

Agriculture and Climate Change Mitigation in the Developing World

Working Paper No. 61

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

Robert J Scholes
Cheryl A Palm
Jonathan E Hickman



RESEARCH PROGRAM ON
**Climate Change,
Agriculture and
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Contact:

CCAFS Coordinating Unit - Faculty of Science, Department of Plant and Environmental Sciences, University of Copenhagen, Rolighedsvej 21, DK-1958 Frederiksberg C, Denmark. Tel: +45 35331046; Email: ccaafs@cgiar.org

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Abstract

Agricultural activities in the developing world directly contribute about 4.23 GtCO_{2eq}/y to the current anthropogenic forcing of the global climate, and indirectly a further approximately 3.93GtCO_{2eq}/y through forest clearing and degradation. Together they constitute a quarter of the total global climate forcing from all sources. Many proven agricultural practices and policies can reduce this impact on the global climate without compromising food production, or reduce the climate impact per unit of agricultural production. A reasonable target by 2030 for climate mitigation in developing world agriculture, taking into account the large difference between technical potentials and economically viable adoption rates and noting the equity issues relating to the mitigation activities in the developing world, is around 1.2 GtCO_{2eq}/y for agriculture (~ 22% of projected unmitigated agricultural emissions by 2030) and 1.2 GtCO_{2eq}/y for avoided and more climate-appropriate land use changes (~ 30% of current land use change related emissions).

Keywords

Developing countries; Climate Change; Mitigation; Agriculture.

About the authors

Robert J Scholes, Council for Scientific and Industrial Research, PO Box 395, Pretoria, 0001
South Africa bscholes@csir.co.za

Cheryl A Palm, Agriculture and Food Security Center, Earth Institute, Columbia University,
Box 1000 Palisades, NY 10964 USA cpalm@ei.columbia.edu

Jonathan E Hickman, Agriculture and Food Security Center, Earth Institute, Columbia University,
Box 1000 Palisades, NY USA jeh2179@columbia.edu

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Acronyms

ARIs	Advanced Research Institutes
CCAFS	CGIAR Research Program on Climate Change, Agriculture and Food Security
CIAT	International Center for Tropical Agriculture
CIMMYT	International Maize and Wheat Improvement Center
CRPs	CGIAR Research Programs
CSI	CGIAR Consortium for Spatial Information
FAO	Food and Agriculture Organization of the United Nations
FTA	CGIAR Research Program on Forests, Trees and Agroforestry
GHGs	Greenhouse Gases
GRiSP	Global Rice Science Partnership
ICRAF	World Agroforestry Centre
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IPCC	Intergovernmental Panel on Climate Change
IRRI	International Rice Research Institute
IWMI	International Water Management Institute
NARS	National Agricultural Research Systems
SLOs	System Level Outcomes
WLE	CGIAR Research Program on Water Land and Ecosystems

Introduction

CGIAR has four System Level Outcomes (SLOs). One of these outcomes is "sustainable management of natural resources", expanded in the executive summary of the Strategic Results Framework as "*Agriculture demands natural resources which must be better managed to ensure both sustainable food production and provision of ecosystem services to the poor, particularly in light of climate change*".

Activities conducted by CGIAR that have a climate change mitigation focus currently contribute to this SLO. This paper has the following objectives:

- Quantify the role of agriculture in reducing greenhouse gases (GHGs) and sequestering carbon in developing countries, including agriculture's role in land cover change.
- Identify key agricultural technologies, practices and policies that can contribute to climate change mitigation in developing countries.
- Establish a medium-term target (2035) for mitigation in agriculture in developing countries.
- Identify the major research questions that need to be answered if agriculture in developing countries is to be part of the climate change solution for mitigation.
- Examine whether CGIAR has a role in addressing the research questions.

For the purposes of this paper, the 'developing world' is understood to be the countries *not* listed in Annex One of the UN Framework Convention on Climate Change.

Contribution of developing-world agriculture to climate change

There are three main sources for the information on GHG emissions from agriculture: the FAOSTAT database, which has a new section on GHG emissions (Tubiello et al. 2013; <http://faostat.fao.org/>); the European EDGAR database (EU-JRC/PBL 2012; <http://edgar.jrc.ec.europa.eu>), and the US Environment Agency greenhouse gas database (EPA 2012; www.epa.gov/climatechange/ghgemissions/global.html). They essentially use the same methods and often share primary data sources: therefore they are reasonably consistent with one another but cannot be regarded as independent estimates. The simplest possible general approach (IPCC 'Tier 1') is to assign an 'activity level' for each practice in each country (indexed by a proxy such as the number of hectares managed in that way). This is then multiplied by an 'emission factor', which expresses an average GHG emission per unit activity per unit time. The emission factors usually derive from the IPCC guidelines (2006 is the most recent version, the relevant volume is 4: Agriculture, Forestry and Other Land Use (AFOLU); <http://www.ipcc-nggip.iges.or.jp>). The uncertainties in this simple approach are high – between half and double the 'best guess' – because it does not take into account all the issues that cause local-scale variation in emissions, which would require a Tier 2 or 3 approach. The emission factors are based on expert judgment, founded on the research studies that are known, published and available. With the exception of a few mainly-tropical activities such as rice-growing and agroforestry, the overwhelming majority of the 'underlying studies' are conducted in the temperate, developed world. Their applicability to tropical, developing-world circumstances is substantially more uncertain than their applicability in the area of origin.

Every six years the IPCC assesses what is known about global GHG emissions, including from agriculture and land clearing. It bases its quantitative analysis largely on the three databases listed above. What follows should therefore be consistent with the IPCC Fifth Assessment Report, only citable in 2014; but a recent paper (Smith et al. 2013) is likely to represent the analysis conducted for the IPCC Fifth Assessment. The most recent citable IPCC assessment is the fourth (Smith et al. 2007b).

The combined effect of different GHGs is conventionally reported as ‘gigatonnes carbon dioxide equivalent’ (GtCO₂eq)¹. There is widespread agreement that the current (2010) direct greenhouse emissions from agricultural activities up to the farm gate contributes 10-12% of the global human-caused emissions from all sources. Land clearing, predominantly driven by agriculture, contributed a further 12-24% in the decade 2001-2010. Thus agricultural activities as a whole – but excluding other elements of the food system, such as food processing, transport or emissions from food waste – are currently responsible for a quarter to a third of global climate forcing. Of this, three-quarters originates from developing countries, since in contemporary times that is the location of 1) nearly all new land clearing, 2) 39% of the global inventory of land cultivated for short-duration crops, 3) 75% of land under tree crops (excluding plantation forests) and 4) 80% of the global livestock biomass (FAOSTAT data for 2010). Aggregated agricultural sector emissions, including land clearing, have grown over the period 1960 to 2010 at a rate of about 0.8% per year, quite similar to the growth rate of GHGs in the atmosphere overall. In other words, agricultural emissions are a fairly constant fraction of global emissions. The growth rate of agricultural GHG emissions is less than either the growth rate of the human population or the growth rate of economic activity. Thus the ‘economic GHG efficiency’ of global agriculture, (the GHG emitted per unit gross value addition in the sector) improved twofold over the period 1991 to 2010, based on FAOSTAT data.

On a global basis, for the year 2010, the relative contributions to the global warming attributable to agriculture (excluding land clearing) were approximately as follows. The estimates have been deliberately rounded to take into account the considerable uncertainty in the estimates and avoid an impression of spurious precision.

- One third from enteric fermentation (largely from cattle, as CH₄)
- One third from nitrogen fertilizer use (N₂O, from synthetic fertilizer and manure)
- A tenth from rice paddy cultivation (mostly as CH₄)
- A tenth from burning of biomass in an agricultural context (mostly CH₄), and
- A twelfth from the management of manure (mostly CH₄ and excluding the N₂O already accounted for under N fertilizer use)
- The remainder from miscellaneous smaller sources, such as fossil fuel use on farms.

¹A gigatonne (Gt) is a billion metric tonnes, equal in scientific notation to a petagram (Pg, 10¹⁵ g). The contributions of the other main greenhouse gases methane (CH₄) and nitrous oxide (N₂O), on a mass basis relative to carbon dioxide (CO₂), are called their ‘Global Warming Potentials’ (GWP), which in this analysis are assumed to be 21 and 310 respectively. The GWP is a *convention* rather than an indisputable scientific constant. It involves a number of assumptions, such as the period over which the warming is integrated (100 years in this case). The use of GWP as the sole metric of the climate effects of greenhouse gases is attracting increasing criticism. Furthermore GWP does not link directly to the different actions needed to mitigate different gases. In this briefing note we use the CO₂eq notation for simplicity, but also report the quantities of the different gases separately, as far as possible.

These proportions are projected to remain fairly stable between now and 2035, with the exception of a small increase in the dominance of N fertilizer sources, especially in the developing world. The proportional contribution of the various sources differs across the developing world. For instance, most rice is cultivated in Asia where more synthetic nitrogenous fertilizer is used than in other parts of the developing world, while cattle-raising and biomass burning are prominent in Africa and Latin America. Ambiguities introduced by the UNFCCC/IPCC reporting categories make it hard to disaggregate some parts of the inventory: for instance, fossil fuel use on farm versus in the general economy, wildfires versus prescribed burns, residue burning versus rangeland burning, and the emissions from manure while it is being collected and stored *versus* during its use as a fertilizer on fields *versus* its direct deposition on rangelands or pastures.

The measurement uncertainties in all of these sources (particularly in the emission factors, and to a lesser extent in the activity levels) are large, especially for developing countries. The greatest uncertainties in absolute emission terms (rather than relative error) are:

- **Livestock.** The emissions per head depend on animal type, body mass, diet and activity level, among other factors. These are all substantially different in developing countries from the norm in developed countries - the breeds are different, the body mass tends to be smaller, the diets less nutritious and the distance walked by the animals higher. According to the standard models used for inventory purposes, these factors lead to high GHG emission estimates. The models were developed and calibrated using temperate region breeds, forages and management practice, and are hardly validated outside of that range. The emission of CH₄ and N₂O from excreta depends on the environment in which it is deposited: is it oxygen-deprived or not? Free-ranging livestock in dry rangelands distribute their dung widely, resulting in small manure-related emissions; but dung deposited on wet pastures or feedlot floors can generate high emissions. The databases make a global assumption that 3.5% of the nitrogen in the excreta is emitted as N₂O. Applying these global assumptions means that about three-quarters of the global emissions from livestock are suggested to originate in developing countries. The true value may be substantially smaller – or somewhat larger.
- **Land clearing.** Emissions from land conversion vary greatly from year to year. They have been declining, in absolute terms and as a fraction of the total anthropogenic emissions over the past decade and are likely to continue to do so. Clearing rates have peaked in Latin America and Southeast Asia. They are rising in Africa, but it is highly uncertain at what level they will peak, and when. Estimates of carbon stored in the biomass of forests differ by a factor of 2, adding to the uncertainty.
- **Rice cultivation.** The FAO database uses the IPCC (1996) method, which estimates an annually integrated methane emission per area of rice. In the tabulated studies, the emission factor varies between 10 gCH₄/m²/y in India and 18 in Indonesia (for comparison, 25 in the USA and 36 gCH₄/m²/y in Italy). The emission factor is then modified by various multipliers, which account for the practices such as interrupted flooding and the addition of organic amendments to the soil, which in extreme cases can increase the emissions five-fold, or decrease them five-fold. The IPCC 2006 Tier 1 method proposes 0.13 gCH₄/m²/day (with an uncertainty range of 0.08 to 0.22) for the cultivated period only, again modified by practices, in a similar way to the 1996 guidelines. For a single cropping season of 120 days and no modifiers, this comes to 15.6gCH₄/m²/y. There is thus not only substantial uncertainty, but

also apparently large scope for mitigation by managing the wetting regime and reducing the inputs of organic materials.

- **Nitrogen fertilizer.** The fraction of applied N which ends up as nitrous oxide (N_2O) depends on the form in which it is applied and the environment it ends up in. N_2O is emitted from soils as ammonium is converted to nitrate through nitrification and through denitrification and the conversion of nitrate to N_2 . The amount of N_2O formed depends on the water content of the soil and formation of anoxic conditions. Anoxia sets in faster if the soils are warm and contain an energy source in the form of readily-decomposable carbon (such as straw or manure). If the plant has already taken up the available nitrate, it is less likely to be lost as N_2O , so timing of the fertilizer application relative to plant growth and soil wetness is critical in reducing N_2O emissions. Given that so many variables are in play, it is hardly surprising that the uncertainty range is large. It can be reduced by more detailed models and driver information, parameterized with tropical data.
- **Inclusion of wildfires in biomass burning.** The largest single component of developing world agricultural biomass burning (excluding fires associated with land clearing) is wildfires, particularly in savannas, and particularly in Africa. Some accounts include this source, while others include only the CH_4 and N_2O from the burning of agricultural residues. ‘Wild’ fires are generally ignited by people and burning is a widespread pastoral practice. This does not necessarily make them ‘anthropogenic’ in the sense defined by the UN Framework Convention on Climate Change, since there is little evidence that the extent of fires has changed since 1750, and much evidence that the aggregate burned area is under climate rather than direct human control. If not lit by people, the dry vegetation would eventually burn from natural causes.

Together these sources of uncertainty add about 10% absolute uncertainty to the global anthropogenic greenhouse emissions estimate – not hugely significant to the big picture, but making up $\pm 50\%$ of the estimated emissions due to agriculture in the developing world. Reducing this uncertainty by increasing the number and accuracy of measurements in the developing world and by eliminating ambiguity in the reporting definitions is a high priority if investment in agricultural mitigation is to be successful, but will not necessarily result in a lower estimate of the GHG footprint of developing world agriculture. It could go either way.

Table 1. Rough estimates of current and ‘medium term’ greenhouse gas emissions from agriculture and land use, globally and in the developing world (see Figure 1a). A high-growth scenario, similar to currently-observed trends², is used to make the projections to 2035 (see Figure 1b).

Agricultural System and Practice	Contribution to global emissions in 2010				Portion from the developing world			
	Gt/y				In 2010		2035, no mitigation	
	CO ₂	CH ₄	N ₂ O	CO _{2eq}	%	CO _{2eq}	Growth rate % ^e	CO _{2eq}
Agriculture								
Cropping systems								
Paddy rice		0.023		0.49	94	0.46	0.70	0.55
Synthetic N fertilizer			0.0022	0.68	70	0.48	2.00	0.78
Manure N fertilizer			0.0028	0.88	80	0.70	0.95	0.89
Burning of biomass		0.030		0.62	90	0.56	0.00	0.56
Fossil fuel use on farm	0.45 ^a			0.45	20	0.09	1.00	0.12
Livestock								
Enteric fermentation		0.095		2.00	75	1.5	0.95	1.90
Manure management		0.042		0.88	50	0.44	0.95	0.56
Total for agriculture	0.45	0.190	0.0050	6.00^c		4.23		5.35
Land Cover Change								
Forest clearing	3.52			3.52	95	3.34	-2.00	2.02
Forest degradation	0.62 ^b			0.62	95	0.59	0.00	0.59
Total for Forestry LUC	4.14			4.14^d	95	3.93		2.61
Total for AFOLU	4.59			10.14	80	8.16		7.96

Notes:

- Given as 0.4 to 0.5 GtCO_{2eq}/y by Ceschia et al. 2010. This term is usually hidden in the transport sector part of the inventory.
- Assumed to be about 15% of the total emission from forest land use change.
- The uncertainty range for the agriculture total (95% confidence) is around 5 to 7 GtCO_{2eq}/y.
- The uncertainty range for deforestation is from 1.1 to 6.9GtCO_{2eq}/y.
- The growth rate is an expert judgment by the authors and is based on trends over the past decade or two, modulated where we believe the trend in developing countries is slowing or accelerating.

² For example, the Special Report on Emission Scenarios SRES A2 or the more recent Representative Concentration Pathway RCP8.5

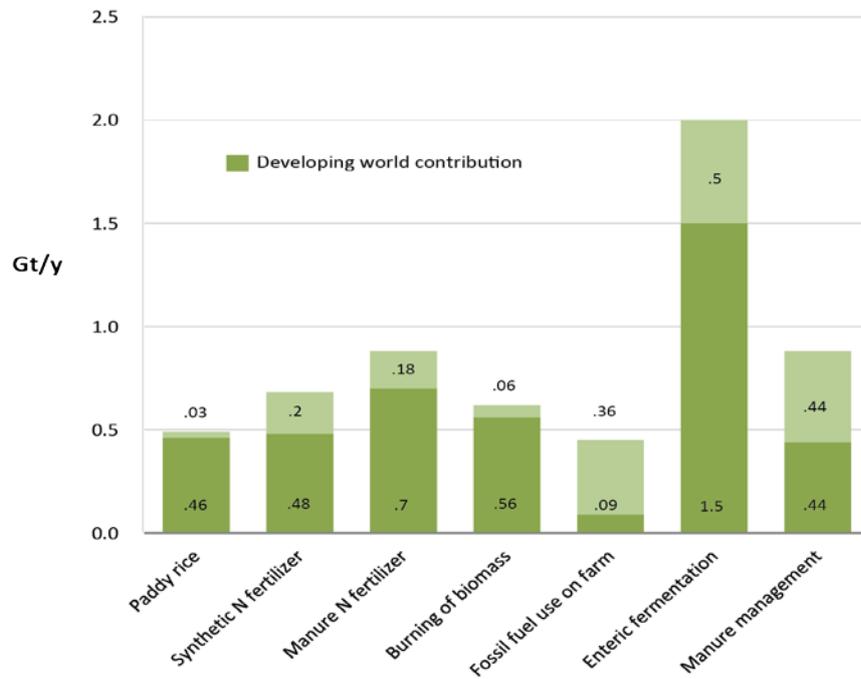


Figure 1a. Rough estimates of current and ‘medium term’ greenhouse gas emissions from agriculture and land use, globally and in the developing world

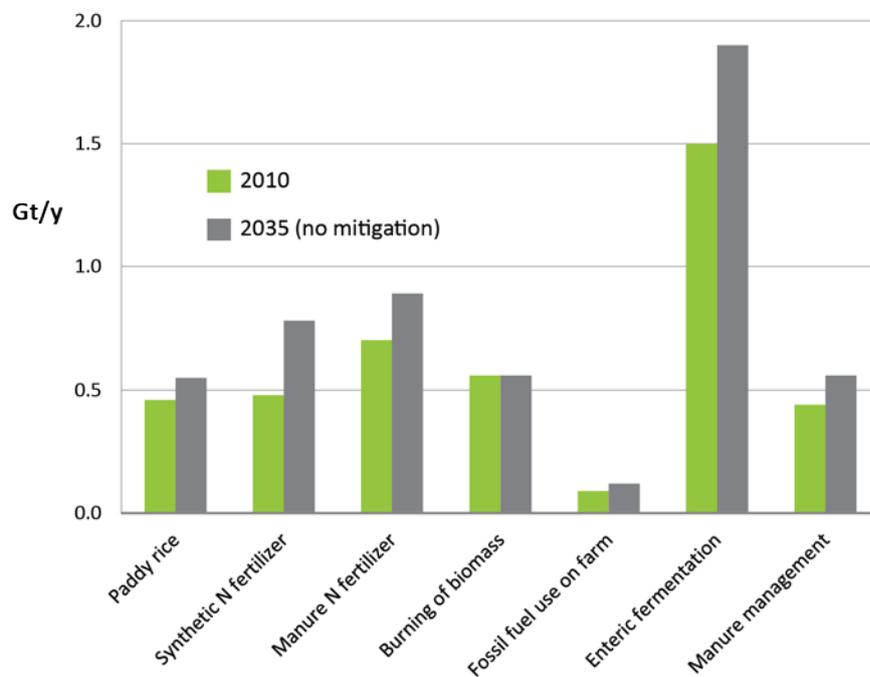


Figure 1b. Projections to 2035 of current and ‘medium term’ greenhouse gas emissions in the developing world from agriculture and land use based on a high-growth scenario, similar to currently-observed trends.

Key agricultural technologies, practices and policies for mitigating climate change

Global technical mitigation potential of agricultural management practices by 2030 is estimated to be 5.5 to 6.0 Gt CO₂eq/y. However, there is a large difference between the technical potential and economically viable adopted practices (see Table 2 for developing countries). Increased productivity and poverty reduction should take priority over GHG mitigation from the agricultural sector in regions such as sub-Saharan Africa; in that light, the technical mitigation potential for 2030 may not be achievable or even desirable. The economic potential is sensitive to the value which society puts on avoiding climate change, expressed here as ‘the price of carbon’. Of the technical potential, 89% is based on CO₂, largely through increased storage of C in soil and biomass, with some as reduced emissions; 9% on reduced CH₄ emissions; and 2% on reduced N₂O emissions (Smith et al. 2008). Crop land management, grazing land management, and restoration of cultivated organic soils had the highest potential, each mitigating 1.3 to 1.4 Gt CO₂eq/y. The next most promising activities are restoration of degraded lands (0.7 Gt CO₂eq/y), management of paddy rice systems (0.2), livestock management (0.2), and less than 0.1 Gt CO₂eq/y each for bioenergy, water management (other than in rice cultivation), set asides, agroforestry and manure management. A rough estimate of the fraction of the global technical mitigation potential located in developing countries is between 50 and 70% (Smith et al. 2008), i.e. 3 to 4 Gt CO₂eq/y. We use this summary as the basis for our own assessment of feasibility and economic potential in the developing world but include additional studies relevant to developing countries (Table 2) and come to 2.2 GtCO₂eq/y. The range of uncertainty in our judgment is large.

Agricultural climate mitigation can be absolute, or relative to the agricultural yield, i.e. a gain in ‘GHG efficiency’, the gCO₂eq/kg product. Ultimately, global GHG reductions need to be absolute if climate stabilization is to be achieved, but in the medium term, while managing the somewhat divergent imperatives of climate change mitigation and increased food security, efficiency gains are also beneficial. If efficiency rises faster than demand, then the outcome is an absolute reduction in climate forcing.

In general, mitigation efforts involving sequestration of C in agriculture can be reversed if the land is subsequently cleared, burned or tilled. In contrast, the climate benefits from reduced emissions of CH₄ or N₂O achieved through practices such as breeding, improved fertilizer management, changes in feed stocks, inhibitors, and periodic drainage are not reversed even if the practice is discontinued. Reduced fossil fuel use in agriculture life-cycle is also a non-reversible mitigation benefit.

The notion of climate-smart agriculture has gained substantial traction over recent years; the term is a catch-all for describing practices that have demonstrated some potential for providing increased productivity, reduced net GHG emissions, and reduced vulnerability to climate variability and change. Such practices are developed around the recognition that GHG mitigation is justifiably a secondary concern for the agricultural sector in parts of the developing world where attaining food security and reducing poverty must take precedence for farmers and decision makers. Climate-smart agriculture is often highly location-specific and can require substantial knowledge and careful management to realize the full range of benefits.

Cropland management

Cropland management has the single largest agricultural mitigation technical potential globally. The potential for GHG efficiency increases through cropland management in the developing world is good. The practices that contribute to this potential include improved agronomy (increased yield for the same emissions, reduced or no tillage practices and residue management), nutrient management (specifically, precise and calibrated nitrogen applications) and water management (particularly as it effects increased production and the regulation of CH₄ and N₂O emissions). The largest mitigation potential from cropland management is increased soil C stocks.

Nitrogen management

Where N application rates are already much higher than crop needs (such as in parts of Asia), decreased N application reduces absolute emissions of N₂O with little impact on yield, with co-benefits for water quality (Matson et al. 1998). On the other hand, where the system is N-depleted (such as in many parts of Africa), increased application of N either in synthetic or organic form raises the yield more than it increases N₂O emissions, thus increasing the GHG efficiency. N additions will also increase soil carbon storage in many such cases (Hillier et al. 2012). Above a threshold of 100 to 200 kg N/ha, N₂O emissions rise steeply per unit N addition (van Groenigen et al. 2010; McSwiney & Robertson 2005).

Hillier et al. (2012) conclude that at application rates above 200 kg N/ha for virtually any agricultural site in the world, reducing N inputs is the mitigation activity with the greatest potential. At 150-200 kg N/ha, it is still the highest-potential mitigation activity throughout much of China, India, and parts of Latin America and sub-Saharan Africa. At 100-150 kg N/ha, reduced N inputs remain the best mitigation option in parts of India, Brazil, and sub-Saharan Africa. Improved N use efficiency can also be achieved with improved crop varieties, time-released fertilizer, nitrification inhibitors, and optimized timing, placement and type of fertilizer. Low-emission fertilizer formulations provide some mitigation potential; if they result in yield or N efficiency reduction, nitrification inhibitors offer another option. Globally, Hillier et al. (2012) conclude that low-emission fertilizer formulations can reduce N₂O emissions by 20% and nitrification inhibitors can reduce emissions by a further 20%.

Large areas of sub-Saharan Africa and parts of Central America, South America and South and Southeast Asia have low crop yields and food insecurity partly as a result of insufficient N fertilization. Average synthetic N fertilizer use in Africa is 1.8 kg N/ha, in contrast to 75 kg N/ha in Asia (Potter et al. 2010, Siebert 2005). The required development trajectory for these areas is for *increased* N application, but not exceeding the thresholds described above, where additional application of fertilizer is unlikely to provide significant gains in productivity or a net return on the additional investment. This additional application could also result in unnecessary N loading to terrestrial and aquatic ecosystems.

Table 2. A synthesis of the technical and economic potentials (at a carbon price of \$20/tCO₂) for the main agricultural and land use-based climate mitigation options in developing countries (DC), up to about 2030. There is much expert guesswork and approximation in this table since the underlying studies use a variety of approaches. The values given here should only be used as a guide to the relative contributions by different activities.

Practices	Technical potential GtCO _{2eq} /y	Economic potential 20\$/tCO ₂	Logic applied to reduce the technical potential to an economic potential in the developing world	References
Cropland management				
N management	0.312	0.162	50% economic fraction*upper DC potential	Hillier et al. (2012)
Residue and tillage	0.452	0.234	80%(C storage)x40%(DC fraction)* 0.75 global potential	Smith et al. (2007a),Hillier et al. (2012)
Rice management	5.490	0.162	90%(DC fraction)*0.18 (global economic potential)	Smith et al. (2007a),Yan et al. (2009)
Rangeland and livestock				
Livestock	0.209	0.096	80%(DC fraction) *0.12 Global economic potential	Eckard et al. (2010),Thornton and Herrero (2010)
Manure management	0.480	0.024	80%(DC fraction)*5%(economic fraction)*DC potential	Smith et al. (2007a)
Restoration				
Degraded rangelands	0.151	0.151	Developing country estimate in reference	Thornton and Herrero (2010)
Degraded croplands	0.240	0.060	40%(DC fraction)*0.15(global economic potential)	Smith et al. (2007a)
Organic soils	0.840	0.150	60%(DC fraction)*0.15(global economic potential)	
Avoided/guided Land Use Change				
Land sparing by intensification	3.200	3.200	Extrapolation of the rate of sparing since 1961	Burney et al. (2010)
Agroforestry	2.200	0.600	100%(DC fraction)*0.2 (global economic potential)	Smith et al. (2007a), Verchot et al. (2007)
Bioenergy crops				
Biochar	1.080	0.270	60%(DC fraction) *25%(economic frac)*1.8 global potential	Woolf et al. (2010)
Increased soil C under bioenergy crops	0.120	0.030	60%(DC fraction)*0.05 (global economic potential)	Smith et al. (2007a)
Fossil fuel substitution	7.671	0.261	62%(DC fraction) * 0.24 (global economic potential)	IPCC (2011)
Total excluding land sparing	19.245	2.200		

Residue management and reduced- or no-till cultivation

Hillier et al. (2012) estimate that reducing tillage can achieve a mitigation of 585 kg CO_{2-eq}/ha/y as a global average, and increasing C inputs to soil can result in further sink of 607 kg CO_{2-eq}/ha/y. The rate of CO₂ reduced emission or uptake or by both activities will decrease after a few years to decades of application (depending on how depleted the soil C is to start off with) as soil C reaches its upper limits. Estimates of increases in C stocks as a result of these practices are very variable and depend on the climate, soil type and the time-horizon examined. During the first years of the practice, GHG emissions can *increase* rather than *decrease*, and the mitigation potential tends to be higher in humid rather than in dry climates (Six et al. 2004). Reduced tillage may lead to increased N₂O emissions

(Smith and Conen 2004). Employing reduced tillage and residue management involves trade-offs, including demands on labor or alternate use of the residues as fuel or fodder, that may present obstacles to adoption (Arslan et al. 2013; Valbuena et al. 2012). The mechanization required for practices such as direct seeding is not yet readily available in many developing countries and compaction from off-season grazing can reduce the benefits of reduced tillage. Reduced-till fields that are poorly managed experience yield penalties, especially in the first years after adoption; with benefits emerging in the longer-term, opportunity costs and tenure insecurity could reduce the incentive for adoption. Reduced erosion of topsoil is a co-benefit. Effective knowledge transfer will be a challenge but is likely necessary for successful adoption and productivity benefits.

Additions of organic inputs (manures, crop residues or deliberately cultivated cover crops) to agricultural soils usually increases soil C and boosts crop productivity. The benefits vary, depending on the level of intensification and soil degradation. Increased C amendments have a 2 to 7 times higher benefit on soils that already have substantial C stocks than in low-C soils, and are 2 to 3 times larger in soils receiving less than 100 kg N kg/ha than with inputs of 150 kg N kg/ha or higher (Hillier et al. 2012). Highest mitigation potentials may be found in high carbon (4-5%), well-drained tropical soils, where C additions can reduce GHG emissions by over 50% (Hillier et al. 2012). In tropical soils overall, soil amendments may mitigate 7% to roughly half of agricultural soil emissions, diminishing over time as soils become saturated with carbon.

Additions of biochar³ to agricultural soils may provide a means of increasing soil C beyond its normal saturation level. The global mitigation potential for biochar is estimated at 1.8 Gt CO_{2eq}/y (Woolf et al. 2010), about a third of which could come from using currently unused crop residues (Roberts et al. 2010). There are many questions to be addressed before biochar feasibility and agricultural and environmental impacts at climate-altering scale can be rigorously assessed. Conversion of some feedstocks to biochar result in net GHG emissions, while others may require high valuations of CO_{2eq} to be economically viable. Ultimately, climate change mitigation benefits may only be experienced in a system using wastes as feedstocks and limited transportation of feedstocks or biochar (Roberts et al. 2010). Biochar impacts on agricultural production can be positive or negative, varying with soil and management practices (van Zwieten et al. 2010). Current modes of production of biochar for agricultural applications in developing countries can have adverse health effects, notably through the production of particulate matter (Sparrevik et al. 2013).

Rice management

Water management in rice paddies, such as mid-season drainage, reduces CH₄ emissions though it may increase N₂O emissions. Assuming that water management practices globally mirror those in developing countries, Yan et al. (2009) estimate the global mitigation potential from draining rice fields at least once per season to be 4.1 Tg CH₄ /yr, with the same potential from off-season application of rice straw. Together, these practices provide a mitigation potential of 7.6 Tg CH₄ /yr. Breeding for reduced-CH₄ rice can provide mitigation of potential around 2 TgCH₄ /y. Large areas of sub-Saharan Africa currently under low-input rainfed lowland rice systems are targeted for intensification. This would result in increased CH₄ emissions, some of which may be offset by mitigation actions such as those described above.

³Biochar is a partially-combusted form of biomass, from which the high-energy volatiles have been extracted and used, leaving the stable carbon-rich residue.

Grazing land and livestock management

Well-managed grazing land has higher levels of ecosystem carbon per unit area than over-grazed lands, and in some instances than under-grazed lands. These effects are highly variable across soils, climates, and ecosystems. The range of estimates spans an order of magnitude (Conant et al. 2001; Smith et al. 2007a). The “LivestockPlus” estimate by Peters et al. (2012) is on the optimistic side, suggesting a mitigation potential equal to 100% of livestock emissions. Thornton and Herrero (2010) estimate a more modest mitigation potential of 7%, even with 100% adoption. The practices examined include improved pastures, mostly in Latin America (0.044 Gt CO_{2-eq}/y), improved ruminant diets using more digestible stover (0.062 Gt CO_{2-eq}/y), restoration of degraded pastures (0.054 Gt CO_{2-eq}/y in Central/ and South America and 0.097 Gt CO_{2-eq}/y in sub-Saharan Africa), agroforestry-derived forages (0.143 Gt CO_{2-eq}/y, mostly through C sequestration in the forage trees), and changing breeds of large ruminants (0.020 Gt CO_{2-eq}/y). Moderating grazing intensities may require expensive enforcement and greater capacity for collective action than other mitigation activities (McCarthy et al. 2011).

Livestock management

Many technologies exist for reducing enteric CH₄ emissions, with reported effectiveness between 0 and 91%; they are often expensive and only superficially studied (Eckard et al. 2010). The main approach is to alter the diet, by supplementing with grain or oils, breeding crops with more digestible stover and including cut-and-carry forage from agroforestry systems. This increases animal production and simultaneously decreases CH₄ emissions per animal. These practices may provide a 2 to 7% reduction in emissions from enteric fermentation.

Manure management

When dung and manure decompose under anaerobic conditions – for instance, in a pile, in a pit or lagoon – the emissions of CH₄ and N₂O are high. By contrast, if the excreta are deposited as individual pats on rangeland, or are collected daily and spread in fields, the emissions are relatively low (less than a fifth). If the excreta are decomposed in a biodigester, and the resultant CH₄ is used to substitute for fossil fuel energy, a net climate credit accrues.

Restoration of degraded lands

Restoration of cultivated tropical organic soils

The largest mitigation potential per unit area (7 to 124 t CO_{2-eq}/ha/y) is for activities involving restoration of organic soils⁴, and it is among the largest potentials in total, roughly half the potential provided by cropland and grazing land management, despite its much smaller area. An estimated ninth of the global soil C stock is located in tropical peat-lands, primarily in Southeast Asia. Restoration involves removing them from agricultural use, elevating the water table if necessary and restoring native vegetation (Smith et al. 2007a, Eagle et al. 2012).

Restoration of degraded crop and grazing lands (non-organic soils)

This is a category of agricultural practices with medium mitigation potential. There are contrasting definitions of degraded land resulting in different areas of land under the different definitions. Different types of degradation – losses of fertility, physical degradation, require different practices

⁴previously flooded peaty soils, able to accumulate large amounts of C over time if re-flooded.

and inputs (fertilizers, mechanization, and others) that may offset some of the soil or vegetation C mitigation potential. Currently there is insufficient data on the area and distribution of these degraded lands.

Avoidance of land conversion, or guiding it onto more climate-friendly paths

Conversion of native vegetation to cropland or pasture usually results in a large loss of biomass C, but the effects on soil C are less clear. Several studies have found large decreases in topsoil C with conversion to pasture (e.g., Rasiaha et al. 2004), but others found the opposite: that soil C increases with conversion from forest to pasture (Guo & Gifford 2002). Changes in soil C can be affected by the method of clearing (e.g., bulldozing vs. slash and burn) (Okore et al. 2007).

Land sparing through agricultural intensification

Sustainable intensification (Garnett et al. 2013), particularly in areas with substantial population growth, low nutrient inputs, and low yields (e.g. much of sub-Saharan Africa), may provide a particularly large climate-smart win-win-win scenario (food production, climate change adaptation, and mitigation) in large part by avoiding new land-clearing for agriculture. Tropical agriculture was responsible for 98% of CO₂ from land-clearing in the decade 2000-2009 (DeFries, Rosenzweig 2010). Land clearing rates can be reduced by increasing production on existing tropical agricultural lands. To date, increased production per unit area in the tropics has had a net mitigating effect, up to 161 Gt CO_{2eq} avoided from 1961-2005 (Burney et al. 2010). The net mitigating effect of higher rates of agricultural yield-per-area growth than area expansion is projected to continue in the future (Tilman et al. 2002; 2011). In East Africa, modeled intensification using mineral fertilizer or agroforestry with legume tree fallows resulted in net mitigation of roughly 1 to 6.5 t CO_{2-eq}/ha, largely through afforestation and avoided deforestation (Palm et al. 2010). The mitigation potential of intensification is likely to be highest in developing countries that have achieved some measure of food security. This is because the relationship between higher yields and land-sparing is strongest where the food supply is relatively high. Experience in developed countries with agricultural subsidies is that a higher yield for non-staple crops actually leads to agricultural land area expansion (Ewers et al. 2009). Avoidance of land-clearing emissions through intensification is not necessarily permanent – the land may be cleared at a later stage.

Agroforestry

There are contradictory assessments as to the technical potential of agroforestry for climate mitigation (Verchot et al. 2007; Smith et al. 2008). It has high technical potential for C sequestration due to the large area available for its implementation in developing countries (Verchot et al. 2007; IPCC 2000). It is a particularly appropriate alternative to clearing for cropland or pasture in naturally forested or wooded ecosystems and is an option for their restoration. Verchot et al. (2007) estimated an economic potential by 2040 of 0.6 Gt C/y over an area of 630 million ha; the economic potential at low carbon prices may be much less. Albrecht & Kandji (2003) suggest 12-228 tC/ha, for a global potential (closer to a technical than economic potential) of 1.1-2.2 Gt C/y over the next 50 years. Numerous obstacles may prevent adoption of agroforestry in developing countries—access to information on suitable agroforestry systems, access to suitable seeds and seedlings, opportunity costs associated with taking land out of annual crop production, labor during plant establishment, land tenure insecurity, and capital for the initial financial investment can all inhibit adoption (McCarthy et al. 2011).

Some of the benefits of CO₂ uptake through agroforestry may be offset by reductions in albedo when a darker, more permanent canopy is developed over a light soil background, in areas of low cloud cover.

Bioenergy

Bioenergy crops (including biofuel crops for the production of biodiesel or ethanol) mitigate climate change by substituting for fossil fuels; estimates for the global mitigation potential of substituting bioenergy for fossil fuels is of the same order of magnitude as the potential gains that can be made through improved management of rice crops. Calculating the true contribution of bioenergy to reducing climate change requires a consideration of all GHGs, over the entire life cycle, and including direct and indirect land use change -the result is invariably much less than an estimate based on the fossil fuel substitution calculation alone, and in some circumstances can even be negative (in other words, some biofuel options are climate damaging). Different scenarios of biofuel intensification can lead to net mitigation or net emissions through 2050 (Melillo et al. 2009), or effectively no net benefit to surface air temperature (Hallgren et al. 2013).

Bioenergy crop production is already substantial in countries such as Brazil, where 7% of soybean production is used for biodiesel (The Soybean and Corn Advisor 2010), and Indonesia and Malaysia, where palm oil production doubled in area between 2000 and 2007 (FAOSTAT 2011). In both examples, the expansion of these crops came almost entirely at the expense of natural forested area and existing cropland or grazing land (Koh and Wilcove 2008, Miyake et al. 2012) and is projected to continue to do so. Conversion of forested area substantially reduces species richness and incurs a large 'carbon debt' that will take decades to pay off through the mitigation benefits of biodiesel. While the majority of oil palm plantations in Indonesia and Malaysia are established in existing natural forest, roughly 40-45% is converted from existing cropland; in Brazil, soy tends to displace existing grazing land. The use of food and feed crops for ethanol production has been blamed for an over 75% increase in global food prices (Pimentel 2009).

Bioenergy cultivation at a large enough scale to be a significant climate mitigation strategy will be in direct competition with human and animal food needs for land and water, with effects on food price, food availability, and poverty that need to be better understood; it can also result in conflict between economic and environmental priorities and policies. This points to a research need focused on a robust multi-dimensional tradeoff analysis for the key bioenergy crops. Growing bioenergy crops on marginal land and using crop residues as a bioenergy feedstock are two strategies proposed to reduce direct or indirect competition with food production and the further clearing of forests. However, in developing countries, 'marginal land' and 'crop waste' are often critical for livelihoods, particularly among the poor. Marginal lands are also marginal for bioenergy production, and would require large inputs of nutrients and water to attain higher yields, both of which increase emissions.

Demand-side mitigation

Two climate mitigation strategies have been proposed involving demand-side approaches in the food system. The first is waste minimization. Waste increases the amount of agricultural activity and land area needed to satisfy demand, and also contributes CH₄ emissions from waste decomposition. It is estimated that a third of food production is wasted (Gustavsson et al. 2011). In developing countries, much of this occurs on-farm or in post-harvest storage. The second demand-side mitigation approach is to curb the growing global demand for animal proteins (much of it in the emerging economies of

the developing world) as diets in the developing world converge on the meat- and dairy-rich diets of developed countries and the reduction of meat consumption in developed countries. Fundamentally different research and policy approaches are needed to reduce the demand for agricultural commodities than are needed to increase their efficiency or quantity of production. This may make such research a poor fit for CGIAR's mandate, even though the technical potential for demand-side measures is as large as from supply-side measures.

A reasonable target for climate change mitigation through agriculture in developing countries

The notion of 'reasonable' applied here includes consideration of technical and economic feasibilities, as well as issues of equity between developed and developing countries (as captured in the UNFCCC phrase of 'common but differentiated responsibilities') and the minimization of known negative environmental impacts, bearing in mind that the biggest environmental impact to be avoided, particularly for agriculture, is climate change itself.

At a relatively low estimate of future carbon values (20\$/tCO_{2eq}, a price nevertheless much higher than currently offered in this highly volatile market), emission reduction potentials in agriculture through practices such as better management, livestock, manure, fertilizer and croplands in the developing world amount to about 1.2GtCO_{2eq}/y. This rises to about 2GtCO_{2eq}/y at a carbon price of 50\$/t and 3GtCO_{2eq}/y at a price of 100\$/t (Smith et al. 2008, Smith et al. 2013), with soil carbon accumulation as the dominant underlying process. Above 100\$/t many industrial processes become more attractive than agriculturally-based mitigation. When global economic models are used to estimate the economic mitigation potentials relating to actions to prevent forest loss, restore deforested or degraded lands and better manage forests, the potentials are estimated to be about three times higher than those from agriculture: 4 to 7 to 9 GtCO_{2eq}/y in the developing world, respectively, for carbon prices of 20, 50 and 100 \$/t. Estimates of the realistic forest mitigation potential aggregated from project analysis at a local and regional scale are perhaps more realistic than those from top-down global models: They suggest a practical potential (conceptually more-or-less equivalent to the low end economic potential) a third to a tenth of the global model estimates (Coren et al. 2011, Busch et al. 2010, Merger et al. 2012), i.e. in the same range as for agricultural mitigation.

Large potentials lie in 'demand side management', specifically, promoting a diet with sufficient nutrition but low in animal-based products, and the radical reduction of waste in the food system. It has been suggested (Stehfest et al. 2009) that about 2 GtCO_{2eq}/y could be mitigated by 2030 by global convergence to a 'healthy diet'⁵; about half of this would be in those parts of the developing world where the diet is rapidly changing. A further 0.5 GtCO_{2eq}/y could be saved globally by 2030 by reducing food system waste; again we assume about half of this is in the developing world, where the waste tends to be post-harvest, rather than in the retail chain or post consumption.

In summary, a conservative estimate of developing world mitigation potentials, assuming the presence of a mechanism compensating farmers for their efforts to reduce climate impacts, is in the region of 1.2 GtCO_{2eq}/y through improved agricultural practices and a further 1.2 GtCO_{2eq}/y in avoided deforestation and restoration of degraded land. Together these amount to 30% of the estimated

⁵A nutritionally-balanced and sufficient diet, not meat and dairy-free, but with a major proportion of protein supplied from vegetables.

unmitigated emissions from agriculture and land use change in 2035 (22% reduction in agricultural emissions relative to the ‘business as usual’ baseline and 46% reduction in forestry and land use change, relative to a projection of current trends). A further 1.2 GtCO_{2eq}/y could be gained from diet behavior change and waste elimination in the developing world.

Major research questions

Success in diagnosing the issues and directing the responses to all of the below questions depends on having ready access to improved information on the current and emerging agricultural systems, management practices, biophysical and social circumstances in developing countries. The availability and quality of such data vary greatly between and within developing countries. High-resolution, detailed geospatial databases that include current levels of N inputs, energy and water use and carbon stocks and fates are needed for determining mitigation potentials but also for targeting the best mitigation options for the different agricultural typologies. This is an ‘underpinning requirement’.

Climate mitigation research relevant to developing regions falls under four broad categories: characterizing agriculture and GHG in the developing world; basic research on agriculture and GHG emissions; applied studies on mitigation activities; and adoption and policy studies. Within the categories, the questions have been selected by their potential to mitigate emissions at a scale that is globally meaningful, while improving livelihoods and helping to ensure food security.

Characterization of developing country agriculture in relation to GHG emissions

This research involves characterization of current and emerging agricultural practices, the biophysical and socioeconomic conditions under which they occur, and the GHG emissions they generate. More reliable, geospatial estimates might lower the reluctance of investors to support mitigation activities based on developing world agriculture. They could also re-order the priority of mitigation activities and re-focus the research agenda.

What are the emissions from livestock, crops, biomass burning and land clearance from diverse agro-ecological situations and the impact of related mitigation measures?

A sufficiently large and well-distributed database of good-quality emission measurements, with and without mitigation actions, is a prerequisite for the widespread adoption of these practices.

What constitutes degraded lands and where are they located?

Rehabilitation of degraded lands ranks high in mitigation potential and also holds potential for improving the livelihoods of the poorest and most marginalized people while improving their resilience to climate and other shocks. Degradation in this context has a clear definition: a persistent reduction in the capacity to deliver ecosystem services, including provisioning services such as grazing, food, fuel and water, but also climate-regulating services such as carbon storage. Current maps of degradation only partially reflect this definition, making prioritization of action somewhat arbitrary and ineffective. An understanding of the underlying causes of degradation and how to address them is essential if rehabilitation efforts are to be sustainable.

Basic research into agricultural GHG emissions and sinks

How much soil carbon can be sequestered in soils with different land use legacies and environments?

Increasing soil carbon is the single largest potential mitigation action on agricultural lands and carries mostly positive co-benefits such as improved soil fertility and erosion resistance (Powlson et al. 2011). Several questions remain as to how much soil carbon sequestration potential exists in developing countries and where those soils are located. The amount of carbon that a soil can sequester depends on the amount of carbon that has been lost relative to the 'carbon saturation' level of that soil (Hassink, 1996). In other words, soils that were cleared and cultivated more recently have lost less carbon on an absolute basis and have a lower potential to sequester carbon than those cleared for 20 years or more. These relative changes in carbon stocks are fairly well documented from extensive field and modeling studies in developed regions, but are less well known for developing regions.

How much can CH₄ emissions be reduced from enteric fermentation in tropical systems?

Ways to reduce CH₄ emissions from enteric fermentation are being explored in many institutions; but there is wide disagreement about their technical potential. Cattle breeds, forage quality and herd and range management practices in developing countries are substantially different from developed countries. A first step is to acquire reliable data for developing country circumstances, and the next is to explore and quantify practical livestock breeding, feeding and management schemes that increase production more than they increase either cost or GHG emissions.

Applied tests of agricultural mitigation technologies

These studies demonstrate the net full life-cycle mitigation potential of a range of agricultural practices and technologies in real developing-world contexts, and document their costs, potentials, limitations and applicability.

What management practices are most effective for increasing carbon storage?

Increasing soil carbon through cropland management has been indicated as an activity with one of the greatest mitigation potentials. Several practices can increase carbon inputs and cycling in crop lands with the potential to increase carbon storage in the soil and biomass. Some of these practices also influence emissions of N₂O or CH₄ either negatively or positively. Some of them can also do so without compromising production. Some unanswered questions are:

- What threshold amounts of residue return are needed to increase soil carbon? Crop residues are usually in short supply in the developing world, since production is low and they have alternate uses as forage or fuel.
- How much are N₂O emissions offset by increased soil C? Increasing soil C stocks in low input systems usually requires increased applications of N, possibly resulting in increased N₂O emissions.
- Under what circumstances does reduced tillage lead to carbon storage? A switch from tillage to reduced or no-tillage is considered one of the more cost effective ways of sequestering C, but about half of the studies show no increase in C storage. Guidelines on the soil and climate types where sequestration is most likely to occur with no- or reduced tillage are needed.
- What is the potential for the use of biochar (partially combusted biomass) to simultaneously meet energy and carbon sequestration needs? The uptake capacity and positive and negative

impacts of biochar in tropical soils is hardly investigated, yet this strategy is receiving prominence as one of the few ways to achieve global ‘negative emissions’.

What N fertilizer application rates and practices increase production while maintaining or reducing N₂O emissions per unit product?

The default emission factor for N₂O emission is 1% of fertilizer N applied though some studies recommend 2.5 to 4% (Crutzen et al. 2008; Davidson, 2009). N₂O emission factors are mostly derived from experiments with N applications rates between 100 and 250 kg N/ha (Bouwman and Boumans, 2002); these rates are much higher than typical rates in tropical zones of developing regions. Although N application rates are increasing in these regions, they are likely be less than 100 kg N/ha for the next 20 years and may be below a threshold N fertilizer rate at which N₂O emissions per unit input and per unit product increase substantially, though more data on different soils, crops and climates is needed.

How can water, fertilizer, residue and cultivar management be used to reduce emissions per unit yield in rice?

Rice is such a critical crop in large parts of the developing world that GHG-reducing strategies need to be exceptionally careful not to reduce production. Approaches for modifying water and fertilizer regimes have the potential to reduce GHG emissions and increase yields in well-managed fields as well as making resource use more efficient. Savings of water and fertilizer can lead to the irrigation and fertilization of new fields, which could cause an overall increase in yields and GHG emissions from rice production at a regional scale. While there may be a net increase in GHG emissions from such a shift in resource use efficiency, it should also result in an overall increase in the efficiency of rice production per unit GHG emitted.

How can tropical organic soils be rehabilitated in order to restore carbon stores?

Significant areas of tropical peatlands have been converted to agriculture, with climate consequences quite disproportionate to the production benefits. Recuperation of soil carbon in tropical peatlands has enormous mitigation potential but it is unclear how this should be carried out, how long it will take, and what the costs and social implications might be.

Are there agricultural or forestry options on tropical organic soils which preserve their carbon and other ecosystem services?

Keeping tropical organic soils undisturbed is less risky, and probably more cost-effective, than trying to fix their negative outcomes after the fact, but that may not be achievable in all cases. Can productive agriculture or forestry take place on these soils without leading to excessive carbon loss?

Adoption and policy studies

This category involves the technology adoption and policy studies needed to ensure that the various mitigation practices reach their potential. In the absence of a robust carbon market, mitigation of agricultural GHG emissions in the developing world must be driven by practices that provide clear benefits to farmers in the form of increased productivity and increased resilience to climate variability and change, and where GHG mitigation may be considered an ancillary benefit. These practices must provide a clear net benefit to farmers’ livelihoods, particularly given that many of these practices are knowledge-intensive, may involve increased labor and other costs, and may not provide immediate benefits.

What policy instruments would increase the adoption of agricultural and land use mitigation practices in the developing world?

Only 35% of the technical mitigation potential is expected to be met by 2030, due to financial and social adoption barriers (Smith et al. 2007a). The degree of adoption is projected to increase with an increasing 'price of carbon', in other words, the ability of the land custodian to earn a local reward from providing a global benefit. Why do farmers adopt or not adopt climate mitigation policies? Can the incentives and the efficiency of supplying the incentives be improved? Institutional mechanisms for achieving this efficiently, transparently and sustainably remain a major challenge. At present a large part of the payment for the climate service is dissipated by brokerage and verification costs before it reaches the farmer. Thus practices which generate their own incentives, for instance through improved productivity, have a higher chance of adoption (Wollenberg et al. 2012). Adoption rates of agricultural practices are often overestimated. In order for agriculture to deliver on its mitigation potential there is a need for studies that determine the number and types of farming enterprises adopting specific practices, the biophysical and socioeconomic conditions under which they are farming, and the reasons for which they adopt a practice. Likewise, the constraints to adoption expressed by non-adopters are critical. Some key issues essential to mitigation of agricultural in developing regions that need to be addressed through policy are:

- What are effective incentives or disincentives to reduce N application rates in areas where they are currently too high?
- How will increased application of fertilizer N be attained where needed with the increasing costs of fertilizers?
- What are incentives that would increase the crop residue return to soils in areas where there are competing, more profitable uses?
- How can biofuel policies benefit energy and not undermine food production?
- How would climate targets be affected if certain countries or sectors adopted low emissions strategies?
- What institutional conditions are required to channel international finance for low emissions agriculture via Nationally Appropriate Mitigation Strategies?
- How can innovation networks improve communication of mitigation opportunities?
- What conditions support commodity supply chains to reduce deforestation and emissions?

In the absence of direct financial incentives for mitigation, a similar array of questions can be developed to understand incentives and patterns of adoption of agricultural practices that can fall under the "climate-smart" umbrella, which provide yield and adaptation improvements.

How can climate-altering land use change be minimized while satisfying food security and livelihood improvement needs?

Protecting ecosystems with a disproportionately high climate regulating role (which are often also hotspots of biodiversity and water yield) from inappropriate agricultural development arguably leads to better overall welfare outcomes both locally and globally even though it reduces, rather than increases, agricultural production. If coupled with effective mechanisms to reward local custodians for their loss of options, these ecosystem protection activities can improve local livelihoods as well. Three strategies hold promise here: optimization, at landscape, regional and global scales, of what activities take place where; 'sustainable intensification' (i.e.increasing production on land already converted, within sustainable limits, thereby sparing unconverted land); and when conversion of new

lands occurs, ensuring that it takes forms that are less climatically-damaging. An example of the latter is practicing agroforestry in forest and woodland environments, rather than converting them to pastures or short-duration croplands.

What policies work best to reduce the loss of forest and other high carbon density ecosystems, and guide land use to climate-beneficial directions?

The drivers of land use change are complex and variable between places and over time. Nevertheless, certain key commodities, such as soybeans and palm oil, due to demand, have been implicated in widespread deforestation in recent decades. The policies which underlie increases in the demand for these products are often formed outside the countries where the deforestation is occurring, for instance in relation to biofuel requirements in the developed world. How can there be better coordination of local, national and international policies to achieve a common objective, and what balance of regulation and incentives is implementable and effective? It is more than a simple deforestation/protection choice: there are already deforested lands which can be channeled into land uses which remain agriculturally productive, but are more suitable for climate protection, such as agroforestry.

How can a growing demand for animal protein be satisfied at lower climate cost?

A consequence of rising wealth in the developing world is an increased demand for animal protein, including fish, poultry, pork, beef, mutton, dairy and other products. Beef, in particular, has a high GHG emission per unit product, but also substantial room for improvement through better animal diets, management and genetics. There is scope for demand-side research too, on how to satisfy the need and desire for more protein in the diet without reaching unhealthy levels, but there are valid equity issues relating to denying developing world inhabitants the dietary choices available to the developed world. Livestock-based agriculture is fundamental to livelihoods and cultural identity in many parts of the developing world and is arguably the most appropriate agricultural use of arid lands, when sustainably practiced. Since the size of the free-grazing herd has an upper limit, in most cases already reached or surpassed, increased production must focus on efficiency improvements, using greenhouse gas emissions per unit product as one of the performance metrics. The trend will be towards more intensive systems based on feed supplementation, which simultaneously reduces emissions and increases live weight gain per animal, while making emission-reducing methods of dealing with manure more feasible. However, rising demand for cultivated animal feeds is increasingly in land competition with direct food production for people and with industrial bioenergy demands.

How sensitive are the agricultural and land use climate mitigation strategies to shocks, including climate change itself?

Building an agricultural and development strategy on a climate mitigation foundation would be unwise if it has a high risk of unraveling under anticipated levels of climate change or is totally dependent on institutional arrangements that are unsustainable in a food-scarce or economically stressed world. Much of the mitigation potential of agriculture in developing regions is related to increased soil C which can be affected positively or negatively by climate change. The proposed strategies need to be evaluated in terms of their resilience to the plausible stresses to which they may be exposed.

Regional priorities

Different priorities for research can be set depending on ecological zones and regions. Within the humid tropics of Southeast Asia, the Amazon region, and Central Africa priorities should be focused on reduction of deforestation (the key approaches are policy-based and sustainable intensification of already cleared land); restoration of organic soils and the management of rice systems, both of the latter particularly in Asia. In the subhumid tropics the key areas are on improved cropland management: management to reduce or reverse the loss of soil carbon is particularly relevant to sub-Saharan Africa; optimal N fertilization practices will depend on the region, with decreased applications possible in large areas of East Asia, South Asia, and Latin America whereas increased inputs are required in Africa. This research needs to address the balance between N application rates, N₂O emissions, soil carbon and food security. The place of agroforestry both in terms of ecological zones and regions needs to be better defined. In the semi-arid tropics the key issues relate to livestock and grazing land management: restoration and the prevention of degradation; livestock feeding and production optimization; handling of manure.

The role of CGIAR in climate change mitigation through agriculture

CGIAR has played a significant role in researching the potential of agriculture to mitigate climate change (Box 1) and is likely to continue to do so. Past and current CGIAR research on this topic spans the continuum from basic process-level controls on GHG emissions, through conceptual frameworks, protocols for assessing mitigation options, system-level integration, to policy and adoption studies. Much of this research is already directed towards the key research themes highlighted in this report. There are many other actors in this research space, including Advanced Research Institutes (ARIs) in the developed and developing world, National Agricultural Research Systems (NARS), and universities. A rational strategy for CGIAR centers is to focus on their domain of comparative advantage, while ensuring that they are well-connected to the ARIs and NARS. The goal is to stimulate and support rather than displace research within the developing countries themselves. The areas of CGIAR advantage in climate mitigation research are outlined in the following sections; and thereafter some institutional issues are discussed.

Box 1. Climate change mitigation research by the CGIAR

Several of the CGIAR centers along with their partners are already involved in climate change mitigation research, including field studies, syntheses, and modeling. Since 2011 when CGIAR was organized into 15 research programmes, climate change mitigation has appeared in several of those. Some of the topics, centers and programmes involved are listed below.

Crop and soil management:

- Soil carbon sequestration with nutrient, tillage, residue management (CIMMYT, ICRISAT, CIAT, ICRAF, IITA, IWMI, IRRI, CCAFS, WLE)
Govaerts et al. (2009) – synthesis of soil C sequestration with conservation agriculture; numerous field studies on conservation agriculture and nitrogen management in Mexico, India, Eastern Africa
- Carbon sequestration by trees and soils in agroforestry systems (WLE)
Albrecht and Kandji (2003).
- N₂O emissions with management of N fertilizers, manures, and green manures (ICRAF, ILRI, IRRI, CCAFS)

Livestock and grazing land management:

Thornton and Herrero (2010) modeling of total mitigation potential from tropical livestock diets and management (ILRI, CCAFS)

- Soil carbon sequestration with improved pasture grasses and management practices (ILRI, IWMI, ICRAF, CCAFS)
Fisher et al. (2007)
- N₂O emissions with nitrification inhibition by grasses (CIAT, CCAFS)
Subbarao et al. (2013)

Rice management:

- CH₄ and N₂O emissions with water and nutrient management in flooded rice systems (IRRI, CCAFS, GRiSP)

Land use change, sustainable commodities and REDD:

- CO₂ emissions with forest clearing and land use options (ICRAF, CIFOR, FTA, CCAFS)
- CO₂ and CH₄ emissions with conversion and management of peatlands
Murdiyarsa et al. (2010) (CIFOR, CCAFS)
- Governance arrangements
Newton and Agrawal (2013) Mitigation and governance of agriculture-forest landscapes (CCAFS)

Integrated assessments, protocols, modeling, and policies -net greenhouse gas emissions, including tradeoffs with livelihoods (CIAT, ICRAF, IFPRI, ILRI, IMWI, IRRI, IITA, CIMMYT, CCAFS, FTA)

Rosenstock et al. (2013) protocols for quantifying GHG at landscapes scale.

Vermeulen et al. (2012) and Stringer et al (2012) on options and incentives for small holder farmers.

van Noordwijk (in press) carbon markets to avoid land degradation.

Bhatia et al. (2010) Trade-offs between productivity enhancement and global warming potential of rice and wheat in India.

Adoption of climate smart agriculture (CCAFS)

Cooper et al. (2013) Large-scale implementation of adaptation and mitigation actions in agriculture.

De Pinto et al. (2013) Adoption of climate change mitigation practices by risk-averse farmers in the Ashanti Region, Ghana.

Areas of CGIAR comparative advantage

A global network of place-based research

CGIAR operates, usually in collaboration with local partners, a widely-distributed network of projects, experiments and sentinel or benchmark sites for conducting basic and applied research and promoting the implementation of best practices. A systematically selected subset of the available sites could be a platform for targeted and standardized climate mitigation research. The subset should be selected to represent major agroecological zones and farming systems, spanning the range of biophysical and socioeconomic conditions needed to understand the factors that determine emission processes. A review of currently available information may reveal the need for new studies representing important but understudied systems.

A global information resource of agricultural management practices and conditions

CGIAR has the disciplinary and geographical reach to be able to collate, in a harmonized system, the enormous body of existing information relevant to climate-smart agriculture, and act as a repository and synthesizing body for future findings. It is a truism in science that we never know enough – but we know a great deal more than is actually used in decision-making. Some of the most cost-effective and innovative advances come not from the generation of primary knowledge, but by mining and recombining in novel ways the information already collected, but often not easily accessible.

Use of spatial data sets

The CGIAR Consortium for Spatial Information (CSI) already has (or could have) much of the spatial data needed for assessing and targeting mitigation potential alternatives. Technical advances in geostatistics, remote sensing and geospatial data analysis are creating the opportunity for genuinely comprehensive, highly-resolved and fit-for-purpose data assemblages in parts of the world that have historically been poorly served, and will remain so for the near future unless an organization such as CGIAR acts as a data broker.

Policy studies

CGIAR has a history of conducting policy-oriented, but reality-grounded studies which are neither the priority of advanced studies institutions, nor the strength of national agricultural agencies. These include adoption studies, development and testing of incentive systems, economic analyses of mitigation practices, decision support tools, and exploration of the institutional and regulatory environments necessary for implementation.

Impact studies

CGIAR can cover some of the blind spots of other institutions with respect to the broader impacts of particular measures, beyond just agricultural production and GHG emissions. Many CGIAR centers have well developed monitoring and evaluation programmes that could address the tradeoffs and synergies between agricultural production and livelihoods. For instance, what is the social impact of the practice, its sustainability? Does it have gender-differentiated impacts? There is additional need within CGIAR to develop a wider range of environmental monitoring.

Organizing to deliver mitigation research: CGIAR institutional issues

Climate adaptation and mitigation are high on the agendas of donors and researchers, but so far are low priorities for many developing countries, because of a sense that this is a northern agenda that will dilute the development focus of CGIAR. Two facts are salient in this regard: climate stabilization

cannot be achieved without the active participation by the developing world; and without climate stabilization at a low level of global warming, agriculture and other development in the developing world will be seriously compromised.

Currently mitigation research is conducted in several of the 15 CGIAR Research Programs (CRPs), though the main focus is often towards other objectives (e.g. nutrient management in various crops). The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) brings together a focus on mitigation outcomes across production systems. Climate mitigation is one of four programs in CCAFS and is closely linked to the two adaptation programs. There is also a dedicated component on climate change adaptation and mitigation in the CGIAR Program on Forests, Trees and Agroforestry (FTA). This includes a focus on Reduced Emissions from Deforestation and Forest Degradation (REDD) and on afforestation and reforestation under the Clean Development Mechanism. The Global Rice Science Partnership (GRiSP) also has a section where mitigation is the focus.

In its reform CGIAR is structured around four system level outcomes (SLOs), one of which focuses on natural resources: “sustainable management of natural resources”. The other three cover poverty alleviation, food security and nutrition. These SLOs relate to the long-term goals of CGIAR. One of the indicators of the sustainable management SLO should relate to greenhouse gas emissions. The mitigation outcome targets for that indicator in the various CRPs could be set using the kind of information provided in this report. There is an ongoing process to define about 15 Intermediate Development Outcomes (IDOs), one of which could be explicitly related to mitigation.

Are climate-related mitigation issues such an overwhelmingly dominant part of sustainable management that they should be lifted out as a fifth SLO? Doing so may increase the focus, but at the price of further isolating climate considerations from the sustainability and food security context in which they must be considered. Similarly, a new mitigation-focused CRP would make little sense, given that mitigation work often needs to go hand-in-hand with topics that form the main focus of the various CRPs (e.g. breeding for alternate wetting and drying regimes in rice to go hand-in-hand with other rice related research in GRiSP). Nonetheless, in order to establish a credible and strategic program of research on mitigation, it is crucial that some part of CGIAR coordinates the work. This is also needed for priority setting and budget allocation to different parts of CGIAR – resources need to be allocated to the Centers, CRPs, agro-ecological systems, research themes and agricultural sub-sectors where returns on research on mitigation are likely to be greatest. This function either needs to reside in the Consortium office (e.g. through facilitating an “independent mitigation advisory group” for priority setting) or in one of the CRPs. If the latter, then the obvious choice is CCAFS, which already covers all agricultural sectors, has an independent science panel that can be tasked with priority setting for mitigation research, and has a mitigation theme. The mitigation research would then be conducted in the research programs that are relevant. The Consortium office or CCAFS would take on a coordinating role, giving particular attention to research topics that need cross-CRP and cross-Centre collaboration. CCAFS, and other programs doing mitigation work, need to ensure that the adaptation-mitigation linkages are addressed.

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RESEARCH PROGRAM ON
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