughter and render low yields of meat per animal. Cow's milk production in India still has a potential for improving productivity and reducing emissions intensity.

Emissions from rice production remained unchanged despite an 18% increase in production. Emissions intensity decreased due to an 18% increase in yields with unchanged emissions per unit of land. Further improvements could be achieved through increases in productivity and better rice management to reduce emissions per unit of land.

The lowest emissions intensity in the country lies in cereals production, but this sub-sector compares very poorly in emissions efficiency terms at the global level.

Indonesia

Indonesia's largest contributors to its direct agricultural emissions are rice production (47%) and cultivated organic soils (21%). Emissions from rice have been increasing, despite a 12% fall in emissions intensity, due to an expansion in output (index Q = 138) associated with increases in yield, which however still lags behind other countries examined in this report.

The cultivation of organic soils is associated with plantations of palm oil, largely established for use in bioenergy. Given the impact on emissions from converting the soils to cropland and from their cultivation, however, it is doubtful that this contribution to bioenergy is efficient from a global mitigation perspective.

New Zealand

New Zealand's emissions come almost entirely from ruminant production. Nevertheless, New Zealand has one of the lowest emissions intensities per unit of output across the countries examined, due to high productivity. Over the years, livestock production shifted away from extensive use of land to land sparing (L index is 111 for dairy cattle, 78 for non-dairy cattle, 91 for cattle, 58 for sheep) and the more intensive use of grazing land.

New Zealand offers an example of the carbon leakage that could result if mitigation targets were imposed on countries regardless of production efficiency. Taking into account that New Zealand is a significant exporter, its emissions data suggest potential benefits of carbon reallocation by shifting the supply of exports from high emitting producers of ruminant products (e.g. Brazil) to low-emitting suppliers, such as New Zealand.

United States

Half of US agriculture's direct emissions are generated by cattle production, which exhibits the lowest emissions intensity per unit of beef and cow's milk globally, due to productivity performance that is substantially above that in the second most efficient country in each case (beef yield in the United States is 144 kg per head, followed by 114 in New Zealand; milk yield is 10 319 kg per head, followed by 6 683 in the European Union).

As in the European Union, ruminant production in the United States has shifted to more extensive systems, but this has been accompanied by productivity gains without loss in emissions efficiency.

Cereals is the sub-sector with the highest increase in emissions (17%), associated with a 27% increase in production due to higher yields (19%). The country has had the highest yield increase among developed countries with significant cereals production (i.e. excluding New Zealand).

Key points on mitigation options from reviewed literature

As is demonstrated by the analysis above, mitigation potential and options will vary across countries. While the industrialized world (Annex I countries) may focus on mitigation through changes in land use (through FOLU), potential actions by non-Annex I countries are likely to be heavily constrained by food security, equity and development considerations, as well as by adaptation to climate change (Richards et al., 2015). Other contributions to the literature support some of the major conclusions reached by the analysis presented in this study. In this section we review some of those conclusions.

Mitigation efforts in the livestock sectors of developing countries should include investment for enhancing market orientation. Leakage and rebound effects need to be addressed (Herrero et al., 2016).

Existing literature highlights differences in the activities with the highest mitigation potential among countries (Tian et al., 2016). Countries that have not yet exhausted improvements in productivity or input use efficiency need to follow this path. In countries/regions where productivity is already very high (e.g. the European Union), mitigation effort in agriculture should focus on the development and adoption of mitigation-friendly (i.e. low carbon and high-efficiency) technologies, as well as on change in human diets (Bryngelsson et al., 2016; Tilman et al., 2011; Smith et al., 2014).

Some of the factors identified as affecting mitigation policies in different countries are as follows:

1. **Intensification of livestock systems.** There is substantial heterogeneity in productivity and emissions intensity among existing livestock production systems. Autonomous transitions from extensive to more intensive productive systems would decrease GHG emissions associated with a given volume of output while increasing productivity and improving food availability (Havlík et al., 2014: 3709-3710). Feasible increases in livestock productivity could lead to land saving.

The adoption of feeding practices that substitute better quality feeds for extensive grazing, in addition to improved breeding and animal health and improved grassland management constitute the transition from low-input low-output systems (i.e. extensive rangeland systems) to more efficient and productive livestock systems (i.e. mixed crop-livestock and industrial livestock systems) that are land sparing (Havlík et al., 2014). The substitution of feed grains for grass even at a modest level can have a substantial impact on land use.

Currently there is a large diversity in livestock management practices among regions. The potential for intensification in extensive livestock systems in Africa, Latin America and South

Asia faces challenges from socio-cultural factors (e.g. ruminants as a source of wealth in Africa, restrictions on the slaughter of cattle in India). These challenges may need to be addressed through improved technology, (e.g. the use of sexed semen and artificial insemination to produce more female offspring for milk production in India) or through the development of market-oriented production systems in Africa.

The transition from grazing to mixed systems would raise feed-use efficiency and forage productivity with substantial productivity gains for sub-Saharan Africa (+19% for ruminant meat), Latin America (11%), SE Asia (+19% for milk) and Middle East and N. Africa (+11%). This increase in land productivity would also improve food availability through reduced livestock product prices (Havlík et al., 2014: 3711). Thus, autonomous mitigation through livestock production system transitions saves emissions substantially, even though larger reductions would require economic incentives or regulations (Havlík et al., 2014: 3711).

2. **Shifting from ruminant meat production to non-ruminant meat production** to meet the demand for protein in Africa faces challenges posed by the prevalence of smallholder agriculture. Livestock operations provide a livelihood for over a billion people, including 600 million households in less developed areas (Thornton, 2010). Livestock operations may include cattle, dairy, swine and/or poultry and may be part of farm operations that also grow crops (“mixed” systems). Mixed agricultural systems are common in low- to middle-income countries, where animals are commonly raised outdoors and fed with crops grown on-site or with forage, or a combination of the two (Naylor et al., 2005).

Livestock may also be raised separately either indoors and fed with crops grown elsewhere (e.g. poultry houses) or outdoors on forage (i.e. grazing systems). Evidence on the potential for changes in production systems suggest that these could contribute to a significant reduction in emissions intensity (e.g. Robinson et al., 2011; Gerber et al., 2013).

3. **The use of regulations and enforcement of land-use restrictions** (e.g. Brazil, Indonesia) as well as **the provision of inducements through conservation programs or land retirement schemes** (e.g. European Union, Norway, and the United States) can reduce emissions from the use of organic soils and increase carbon sequestration through forestry. Some work has been done in this area, e.g. work by Blandford, Gaasland and Vårdal (2014a, 2015), discussed earlier, on afforestation payments and payments for peatland retirement in Norway.
4. In Sub-Saharan Africa, a region with low and declining soil fertility and inadequate fertilizer inputs, **investments in agricultural research and wider adoption of new technologies** could lead to improved productivity and reduced emissions intensity if challenges related to weak scientific capacity and poor support, as well as a number of other constraints such as limited mechanization of small farms, could be overcome (Brown et al., 2015). The shrinking size of smallholder farms due to population growth limits the viability of mechanization (Funk et al., 2008).
5. Southern Asia has about 90% of the world’s rice fields and accounts for more than 60% of the world’s nitrogen fertilizer consumption. It accounts for 64-81% of CH₄ emissions and 36% – 52% of N₂O emissions derived from agriculture and waste sectors. Thus, **improvements in fertilizer use efficiency, rice management and animal diets could substantially reduce agricultural N₂O and CH₄ emissions in this region** (Tian et al., 2016: 227).
6. According to Agrawala et al. (2014: 1106), studies reveal large differences in the regional mitigation potential and clear differences in the ranking of the most-effective options. Nevertheless, for a range of scenarios, **Asia shows the largest economic mitigation potential in AFOLU**, followed by Latin America, OECD-90, Middle East and Africa and Economies in Transition. **Reduced deforestation dominates the forestry mitigation potential in Latin America and Middle East and Africa** (Agrawala et al., 2014: 1106).

Final words

As has been indicated in this study, it is imperative that agriculture and the food system play their part in reducing anthropogenic emissions of greenhouse gases, if the target limit of a 2°C increase in global average temperature by the end of the century is to be met. Countries will differ in their ability to contribute to mitigation by limiting emissions in agriculture and other land uses, including forestry.

Because agriculture is related to the production of food for human survival, agriculture's direct and indirect emissions cannot be eliminated as is potentially the case in other sectors (e.g. energy, where renewable sources that do not generate GHG emissions can replace fossil fuel), even if FOLU emissions caused by the expansion of agriculture (e.g. deforestation, cultivation of organic soils) were eliminated. If increasing demand for food and agricultural raw materials is to be met without damaging land-use change, it will be essential to increase productivity in agriculture.

FOLU offers high potential for mitigation, both by avoiding emissions (i.e. by reducing deforestation, conversion of organic soils to agricultural land, and fires) and increasing removals (i.e. by enhancing area and carbon stock of forests and by restoring organic soils, currently under cultivation).

Agriculture's mitigation focus should be on technological advancements and improvements in techniques and management that increase productivity while reducing land use. Because of the potential implications for food security, options targeting emissions per unit of land should only be used if there are no other alternatives, including increasing sequestration in FOLU.

It will also be essential to encourage changes in consumption towards diets that have a lower carbon footprint and to reduce food loss and waste.

Mitigation potential varies with the extent to which emissions are priced. Low potential conceals high resistance due to economic, socio-cultural or institutional constraints; changes in potential induced by carbon pricing are indicative of how easily constraints could be relaxed with the use of appropriate incentives or disincentives. Mitigation options with relatively high initial costs of adoption may require subsidisation.

In identifying effective mitigation options, indicators that account for the importance of other goals and for policy effects may need to be considered alongside an indicator of emissions intensity per unit of output. This applies in developing countries, where sustainable development should also be a priority, and in those developed and developing countries with policies that use market interventions to stimulate agricultural output and input use.

International mitigation efforts should consider internalising a carbon price in agriculture, globally, or compensating developing countries for addressing financial, cultural or institutional challenges in adopting highly effective mitigation options. That should include implementation of innovative policies and comprehensive strategies to generate "natural incentives".

International co-ordination of mitigation efforts is required for the globally maximum feasible mitigation potential to be realized. Global consensus and global action are necessary to achieve a more sustainable food and agricultural system.

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Annex 1.

Additional Figures and Tables

Figure A1.1 . Contribution of AFOLU and fossil fuels to global anthropogenic CO₂ emissions

Source: IPCC (2014), Online Graph 1.05-01.

Figure A1.2 . Contribution of Annex I and non-Annex I countries to global AFOLU emissions (average 2012-14)

Source: FAOStat data.

Figure A1.3 . Brazil: Direct agricultural emissions per dollar of agricultural output (1961-2013)

Note: Emissions from cultivation of organic soils only included from 1990 onwards.

Source: FAOSTat data.

Figure A1.4 . Beef yield by region (1961-2013)

Note: Includes beef and buffalo.

Source: FAOSTat data.

Figure A1.5 . United States: Direct agricultural emissions per dollar of agricultural output (1961-2013)

KgCO₂e per constant (2004-06) dollar of output

Note: Emissions from cultivation of organic soils only included from 1990 onwards.

Source: FAOStat data.

Figure A1.6 . Africa: Direct agricultural emissions by sub-region (average 2012-14)

Source: FAOStat data.

Figure A1.7 . The Americas: Direct agricultural emissions by sub-region (average 2012-14)

Source: FAOStat data.

Figure A1.8 . Asia: Direct agricultural emissions by sub-region (average 2012-14)

Source: FAOStat data.

Figure A1.9 . Europe – direct agricultural emissions by sub-region (average 2012-14)

Source: FAOSTat data.

Figure A1.10 Oceania –direct agricultural emissions by sub-region (average 2012-14)

Source: FAOSTat data.

Figure A1.11. Africa: Direct agricultural emissions per dollar of agricultural output by sub-region (1995-2013)

Source: FAOStat data.

Figure A1.12. Americas: Direct agricultural emissions per dollar of agricultural output by sub-region (1995-2013)

Source: FAOStat data.

Figure A1.13 Asia: Direct agricultural emissions per dollar of agricultural output by sub-region (1995-2013)

Source: FAOSTat data.

Figure A1.14. Europe: Direct agricultural emissions per dollar of agricultural output by sub-region (1995-2013)

Source: FAOSTat data.

Figure A1.15. Oceania: Direct agricultural emissions per dollar of agricultural output by sub-region (1995-2013) **Figure A1.16. Milk yield by region (1991-2013)**

Table A1.1 Projected yield impacts for crops and livestock by region under future scenarios

Projected impacts for crops and livestock in global regions and sub-regions under future scenarios. Crop yield impacts in parentheses correspond to parenteticals in the scenario column. $-CO_2$ = without CO_2 effects; $+CO_2$ = with CO_2 effects; (I) = irrigated; (R) = rainfed. ARPEGE = Action de Recherche Petite Echelle Grande Echelle; CSIRO = Commonwealth Scientific and Industrial Research Organisation; ECHAM4 = European Centre for Medium Range Weather Forecasts Hamburg 4; GFDL-CM2.0/2 = Geophysical Fluid Dynamics Laboratory-Climate Model 2.0/2; HadCM3 = Met Office Hadley Centre Climate Prediction Model 3; HIRHAM = High-Resolution Hamburg Climate Model; MIROC = Model for Interdisciplinary Research On Climate; MPI-OM = Max Planck Institute; MRI-CGCM2.3.2 = Meteorological Research Institute of Japan Meteorological Agency-Coupled General Circulation Model 2.3.2; PRECIS = Providing Regional Climates for Impact Studies; RCA3 = Rossby Centre Regional Atmospheric Model 3.

Regional impacts on crops

Region	Sub-region	Yield impacts (%)	Scenario	Reference
World		<ul style="list-style-type: none"> • (I) Maize: -4, -7 • (R) Maize: -2, -12 • (I) Rice: -9.5, -12 • (R) Rice: -1, +0.07 • (I) Wheat: -10, -13 • (R) Wheat: -4, -10 	A1B CSIRO, MIROC 2050	Nelson et al. (2010)
East Asia	China	(I) Maize: <ul style="list-style-type: none"> • -10.9 to -1.4 (-7.8 to -1.6), • -21.7 to -9.8 (-16.4 to -10.2), • -32.1 to -4.3 (-26.6 to -3.9) (R) Maize: <ul style="list-style-type: none"> • -22.2 to -1.0 (-10.8 to +0.7), • -27.6 to -7.9 (-18.1 to -5.6), • -33.7 to -4.6 (-25.9 to -1.6) (I) Rice: <ul style="list-style-type: none"> • -18.6 to -6.1 (-10.1 to +3.3), • -31.9 to -13.5 (-16.1 to +2.5), • -40.2 to -23.6 (-19.3 to +0.18) 	+1°C, +2°C, +3°C $-CO_2$ (+ CO_2)	Tao et al. (2011)
	Eastern China	Rice: <ul style="list-style-type: none"> • -10 to +3 (+7.5 to +17.5), • -26.7 to +2 (0 to +25), • -39 to -6 (-10 to +25) 	2030, 2050, 2080 $-CO_2$ (+ CO_2)	Tao and Zhang (2013)
	Huang-Huai-Hai Plain, China	Wheat-maize: +4.5 ± 14.8, -5.8 ± 25.8	+2°C, +5°C	Liu et al. (2010)
	North China Plain	<ul style="list-style-type: none"> • (I) Wheat: -0.9 (+23) • (R) Wheat: -1.9 (+28) 	A1B 2085-2100 $-CO_2$ (+ CO_2) MIROC	Yang et al. (2013)
	Yangtze River, China	<ul style="list-style-type: none"> • (I) Rice: -14.8 (-3.3) • (R) Rice: -15.2 (-4.1) 	B2 2021-2050 $-CO_2$ (+ CO_2)	Shen et al. (2011)
South Asia	South Asia	<ul style="list-style-type: none"> • Maize: -16 • Sorghum: -11 	2050	Knox et al. (2012)
	South Asia	Net cereal production -4 to -10	+3°C	Lal (2011)
	India	Winter sorghum: up to -7, -11, -32	A2 2020, 2050, 2080	Srivastava et al. (2010)
		<ul style="list-style-type: none"> • (I) Rice: -4, -7, -10 • (R) Rice: -6, -2.5, -2.5 	A1B; A2; B1; B2 2020, 2050, 2080 $+CO_2$ MIROC; PRECIS/HadCM3	Kumar et al. (2013)
		<ul style="list-style-type: none"> • Monsoon maize: -21 to 0, -35 to 0, -35 to 0 • Winter maize: -13 to +5, -50 to +5, -60 to -21 	A2 2020, 2050, 2080 HadCM3	Byjesh et al. (2010)
	Northeast India	<ul style="list-style-type: none"> • (I) Rice: -10 to +5 • (R) Rice: -35 to +5 • Maize: up to -40 • Wheat: up to -20 	A1B 2030 $+CO_2$ PRECIS/HadCM3	Kumar et al. (2011)
	Coastal India	<ul style="list-style-type: none"> • (I) Rice: -10 to +5 • (R) Rice: -20 to +15 • (I) Maize: -50 to -15 • (R) Maize: -35 to +10 		
	Western Ghats, India	<ul style="list-style-type: none"> • (I) Rice: -11 to +5 • (R) Rice: -35 to +35 • Maize: up to -50 • Sorghum: up to -50 		
	Pakistan	Wheat: -7, -24 (Swat); +14, +23 (Chitral)	+1.5°C, +3°C	Section 24.4.4.3
		<ul style="list-style-type: none"> • Wheat: -6, -8 • Rice: -16, -19 	B2, A2 2080	Iqbal et al. (2009)

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Region	Sub-region	Yield impacts (%)	Scenario	Reference
West Asia	Yarmouk Basin, Jordan	<ul style="list-style-type: none"> Barley: -8, +5 Wheat: -20, +18 	-20%, +20% precipitation	Al-Bakri et al. (2010)
Africa	All regions	<ul style="list-style-type: none"> Wheat: -17 Maize: -5 Sorghum: -15 Millet: -10 	2050	Knox et al. (2012)
	All regions	Maize: -24 ± 19	2090 +5°C	Thornton et al. (2011)
	East Africa	<ul style="list-style-type: none"> Maize: -3.1 to +15.0, -8.6 to +17.8 Beans: -1.5 to +21.8, -18.1 to +23.7 	A1FI; B1 2030, 2050 HadCM3; ECHam4	Thornton et al. (2010)
	Sahel	Millet: -20, -40	+2°C, +3°C	Ben Mohamed (2011)
Central & South America	Northeastern Brazil	<ul style="list-style-type: none"> Maize: 0 to -10 Wheat: -1 to -14 Rice: -1 to -10 	2030	Table 27-5; Lobell et al. (2008)
	Southern Brazil	<ul style="list-style-type: none"> Maize: -15 Bean: up to +45 	A2 2080 +CO ₂ HadCM3	Table 27-5; Costa et al. (2009)
	Paraguay	<ul style="list-style-type: none"> Wheat: +4, -9, -13 (-1, +1, -5) Maize: +3, +3, +8 (+3, +1, +6) Soybean: 0, -10, -15 (0, -15, -2) 	A2 (B2) 2020, 2050, 2080 PRECIS	Table 27-5; ECLAC (2010)
	Central America	<ul style="list-style-type: none"> Wheat: -1 to -9 Rice: 0 to -10 	2030	Table 27-5; Lobell et al. (2008)
		<ul style="list-style-type: none"> Maize: 0, 0, -10, -30 Bean: -4, -19, -29, -87 Rice: +3, -3, -14, -63 	A2 2030, 2050, 2070, 2100	Table 27-5; ECLAC (2010)
	Panama	Maize: -0.5, +2.4, +4.5 (-0.1, -0.8, +1.5)	A2 (B1) 2020, 2050, 2080 +CO ₂	Table 27-5; Ruane et al. (2013)
	Andean region	<ul style="list-style-type: none"> Wheat: -14 to +2 Barley: 0 to -13 Potato: 0 to -5 Maize: 0 to -5 	2030	Table 27-5; Lobell et al. (2008)
	Chile	<ul style="list-style-type: none"> Maize: -5% to -10% Wheat: -10% to -20% 	A1FI 2050 +CO ₂ HadCM3	Table 27-5; Meza and Silva (2009)
	Argentina	<ul style="list-style-type: none"> Wheat: -16, -11 (+3, +3) Maize: -24, -15 (+1, 0) Soybean: -25, -14 (+14, +19) 	A2, B2 2080 -CO ₂ (+CO ₂) PRECIS	Table 27-5; ECLAC (2010)
North America	Midwestern United States	<ul style="list-style-type: none"> Maize: -2.5 (-1.5) Soy: +1.7 (+9.1) 	+0.8°C -CO ₂ (+CO ₂)	Hatfield et al. (2011)
	Southeastern United States	<ul style="list-style-type: none"> Maize: -2.5 (-1.5) Soy: -2.4 (+5.0) 		
	United States Great Plains	Wheat: -4.4 (+2.4)		
	Northwestern United States	<ul style="list-style-type: none"> Winter wheat: +19.5, +29.5 Spring wheat: -2.2, -5.6 	A1B 2040, 2080 +CO ₂	Stöckle et al. (2010)
	Canadian prairies	<ul style="list-style-type: none"> Small grains: -48 to +18 Oilseeds: -50 to +25 	+1°C, +2°C, +20% precipitation, -20% precipitation	Kulshreshtha (2011)
Europe	Boreal	Wheat, maize, soybean: +34 to +54	A2, B2 2080 HadCM3/HIRHAM, ECHAM4/RCA3	Iglesias et al. (2012)
	Alpine	Wheat, maize, soybean: +20 to +23		
	Atlantic North	Wheat, maize, soybean: -5 to +22		
	Atlantic Central	Wheat, maize, soybean: +5 to +19		
	Atlantic South	Wheat, maize, soybean: -26 to -7		
	Continental North	Wheat, maize, soybean: -8 to +4		
	Continental South	Wheat, maize, soybean: +11 to +33		
	Mediterranean North	Wheat, maize, soybean: -22 to 0		
	Mediterranean South	Wheat, maize, soybean: -27 to +5		

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Region	Sub-region	Yield impacts (%)	Scenario	Reference
Australia	South	Wheat: –15, –12	A2; Low, high plant available water capacity 2080 +CO ₂ CCAM	Luo et al. (2009)
	Southeast	Wheat: –29 (–25)	B2, A2, A1FI 2080 –CO ₂ (+CO ₂) CCAM	Anwar et al. (2007)

Regional impacts on livestock

Region	Sub-region	Climate change impacts	Scenarios	Reference
Africa	Botswana	Cost of supplying water from boreholes could increase by 23% due to increased hours of pumping, under drier and warmer conditions.	A2, B2 2050	Section 22.3.4.2
	Lowlands of Africa	Reduced stocking of dairy cows, a shift from cattle to sheep and goats, due to high temperature.		
	Highlands of East Africa	Livestock keeping could benefit from increased temperature.		
	East Africa	Maize stover availability per head of cattle may decrease due to water scarcity.		
	South Africa	Dairy yields decrease by 10–25%.	A2 2046–2065/2080–2100 ECHAM5/MPI-OM, GFDL-CM2.0/2, MRI-CGCM2.3.2	Nesamvuni et al. (2012)
Europe	Netherlands	Dairy production affected at daily mean temperatures above 18°C		Section 23.4.2
	Italy	Mortality risk to dairy cattle increased by 60% by exposure to high air temperature and high air humidity during breeding.		
	French Uplands	Annual grassland production system significantly reduced by 4-year exposure to climatic conditions.	A2 2070	Cantarel et al. (2013)
	France	No impact on dairy yields.	A2 1970–1999, 2020–2049, 2070–2099 ARPEGE	Graux et al. (2011)
	Ireland, France	Grassland dairy system increases potential of dairy production, with increased risk of summer–autumn forage failure in France.	A1B By the end of century	
	Overall Europe	Spread of bluetongue virus (BTV) in sheep and ticks in cattle due to climate warming.	2080	Graux et al. (2011)
		No increase in risk of incursion of Crimean–Congo hemorrhagic fever virus in livestock.		Section 23.4.2
Australia	Northern Australia	3°C increase in temperature will result in 21% reduction in forage production for CO ₂ at 350 ppm level and no change at 650 ppm level. Changes of ±10% in rainfall were exacerbated to ±15% change in forage production at 350 ppm CO ₂ .	A1B 2030	McKeon et al. (2009)
	Australia (other than Tasmania)	Dairy output will decline under 1°C increase in temperature.	A1B 2030	Section 25.7.2.1
	25 sites in southern Australia	Profitability of fodder supply production declined at most sites due to shorter growing season.	A2 2050	
	Southern Australia	Decline in NPP of grassland from historical climate will be 9% in 2030, 7% in 2050, and 14% in 2070. Declines in ANPP were larger at lower rainfall locations. Operating profit (at constant prices) fell by an average of 27% in 2030, 32% in 2050, and 48% in 2070.	A2 2030, 2050, 2070	Moore and Ghahramani (2013)
	Tasmania	Dairy yields increase 0.5–6.2%	A1B, ECHAM5/MPI-OM 2050	Hanslow et al. (2014)
	Victoria	Dairy yields decrease 1.3–6.7%		
	New South Wales	Dairy yields decrease 1.4–6.6%		
	Southern Australia	Dairy yields decrease 2.2–8.1%		
	New Zealand	Change in agricultural production: • Dairy: –2.8%, –4.3% • Sheep and beef: –6.1%, –8.8%	2030 Global temperature change 25%, 75% of the way between lower and upper bounds of scenarios in IPCC 2001 Third Assessment Report.	Wratt et al. (2008)

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Region	Sub-region	Climate change impacts	Scenarios	Reference
Central and South America	Andean Mountain countries	Beef and dairy cattle, pigs, and chickens could decrease between 0.9 and 3.2% while sheep could increase by 7%.	2060 Hot and dry scenario	Section 27.3.4.1
	Colombia, Venezuela, and Ecuador	Beef cattle choice declined.	2060 Milder and wet scenario	
	Argentina and Chile	Beef cattle choice increased.	Future climate change	
	Pernambuco, Brazil	Milk production and feed intake in cattle strongly affected.	Future climate change	Silva et al. (2009)
North America	Central United States	Dairy yields decrease 16–30%.	Baseline CO ₂ , 2× CO ₂ , 3× CO ₂ CGCM/Hadley	Mader et al. (2009)

Source: IPCC (2014).

Annex 2.

Technical Options for Mitigation of Direct Emissions from Agriculture

In terms of the reduction in emissions intensity through changes in farming practices and input use (including land use) the following major categories of options are available: 1. cropland management; 2. grazing land management and pasture improvement; 3. management of organic soils; 4. restoration of degraded lands; 5. livestock management; 6. manure management; and 7. bioenergy.

Under these headings, the most important mitigation options according to Smith et al. (2008) are:

• Cropland management

- a. Agronomy – i. practices that increase yields and uptake of C, e.g. improved crop varieties, extending crop rotations (e.g. with perennials), avoiding or reducing bare fallow and correction of nutrient deficiencies, however, the benefits of N fertilizer can be offset by higher emissions of N₂O from soils and CO₂ in manufacturing; ii. Reduction of chemical inputs, e.g. through rotations with legumes to reduce N, although this can also be a source of N₂O; iii use of catch or cover crops to add C to soils and to extract unused N.
- b. Nutrient management – efficient application of organic and inorganic fertilizers to reduce N₂O, through more precise application rates, use of slow-release fertilizer or nitrification inhibitors, avoiding delays between application and uptake, more precise placement of N in the soil to increase accessibility to plant roots, and avoiding excess N applications or eliminating applications where possible.
- c. Tillage/residue management – i. reduced tillage or no till with reductions in soil disturbance to stimulate C gains, there may also be reductions in N₂O emissions although this depends on soil and climate and in some areas N₂O emissions can increase; ii. retaining crop residues to increase soil C and avoiding burning.
- d. Water management – i. expansion of irrigated area or using more effective irrigation measures to enhance C in soils through enhanced yields and residue returns, although these may be offset by CO₂ used in delivering the water or from N₂O emissions associated with higher moisture and fertilizer inputs; ii. drainage of agricultural lands in humid regions can promote productivity and soil C and improved aeration may suppress N₂O emissions, although nitrogen loss in drainage may be susceptible to loss as N₂O.
- e. Rice management – i. reduction of CH₄ emissions during the growing season by draining once or several times although this may partly be offset by higher N₂O and can be constrained by water availability, rice cultivars differ significantly in generation of CH₄ emissions, the use of off-season drainage, keeping the soil as dry as possible and avoiding waterlogging also reduce emissions; ii. timing of organic residue additions (incorporation of organic materials during the dry period), composting residues before incorporation or production of biogas for use as energy source can also reduce emissions.
- f. Agroforestry – production of livestock or food crops on land that also grows trees for timber, firewood or other tree products, the use of shelter belts or riparian zones/buffer strips with woody species can give gains in the standing stock of carbon above ground in plant material and may also increase soil carbon.
- g. Land cover (use) change – one of the most effective measures is the reversion of cropland to another land cover, e.g. one similar to native vegetation, leading to accrual of soil C, possible

lower N₂O from lower N inputs and higher CH₄ oxidation. The conversion of drained cropland to wetland gives rapid accumulation of soil carbon, although it may increase CH₄ emissions due to the creation of anaerobic conditions. Land-use conversion is an appropriate option primarily for surplus agricultural land or low productivity land.

2. *Grazing land management and pasture improvement* – grazing lands occupy much larger areas than croplands but are usually managed less intensively. Some practices that can be used to reduce emissions and enhance removals are:
 - a. Grazing intensity – intensity and timing of grazing can affect C accrual in soils. Carbon accrual on optimally grazed lands is often greater than ungrazed or overgrazed lands, although the effects vary due to many types of grazing practices employed, diversity of plant species, soils and climates. However, there can be additional impacts on emissions of other GHGs due to reductions in livestock numbers.
 - b. Increased productivity (including fertilization) – higher productivity promotes C storage through greater returns in plant litter to the soil, but this must be weighed against N₂O from added N. Irrigating grassland can promote soil C gains but must be weighed against energy use in irrigation.
 - c. Nutrient management – similar to cropland, but is more challenging due to difficulty of controlling deposition of faeces and urine from livestock.
 - d. Fire management – biomass burning releases CH₄ and to a lesser extent N₂O (CO₂ is reabsorbed by vegetation). Hydrocarbon and reactive nitrogen emissions form tropospheric ozone. Smoke contains a range of aerosols which can have warming and cooling effects, though the net effect is thought to be positive radiative forcing (increased energy in the atmosphere). The blackening of the land surface reduces albedo (reflective capacity) causing warming. Burning can affect the proportions of woody versus grass cover (less C storage in soil and biomass). Reduction in emission effects requires a reduction in frequency or extent of fires or more effective suppression, reducing the fuel load through vegetation management, and burning at a time of the year when less CH₄ and N₂O are emitted. Note that in the absence of human ignition, fire-prone ecosystems would be lit by other agents.
 - e. Species introduction – grass species with higher productivity or C allocation to deeper roots to increase soil C. Introduction of legumes to promote soil C storage through enhanced productivity from associated N inputs and N₂O if reduction in fertilizer use.
3. *Management of organic soils* – these contain high C. Drainage aerates the soil giving high fluxes of CO₂ and N₂O. The most effective option is to avoid draining or to re-establish a high water table.
4. *Restoration of degraded lands* – erosion, excessive disturbance, organic matter loss, salinisation, acidification or other processes result in low productivity. Revegetation (planting grasses), nutrient amendments, application of organic substrates (manure, biosolids and composts), reducing tillage to retain crop residues and conserve water can all be used. These give higher C sequestration but this is partly offset by higher N₂O emissions.
5. *Livestock management* – ruminants account for 18% of total anthropogenic CH₄ emissions. Reduction possibilities:
 - a. Improved feeding practices – feeding more concentrates to replace forage. This gives lower emissions per kg of feed intake and per kg of product. The net benefit depends on reduced animal numbers or younger age at slaughter for beef animals, as well as emissions in producing and transporting feed. Other improvements include adding oils to the diet and improving pasture quality (particularly in less developed countries) to improve productivity and to reduce the proportion of energy lost as CH₄.
 - b. Agents and dietary additives – most aim at suppressing methanogenesis. Ionophores (antibiotics to reduce CH₄ emissions can have transitory effects and are banned in some countries, e.g. the European Union); halogenated compounds inhibit methanogenic bacteria but can have transitory effects and can reduce feed intake; probiotics (e.g. yeast cultures, generally have a small impact); propionate precursors (fumarate or malate – require high doses and are expensive); vaccines

against methanogenic bacteria (not yet commercially available); bST and hormonal growth implants can reduce emissions per kg of product by increasing productivity.

- c. Longer term management changes and animal breeding – animals reach slaughter weight at a younger age.
6. *Manure management* – reduction of CH₄ from manure stored in lagoons or tanks by cooling or covering or by capturing CH₄ emitted; anaerobic digestion and use of CH₄ for energy; storing or handling manures in solid rather than liquid form generates less CH₄ but more N₂O. For most animals worldwide, excretion happens in the field so it is difficult to control.
7. *Bioenergy* – displacement of fossil energy through the use of crop residues and the cultivation of bioenergy crops that do compete with food crops for land.

Annex 3.

The Calculation and Use of an Economic Emissions Intensity Measure (EVAR)

This annex discusses issues in the application of an emissions intensity measure based on emissions from agricultural production relative to economic benefit, and the application of the measure to the eight US agricultural products in this report.

While physical emissions ratios can provide considerable insight into sources of emissions as demonstrated by the use of Equations 1-8 in this report, they provide no insight into the potential trade-off between emissions from an economic activity and its potential contribution to the economy. Expressing emissions relative to total value of output (as employed in parts of this report) provides some information on emissions relative to the economic contribution of the product, but is not an accurate indicator of that contribution. This can be provided by an alternative measure: the ratio of emissions to value added from AFOLU activities (EVAR).

The EVAR for a particular commodity is defined as:

$$EVAR_i = \frac{(E_i - S_i)}{\sum_j P_j Q_j^i - \sum_k P_k Q_k^i}, \text{ for } (E_i - S_i) \geq 0, TVA^i > 0$$

Where:

i = type of AFOLU activity; $i > 0$

j = product per activity i; $j \geq 0$

k = variable input used in activity i; $k > 0$

E_i = total emissions from activity i (in units of CO₂eq); $E_i \geq 0$

S_i = total carbon sequestration from activity i (in units of CO₂eq); $S_i \geq 0$

P_j = price of output j, net of subsidies/taxes (per unit at the farm level)

Q_j^i = quantity of output j from activity i; $Q_j^i \geq 0$

P_k = price of variable input k, net of subsidies/taxes (per unit of input at the farm level)

Q_k^i = quantity of variable input k used in activity i; $Q_k^i \geq 0$

The following characteristics may be noted:

1. The measure allows for joint products in an activity, e.g. sheep farming that yields both meat and wool (or in some countries, yielding an additional product – milk) or dairy production that yields both milk and calves.
2. It allows for the incorporation of sequestration in addition to emissions. The emissions/sequestration estimates per unit of product can be based on a carbon budget in which direct and indirect emissions associated with current production practices and sequestration contributions can be generated to define the numerator. Emissions associated with land use and the direct and indirect emissions associated with intermediate inputs, such as fertilizer in crop production or the feed used in generating livestock products, can be included. Emissions that are calculated on the basis of the area of land or the number of animals used in producing a given commodity can be transformed into units of product (e.g. tonnes of wheat or tons of beef) in order to provide a comparison between total physical emissions from commodities and their value added.
3. A carbon price is not needed to compute the measure.

4. To the extent that it is possible to identify and value other outputs in addition to agricultural products (e.g. other positive or negative externalities associated with production) these can be included in the denominator in order to provide an accurate indicator of social value of production.

The EVAR can be used as a means of ranking commodities in terms of their environmental and economic contribution.

For activities that have net emissions (most of agricultural production):

- Step 1: Use EVAR to identify AFOLU activities that minimize net emissions relative to economic contribution (Total Value Added).
- Step 2: Among activities with the lowest EVAR, try to maintain those with the highest TVA per hectare.

For activities that have net sequestration value and commercial outputs (e.g. commercial forestry):

- Step 1: Use EVAR to identify AFOLU activities that maximize sequestration relative to economic contribution.
- Step 2: Among activities with highest EVAR, choose to promote those with the highest TVA per hectare.

For activities that have net sequestration value and no commercial outputs (e.g. forest preservation):

- Step 1: Use EVAR to identify preservation activity that maximizes sequestration relative to the total opportunity cost of the land involved.
- Step 2: Allocate land to preservation on the basis of lowest opportunity cost per hectare.

The use of the measure has a number of practical benefits:

- Provides a way to overcome the problems of using physical measures of emissions intensity relative to physical quantities of output as a guide to policy for sustainable development.
- Combines economic content and emissions intensity in guiding policy choice.
- Allows estimates to be derived of the relative economic value of both emitting and sequestering activities associated with land use.
- Captures the importance of promoting activities that have low emissions (or high sequestration potential) relative to their economic contribution in achieving sustainable development.
- Captures the importance of markets and prices in realizing mitigation potential and provides a way to highlight the effects of market distortions through adjustments to value added (e.g. output subsidies; subsidized or non-priced variable inputs; price distortions due to inadequate infrastructure).
- Provides a guide to investment priorities across products for sustainable development (activities to increase value added in agriculture or to reduce output variability due to climate change).
- Allows for the incorporation of other positive or negative externalities in the benefit/cost calculation, providing that values can be assigned to these externalities at the level of individual activities or products.
- Provides a guide to the use of incentive payments (nationally and internationally) for mitigation and sequestration activities.

The measure provides a consistent tool for the evaluation of a range of mitigation options:

- Specific technologies that reduce emissions or increase sequestration can be reflected in the emissions figure in the numerator. To the extent that these affect variable input quantities and costs, this can be reflected in the denominator.
- Exogenous changes in output resulting from increased efficiency can be incorporated in the denominator through changes in the volume of output; the impact of changes in the structure of variable inputs (e.g. increased use of fertilizer) can also be reflected in the denominator.

- Although the measure is partial equilibrium in nature, it can be applied to situations in which output and input prices and quantities change as a result of policies or exogenous factors, by using output from a model that incorporates relevant supply and demand elasticities for outputs and variable inputs or generates changes in factor shares in the production process.
- It captures the need for and can reflect the effect of using, multiple policy instruments to achieve desired mitigation at reasonable cost while achieving other environmental, economic, and social objectives.
- It does not require the implementation of a common global carbon price in the identification of emissions “comparative advantage” within a country. Thus, while not providing an optimal solution (i.e. through the implementation of common carbon price across countries and sectors), it meets the requirement to make progress towards global mitigation in agriculture that is compatible with food security and sustainable development.

In the initial calculations of the EVAR for the United States, presented in this report, the following methods were used:

Emissions

- FAOStat data on total emissions from cereals were allocated to individual cereal crops (barley, maize, sorghum, wheat) on the basis of area harvested as a percentage of total agricultural area; emissions from rice cultivation were used in the rice calculation. Estimates of the ratio of synthetic fertilizer use per hectare for soybeans (a leguminous crop) compared to corn fertilizer use per hectare (derived from USDA cost of production data) were used to impute emissions from soybeans.
- FAOStat emissions data for beef, milk and pork were used directly in the calculations for those commodities.
- PSE/CSE data were used for output value and support.

Value added

- The value added calculation was based on output value data from the PSE database and cost of production data from USDA for each crop. Data on variable costs (operating costs) were used.

Physical emissions ratio

- Data from the PSE database on production volumes were used in this calculation. There are slight differences between those numbers and FAO production numbers and these lead to marginal changes in the physical emissions ratios compared to those elsewhere in the report.

Annex 4. Emissions Indicators for Agricultural Commodities in Selected Countries Derived from FAOstat Data

Table A4.1. Australia: Summary of drivers of direct agricultural emissions by product (2014)

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	Kg per hectare (E/L)	Index	Yield per hectare (kgs) (Q/L)	Index	Emis. per fertilizer use (E/F)	Index	Fertilizer per land (F/L)	Index	kg per dollar (E/V)	Index
Cereals	6.6%	9,403	117	0.25	108	525	110	2,100	102	6.7	98	78	132	1.7	102
Rice	0.4%	552	64	0.67	90	7,201	100	10,683	112	92.2	77	78	132	2.6	94
Burning - savanna	29.6%	42,022	64												
Cultivated organic soils	0.2%	348	100												
	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	Emis. per animal (E/A)	Index	Yield per animal (kgs)(Q/A)	Index	kg per hectare (E/L)	Index	Land per animal (L/A)	Index	kg per dollar (E/V)	Index
Cattle	43.2%	61,295	105			2,106	99			238	102	8.9	96	6.4	106
Beef	39.3%	55,749	108	21.6	95	2,033	100	94	106	230	104	8.9	96	8.4	104
Cow's milk	3.9%	5,546	78	0.6	86	3,306	100	5,688	116	373	104	8.9	96	1.9	86
Sheep	16.0%	22,709	65			313	100			235	104	1.3	96	9.1	93
Sheepmeat	16.0%	22,709	65	31.5	68	313	100	9.9	148	235	104	1.3	96	12.3	82
Ruminants	59.8%	84,888	90							236	103			7.0	98
Chicken	0.2%	319	112	0.3	63	3.9	100	13.4	159					0.2	63
Eggs	0.1%	83	106	0.4	67	5.4	98	15.1	147					0.4	67
Pork	0.7%	938	83	2.6	84	407	100	157	118					1.5	86
Non-ruminants	0.9%	1,339	90											0.6	62
Agriculture	100%	141,847	74												

Emissions are in gigagrams of CO₂e.

Emissions for crops are calculated using the following sources: synthetic fertilizers, crop residues and burning of crop residues.

Emissions per constant international dollar (US\$) 2004-06 are for 2013.

Indices = average of most recent three years relative to the average for 1999-2001.

Yield per hectare is based on harvested area.

Fertilizer/land = nitrogen fertilizer use attributed to cereals or rice on the basis of shares of total crop area in cereals and rice.

Emissions/fertilizer use = emissions per crop relative to total fertilizer use attributed to the crop.

Value of production for cattle includes meat and milk; for sheep it includes meat and wool.

Total ruminant emissions includes goats.

Land per animal for ruminants is based on total pasture land and estimated forage requirements per hectare per category of animal.

Table A4.2. Brazil: Summary of drivers of direct agricultural emissions by product (2014)

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	kg per hectare (E/L)	Index	Yield per hectare (kgs) (Q/L)	Index	Emis. per fertilizer use (E/F)	Index	Fertilizer per land (F/L)	Index	kg per dollar (E/V)	Index
Cereals	3.6%	15,923	216	0.18	98	816	166	4,573	168	4.6	86	177	174	1.3	110
Rice	1.4%	5,989	91	0.49	85	2,559	136	5,201	160	14.4	74	177	174	1.8	86
Burning - savanna	1.7%	7,726	131												
Cultivated organic soils	0.0%	5	100												
	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	Emis. per animal (E/A)	Index	Yield per animal (kgs)(Q/A)	Index	kg per hectare (E/L)	Index	Land per animal (L/A)	Index	kg per dollar (E/V)	Index
Cattle	82.4%	364,254	124			1,715	100			1,893	124	0.91	80	9.8	84
Beef	71.5%	316,074	124	32.5	86	1,669	100	51	117	1,843	124	0.91	80	11.9	87
Cow's milk	10.9%	48,181	129	1.4	77	2,093	100	1,526	129	2,310	124	0.91	80	4.5	80
Goats	0.4%	1,886	96			213	100			1,568	124	0.14	80	15.2	93
Goat meat	0.2%	810	85	26.8	84	92	89	3.4	106	673	111	0.14	80	10.9	90
Goat's milk	0.2%	1,076	105	7.0	92	122	109	17.4	118	895	136	0.14	80	21.2	92
Sheep	0.8%	3,367	118			191	100			1,407	124	0.14	80	12.9	100
Sheepmeat	0.8%	3,367	118	39.2	97	191	100	4.9	102	1,407	124	0.14	80	14.1	97
Ruminants	83.6%	369,508	124							1,885	124			9.8	84
Chicken	1.0%	4,225	155	0.3	76	4.2	101	13	132					0.2	77
Eggs	0.4%	1,926	140	0.9	98	6	99	7	101					1.0	98
Pork	1.9%	8,575	119	2.7	96	226	100	84	104					1.6	94
Non-ruminants	3.3%	14,727	130											0.6	75
Agriculture	100%	441,905	128												

Emissions are in gigagrams of CO₂e.

Emissions for crops are calculated using the following crop sources: synthetic fertilizers, crop residues and burning of crop residues.

Emissions per constant international dollar (I\$) 2004-06 are for 2013.

Indices = average of most recent three years relative to the average for 1999-2001.

Yield per hectare is based on harvested area.

Fertilizer/land = nitrogen fertilizer use attributed to cereals or rice on the basis of shares of total crop area in cereals and rice.

Emissions/fertilizer use = emissions per crop relative to total fertilizer use attributed to the crop.

Value of production for cattle and goats includes meat and milk; for sheep it includes meat and wool.

Land per animal for ruminants based on total pasture land and estimated forage requirements per hectare per category of animal.

Table A4.3. China: Summary of drivers of direct agricultural emissions by product (2014)

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	kg per hectare (E/L)	Index	Yield per hectare (kgs) (Q/L)	Index	Emis. per fertilizer use (E/F)	Index	Fertilizer per land (F/L)	Index	kg per dollar (E/V)	Index
Cereals	11.1%	78,422	114	0.22	76	1,218	102	5,449	134	4.8	104	253	93	1.5	78
Rice	23.1%	163,144	103	0.79	94	5,384	102	6,815	108	21.3	108	253	93	2.9	95
Burning - savanna	0.0%	112	65												
Cultivated organic soils	0.1%	883	100												

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	Emis. per animal (E/A)	Index	Yield per animal (kgs)(Q/A)	Index	kg per hectare (E/L)	Index	Land per animal (L/A)	Index	kg per dollar (E/V)	Index
Cattle	26.4%	186,676	124			1,638	103			646	121	2.5	85	6.4	65
Beef	22.7%	160,483	114	24.5	80	1,532	100	63	124	604	117	2.5	85	9.0	82
Cow's milk	3.7%	26,193	256	0.7	59	2,095	100	2,979	168	826	117	2.5	85	2.3	59
Buffalo	5.9%	41,450	103			1,776	101			700	118	2.5	85	19.1	100
Buffalo meat	4.5%	31,684	103	93.2	112	1,357	100	15	89	535	117	2.5	85	34.3	116
Buffalo milk	1.4%	9,765	106	3.2	91	418	103	133	113	165	121	2.5	85	7.8	91
Goats	5.7%	40,068	124			216	100			8,425	57	0.0	176	8.0	74
Goat meat	5.6%	39,739	124	18.9	72	214	100	11	140	8,356	57	0.0	176	8.1	74
Goat's milk	0.0%	329	136	1.1	97	1.8	110	1.6	114	69.2	62	0.0	176	3.4	99
Sheep	5.6%	39,432	147			202	101			989	151	0.2	67	5.2	97
Sheepmeat	4.3%	30,430	158	13.9	108	156	109	11	100	764	163	0.2	67	5.1	106
Sheepmilk	1.3%	9,002	120	5.9	72	46	82	8	114	226	123	0.2	67	14.3	69
Ruminants	43.5%	307,625	123							783	123			7.0	71
Chicken	1.1%	8,027	131	0.7	84	2	97	3	116					0.5	86
Eggs	2.1%	14,522	138	0.6	104	5	97	9	93					0.7	106
Pork	7.8%	54,897	123	1.0	81	116	100	115	123					0.7	84
Non-ruminants	10.9%	77,446	126											0.7	88
Agriculture	100%	707,640	115												

Emissions are in gigagrams of CO₂e

Emissions for crops are calculated using the following sources: synthetic fertilizers, crop residues and burning of crop residues

Emissions per constant international dollar (I\$) 2004-06 are for 2013

Indices = average of most recent three years relative to the average for 1999-2001

Yield per hectare is based on harvested area

Fertilizer/land = nitrogen fertilizer use attributed to cereals or rice on the basis of shares of total crop area in cereals and rice

Emissions/fertilizer use = emissions per crop relative to total fertilizer use attributed to the crop

Value of production for cattle, buffalo and goats includes meat and milk; for sheep it includes meat, milk and wool

Land per animal for ruminants based on total pasture land and estimated forage requirements per hectare per category of animal.

Table A4.4. Ethiopia: Summary of drivers of direct agricultural emissions by product (2014)

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	kg per hectare (E/L)	Index	Yield per hectare (kgs) (Q/L)	Index	Emis. Per fertilizer use (E/F)	Index	Fertilizer per land (F/L)	Index	kg per dollar (E/V)	Index
Cereals	2.3%	2,192	201	0.1	89	217	160	2,323	180	9.3	62	23	211	0.5	87
Rice	0.2%	187	481	1.4	56	3,996	84	2,815	149	171.8	33	23	211	2.6	46
Burning - savanna	3.6%	3,432	79												
Cultivated organic soils	1.5%	1,436	100												

	% of ag emissions	Emissions E	Index E	kg per kg of product (E/Q)	Index	Emis. per animal (E/A)	Index	Yield per animal (kgs)(Q/A)	Index	kg per hectare (E/L)	Index	Land per animal (L/A)	Index	kg per dollar (E/V)	Index
Cattle	72.9%	70,161	145			1,237	104			1,136	158	1.1	66	30.0	109
Beef	53.3%	51,342	124	140.5	122	1,134	100	8	82	1,042	152	1.1	66	49.9	108
Cow's milk	19.6%	18,819	272	5.6	190	1,644	100	292	53	1,510	152	1.1	66	14.4	177
Goats	6.5%	6,233	215			214	100			1,258	153	0.2	66	30.4	103
Goat meat	6.2%	5,980	216	80.5	110	205	100	2.6	91	1,258	153	0.2	66	32.3	104
Sheep	5.9%	5,660	168			193	99			1,086	152	0.2	66	17.9	100
Sheepmeat	5.4%	5,204	170	59.0	105	177	100	3.0	96	1,086	152	0.2	66	18.9	96
Ruminants	85.2%	82,055	150							1,121	155			28.7	107
Chicken	0.2%	210	146	3.4	120	4	99	1.3	83					2.2	115
Eggs	0.1%	68	112	1.6	104	7.2	103	4	100					1.8	101
Pork	0.0%	9	121	4.9	101	276	100	56	99					3.2	100
Non-ruminants	0.3%	287	135											2.1	111
Agriculture	100%	96,256	152												

Emissions are in gigagrams of CO₂e

Emissions for crops are calculated using the following crop sources: synthetic fertilizers, crop residues, and burning of crop residues

Emissions per constant international dollar (\$) 2004-06 are for 2013

Indices for Ethiopia = average for 2012-14 relative to the average for 2002-2004 (due to data discontinuity)

Yield per hectare is based on harvested area

Fertilizer/land = nitrogen fertilizer use attributed to cereals or rice on the basis of shares of total crop area in cereals and rice

Emissions/fertilizer use = emissions per crop relative to total fertilizer use attributed to the crop

Emissions for goats include goat's milk

Value of production for cattle and goats includes meat and milk; for sheep it includes meat, milk and wool

Land per animal for ruminants based on total pasture land and estimated forage requirements per hectare per category of animal

Pasture land in this case = permanent meadows and pastures plus other land category.

Table A4.5. European Union: Summary of drivers of direct agricultural emissions by product (2014)

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	kg per hectare (E/L)	Index	Yield per hectare (kgs) (Q/L)	Index	Emis. Per fertilizer use (E/F)	Index	Fertilizer per land (F/L)	Index	kg per dollar (E/V)	Index
Cereals	14.1%	59,443	103	0.2	94	1,026	108	5,715	115	4.9	103	211	103	1.2	93
Rice	2.2%	9,259	99	2.6	74	21,421	92	8,299	124	101.7	90	211	103	11.4	85
Burning - savanna	0.0%	43	78												
Cultivated organic soils	5.8%	24,168	100												
	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	Emis. per animal (E/A)	Index	Yield per animal (kgs) (Q/A)	Index	kg per hectare (E/L)	Index	Land per animal (L/A)	Index	kg per dollar (E/V)	Index
Cattle	49.5%	207,943	89			2,339	99			3,788	96	0.6	103	3.0	91
Beef	28.6%	120,085	94	16.2	106	1,830	100	113	94	2,964	97	0.6	103	5.7	101
Cow's milk	20.9%	87,858	84	0.6	82	3,690	101	6,683	122	5,977	98	0.6	103	1.8	83
Buffalo	0.2%	728	198			1,877	100			3,041	97	0.6	103	6.9	102
Buffalo meat	0.1%	268	285	17.4	29	692	146	40	576	1,120	141	0.6	103	9.7	30
Buffalo milk	0.1%	460	165	2.3	122	1,186	83	525	69	1,921	81	0.6	103	5.7	122
Goats	0.7%	2,955	88			234	100			2,530	97	0.1	103	3.6	91
Goat meat	0.3%	1,363	101	20.9	133	108	114	5	88	1,166	111	0.1	103	7.1	112
Goat's milk	0.4%	1,592	80	0.8	79	126	90	153	114	1,363	88	0.1	103	2.5	81
Sheep	6.6%	27,676	80			283	100			3,059	97	0.1	103	7.1	94
Sheepmeat	4.7%	19,935	74	23.8	101	204	93	9	92	2,204	90	0.1	103	8.2	95
Sheepmilk	1.8%	7,741	101	2.7	98	79	126	29	128	856	123	0.1	103	7.0	99
Ruminants	57.0%	239,301	88							3,662	96			3.2	91
Chicken	0.8%	3,164	113	0.3	88	4	100	13	113					0.2	89
Eggs	1.2%	5,210	102	0.7	101	10	100	14	99					0.9	100
Pork	8.7%	36,732	93	1.6	90	246	101.9	152	113					1.1	93
Non-ruminants	10.7%	45,106	95											0.8	90
Agriculture	100%	420,140	94												

Emissions are in gigagrams of CO₂e

Emissions for crops are calculated using the following sources: synthetic fertilizers, crop residues and burning of crop residues

Emissions per constant international dollar (I\$) 2004-06 are for 2013

Indices = average of most recent three years relative to the average for 1999-2001

Yield per hectare is based on harvested area

Fertilizer/land = nitrogen fertilizer use attributed to cereals or rice on the basis of shares of total crop area in cereals and rice

Emissions/fertilizer use = emissions per crop relative to total fertilizer use attributed to the crop

Value of production for cattle, buffalo and goats includes meat and milk; for sheep it includes meat, milk and wool

Land per animal for ruminants based on total pasture land and estimated forage requirements per hectare per category of animal.

Table A4.6. India: Summary of drivers of direct agricultural emissions by product (2014)

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	kg per hectare (E/L)	Index	Yield per hectare (kgs) (Q/L)	Index	Emis. per fertilizer use (E/F)	Index	Fertilizer per land (F/L)	Index	kg per dollar (E/V)	Index
Cereals	6.2%	38,857	140	0.3	107	675	140	2,401	131	3.7	94	184	152	1.8	110
Rice	18.8%	117,620	100	0.7	85	3,390	100	4,531	118	18.5	70	184	152	2.7	85
Burning - savanna	0.0%	160	163												
Cultivated organic soils	0.1%	913	100												

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	Emis. per animal (E/A)	Index	Yield per animal (kgs)(Q/A)	Index	kg per hectare (E/L)	Index	Land per animal (L/A)	Index	kg per dollar (E/V)	Index
Cattle	28.2%	176,584	105			944	107			1,716	112	0.550	95	8.3	65
Beef	16.3%	102,196	91	106.8	93	717	100	6.7	108	1,303	105	0.550	95	39.6	93
Cow's milk	11.9%	74,389	133	1.1	71	1,674	100	1,495	142	3,043	105	0.550	95	4.0	74
Buffalo	26.7%	167,538	117			1,523	100			2,768	105	0.550	95	3.0	75
Buffalo meat	17.1%	107,034	109	66.3	86	973	94	14.7	109	1,768	99	0.550	95	3.8	70
Buffalo milk	9.7%	60,505	132	0.8	82	550	114	679.2	139	1,000	120	0.550	95	2.1	84
Goats	4.6%	28,556	109			215	100			2,601	105	0.083	95	9.9	86
Goat meat	3.5%	21,916	108	43.4	100	165	100	3.8	100	1,996	105	0.083	95	18.1	99
Goat's milk	1.1%	6,641	110	1.3	73	50	101	38.9	138	605	107	0.083	95	4.0	75
Sheep	2.0%	12,366	108			196	100			2,378	105	0.083	95	17.0	102
Sheepmeat	2.0%	12,366	108	52.6	100	196	100	3.7	100	2,378	105	0.083	95	19.4	100
Ruminants	61.4%	385,045	110							2,144	111			4.8	71
Chicken	0.2%	1,562	179	0.6	55	4	97	7	174					0.5	66
Eggs	0.3%	2,098	202	0.5	104	6	104	12	100					0.6	104
Pork	0.3%	1,726	76	4.9	100	173	100	35	100					3.2	100
Non-ruminants	0.9%	5,386	127											0.8	65
Agriculture	100%	626,864	113												

Emissions are in gigagrams of CO₂e

Emissions for crops are calculated using the following sources: synthetic fertilizers, crop residues, and burning of crop residues

Emissions per constant international dollar (\$) 2004-06 are for 2013

Indices = average of most recent three years relative to the average for 1999-2001

Yield per hectare is based on harvested area

Fertilizer/land = nitrogen fertilizer use attributed to cereals or rice on the basis of shares of total crop area in cereals and rice

Emissions/fertilizer use = emissions per crop relative to total fertilizer use attributed to the crop

Value of production for cattle, buffalo and goats includes meat and milk; for sheep it includes meat and wool

Land per animal for ruminants based on total pasture land and estimated forage requirements per hectare per category of animal.

Table A4.7. Indonesia: Summary of drivers of direct agricultural emissions by product (2014)

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	kg per hectare (E/L)	Index	Yield per hectare (kgs) (Q/L)	Index	Emis. per fertilizer use (E/F)	Index	Fertilizer per land (F/L)	Index	kg per dollar (E/V)	Index
Cereals	2.2%	3,625	152	0.2	76	945	134	4,954	178	5.7	104	165	115	1.3	77
Rice	46.9%	77,689	121	1.1	88	5,631	104	5,135	118	34.1	89	165	115	3.9	89
Burning - savanna	0.5%	808	108												
Cultivated organic soils	20.6%	34,168	100												
	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	Emis. per animal (E/A)	Index	Yield per animal (kgs)(Q/A)	Index	kg per hectare (E/L)	Index	Land per animal (L/A)	Index	kg per dollar (E/V)	Index
Cattle	14.5%	23,960	134			1,627	102			3,146	130	0.5	78	13.7	82
Beef	13.4%	22,137	131	44.5	83	1,532	100	34.4	122	2,962	128	0.5	78	15.9	85
Cow's milk	1.1%	1,824	192	2.3	100	2,479	100	1,088	102	4,793	128	0.5	78	5.1	86
Buffalo	1.4%	2,330	53			1,745	100			3374	127	0.5	78	18.1	65
Buffalo meat	1.4%	2,330	53	66.1	66	1,745	100	26.4	155	3,374	127	0.5	78	18.1	65
Goats	2.5%	4,135	147			222	101			2,860	129	0.1	78	15.6	99
Goat meat	1.5%	2,562	151	39.3	106	137	103	3.5	98	1,772	132	0.1	78	15.3	99
Goat's milk	1.7%	1,573	142	5.7	101	84	97	14.9	96	1,088	125	0.1	78	16.0	99
Sheep	1.9%	3,092	200			192	99			2,477	127	0.1	78	12.7	138
Sheepmeat	1.4%	2,287	240	52.4	195	142	119	2.7	60	1,832	152	0.1	78	17.1	167
Ruminants	20.2%	33,518	126							2,690	125			14.0	83
Chicken	4.2%	6,933	225	3.6	94	5	105	1	111					2.5	93
Eggs	0.9%	1,544	96	1.1	96	6	100	6	104					1.4	100
Pork	0.9%	1,573	132	2.1	81	204	101	99	124					1.3	82
Non-ruminants	6.1%	10,050	197											2.0	95
Agriculture	100%	165,614	122												

Emissions are in gigagrams of CO₂e

Emissions for crops are calculated using the following sources: synthetic fertilizers, crop residues, and burning of crop residues

Emissions per constant international dollar (\$) 2004-06 are for 2013

Indices = average of most recent three years relative to the average for 1999-2001

Yield per hectare is based on harvested area

Fertilizer/land = nitrogen fertilizer use attributed to cereals or rice on the basis of shares of total crop area in cereals and rice

Emissions/fertilizer use = emissions per crop relative to total fertilizer use attributed to the crop

Value of production for and goats includes meat and milk; for sheep it includes meat and wool; for buffalo it is meat

Land per animal for ruminants based on total pasture land and estimated forage requirements per hectare per category of animal.

Table A4.8. New Zealand: Summary of drivers of direct agricultural emissions by product (2014)

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	kg per hectare (E/L)	Index	Yield per hectare (kgs) (Q/L)	Index	Emis. per fertilizer use (E/F)	Index	Fertilizer per land (F/L)	Index	kg per dollar (E/V)	Index
Cereals	0.5%	202	133	0.2	105	1,472	134	8,026	127	0.6	109	29	105	1.3	105
Burning - savanna	0.0%	1	115												
Cultivated organic soils	1.0%	379	100												

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	Emis. per animal (E/A)	Index	Yield per animal (kgs)(Q/A)	Index	kg per hectare (E/L)	Index	Land per animal (L/A)	Index	kg per dollar (E/V)	Index
Cattle	68.8%	26,586	118			2,564	104			3,638	130	0.7	80	3.5	84
Beef	28.6%	11,057	98	17.7	91	2,012	100	114	110	2,854	125	0.7	80	7.0	93
Cow's milk	40.2%	15,529	139	0.7	84	3,188	100	4,376	119	4,522	125	0.7	80	2.6	89
Sheep	24.0%	9,264	72			311	100			2,940	125	0.1	80	6.2	91
Sheepmeat	24.0%	9,264	72	19.0	82	311	100	16	122	2,940	125	0.1	80	7.8	86
Ruminants	92.7%	35,851	101							3,428	131			4.0	81
Chicken	0.1%	45	117	0.2	72	4	100	16	137					0.2	72
Eggs	0.1%	20	104	0.4	85	6	101	16	119					0.4	83
Pork	0.3%	103	82	2.2	81	360	100	166	124					1.8	88
Non-ruminants	0.4%	168	91											0.5	69
Agriculture	100%	38,654	103												

Emissions are in gigagrams of CO₂e.

Emissions for crops are calculated using the following sources: synthetic fertilizers, crop residues, and burning of crop residues.

Emissions per constant international dollar (\$) 2004-06 are for 2013.

Indices = average of most recent three years relative to the average for 1999-2001.

Yield per hectare is based on harvested area.

Fertilizer/land = nitrogen fertilizer use attributed to cereals on the basis of the share of cereals area in total agricultural area.

Emissions/fertilizer use = emissions per crop/total fertilizer use attributed to the crop.

Value of production for cattle includes meat and milk; for sheep it includes meat and wool.

Land per animal for ruminants based on total pasture land and estimated forage requirements per hectare per category of animal.

Table A4.9. United States: Summary of drivers of direct agricultural emissions by product (2014)

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	kg per hectare (E/L)	Index	Yield per hectare (kgs) (Q/L)	Index	Emis. per fertilizer use (E/F)	Index	Fertilizer per land (F/L)	Index	kg per dollar (E/V)	Index
Cereals	25.2%	88,483	117	0.2	96	1,558	113	7,620	119	7.3	101	214	106	1.4	98
Rice	3.1%	10,963	87	1.1	87	9,237	106	8,492	122	43.1	99	214	106	4.0	89
Burning - savanna	0.2%	808	108												
Cultivated organic soils	2.9%	10,021	100												

	% of ag emissions	Emissions E	Index	kg per kg of product (E/Q)	Index	Emis. per animal (E/A)	Index	Yield per animal (kgs)(Q/A)	Index	kg per hectare (E/L)	Index	Land per animal (L/A)	Index	kg per dollar (E/V)	Index
Cattle	49.5%	173,935	93			2,835	116			693	87	2.8	116	3.0	89
Beef	38.1%	133,751	100	11.7	94	1,683	100	144	106	594	86	2.8	116	4.6	98
Cow's milk	11.4%	40,183	100	0.4	82	4,437	100	10,319	123	1,430	85	3.2	117	1.4	83
Ruminants	49.5%	173,935	93							693	87			3.0	89
Chicken	1.7%	6,027	105	0.3	84	4	101	11	119					0.2	84
Eggs	0.8%	2,806	107	0.5	93	8	97	16	105					0.6	97
Pork	6.1%	21,329	110	2.1	91	315	100	153	110					1.3	94
Non-ruminants	8.6%	30,162	109											0.6	90
Agriculture	100%	351,475	101												

Emissions are in gigagrams of CO₂e.

Emissions for crops are calculated using the following sources: synthetic fertilizers, crop residues, and burning of crop residues.

Emissions per constant international dollar (I\$) 2004-06 are for 2013.

Indices = average of most recent three years relative to the average for 1999-2001.

Yield per hectare is based on harvested area.

Fertilizer/land = nitrogen fertilizer use attributed to cereals or rice on the basis of shares of total crop area in cereals and rice.

Emissions/fertilizer use = emissions per crop relative to total fertilizer use attributed to the crop.

Value of production for cattle includes meat and milk; for sheep it includes meat and wool.

Land per animal for ruminants based on total pasture land allocated to beef and dairy cattle on the basis of their share of the total cattle herd.