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CLIMATE CHANGE AND AGRICULTURE PAPER

Synergies between the mitigation of, and adaptation to, climate change in agriculture

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SUMMARY

There is a very significant, cost effective greenhouse gas (GHG) mitigation potential in agriculture. The annual mitigation potential in agriculture is estimated to be 4200, 2600 and 1600 Mt CO_2 equiv/yr at C prices of 100, 50 and 20 US$/t CO_2 equiv, respectively. The value of GHG mitigated each year is equivalent to 420 000, 130 000 and 32 000 million US$/yr for C prices of 100, 50 and 20 US$/t CO_2 equiv, respectively. From both the mitigation and economic perspectives, we cannot afford to miss out on this mitigation potential.

The challenge of agriculture within the climate change context is two-fold, both to reduce emissions and to adapt to a changing and more variable climate. The primary aim of the mitigation options is to reduce emissions of methane or nitrous oxide or to increase soil carbon storage. All the mitigation options, therefore, affect the carbon and/or nitrogen cycle of the agroecosystem in some way. This often not only affects the GHG emissions but also the soil properties and nutrient cycling. Adaptation to increased variability of temperature and rainfall involves increasing the resilience of the production systems. This may be done by improving soil water holding capacities through adding crop residues and manure to arable soils or by adding diversity to the crop rotations.

Though some mitigation measures may have negative impacts on the adaptive capacity of farming systems, most categories of adaptation options for climate change have positive impacts on mitigation. These include: (1) measures that reduce soil erosion, (2) measures that reduce leaching of nitrogen and phosphorus, (3) measures for conserving soil moisture, (4) increasing the diversity of crop rotations by choices of species or varieties, (5) modification of microclimate to reduce temperature extremes and provide shelter, (6) land use change involving abandonment or extensification of existing agricultural land, or avoidance of the cultivation of new land. These adaptation measures will in general, if properly applied, reduce GHG emissions, by improving nitrogen use efficiencies and improving soil carbon storage.

There appears to be a large potential for synergies between mitigation and adaptation within agriculture. This needs to be incorporated into economic analyses of the mitigation costs. The interlinkages between mitigation and adaptation are, however, not very well explored and further studies are warranted to better quantify short- and long-term effects on suitability for mitigation and adaptation to climate change. In order to realize the full potential for agriculture in a climate change context, new agricultural production systems need to be developed that integrate bioenergy and food and feed production systems. This may possibly be obtained with perennial crops having low-environmental impacts, and deliver feedstocks for biorefineries for the production of biofuels, biomaterials and feed for livestock.

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INTRODUCTION

Agriculture releases significant amounts of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) to the atmosphere. CO_2 is released largely from microbial decay or burning of plant litter and soil organic matter. Methane is produced when organic materials decompose under anoxic conditions, notably from fermentative digestion by ruminant livestock, stored manures and rice grown under flooded conditions. N_2O is produced by the microbial transformations of nitrogen (N) in soils and manures, and is often enhanced where available N exceeds plant requirements, especially under wet conditions. Agricultural greenhouse gas (GHG) fluxes are complex and heterogeneous, but the active management of agricultural systems offers possibilities for mitigation (Smith *et al.* 2008). Many of these mitigation opportunities use currently available technologies and can in theory be implemented immediately. In practice, there are many obstacles for implementing such mitigation measures in actual farming systems. Such obstacles fall into different categories including structural, institutional, financial and educational. Removing such obstacles will require dedicated efforts at many levels.

The challenge of reducing agricultural GHG emissions is intricately linked with the other challenges related to sustainable agricultural production. The greatest challenge of agriculture during the 21st century is probably to feed the increasing number of wealthy people on earth while maintaining soil and water resources (Cassman *et al.* 2003). The world population is expected to increase by 50% from 6 to 9 billion people from 2000 to 2050. At the same time, the consumption of food per capita is increasing. This is projected to lead to the doubling of global meat consumption and a 60% increase in the world cereal consumption from 2000 to 2050 (FAO 2006). While this projected increase in production is certainly feasible, it is likely to come at a high cost for environment and biodiversity unless action is taken to develop and implement farming systems that are considerably more sustainable (in all aspects) than currently seen.

In future, the agricultural sector could contribute much to climate change mitigation by providing bioenergy to substitute fossil fuels, and the increasing oil prices have recently been boosting the biofuel sector considerably (Table 1). As dedicated bioenergy crops will increase the competition for land, they have been hypothesized to raise N_2O emissions from soils, due to intensification on currently used agricultural land and also becoming a driver for cropland expansion. Therefore, concerns about the sustainability of bioenergy, particularly biofuels, are growing (e.g. Crutzen *et al.* 2008; Searchinger *et al.* 2008).

AGRICULTURAL OPTIONS FOR GHG MITIGATION

Agricultural practices can make a significant low cost contribution to increasing soil carbon sinks, reducing GHG emissions and contributing biomass feedstocks for energy use (Fig. 1). Considering all gases, the global technical mitigation potential from agriculture (excluding fossil fuel offsets from biomass) by 2030 is estimated to be *c.* 5500–6000 Mt CO_2 equiv/yr (Smith *et al.* 2007*a*, *b*, 2008). Economic potentials are estimated to be 1500–1600, 2500–2700 and 4000–4300 Mt CO_2 equiv/yr at carbon prices of up to 20, 50 and 100 US$/t CO_2 equiv, respectively. About 0·70 of the potential lies in non-OECD/EIT countries, 0·20 in OECD countries and 0·10 for EIT countries (OECD = countries of the Organisation for Economic Co-operation and Development (the wealthier developed countries); EIT = countries with Economies in Transition, which is defined as an economy which is changing from a centrally planned economy to a free market).

In the long-term (post-2050), climate change may affect the mitigation potential of soil carbon sinks, but the direction and magnitude of this effect is uncertain (Smith *et al.* 2007*a*, *b*, 2008). Agricultural mitigation options are cost competitive with mitigation options in other sectors. Agriculture shows similar potential to forestry, industry and energy supply, and has higher potential than the transport and waste sectors.

A large proportion of the economic mitigation potential (at 100 US$/t CO_2 equiv and excluding bioenergy) arises from soil carbon sequestration which has strong synergies with sustainable agriculture and generally reduces vulnerability to climate change. Significant potential is also available from reductions in CH_4 and N_2O emissions, and such emission reductions are permanent. There is no universally applicable list of mitigation practices; practices need to be evaluated for individual agricultural systems and settings (Smith *et al.* 2007*a*, *b*, 2008). An additional mitigation of 770 Mt CO_2 equiv/yr could be achieved by 2030, by improved energy efficiency in agriculture. Agriculture can also provide feed-stocks for bioenergy, in particular, through the use of agricultural wastes and residues and by converting marginal agricultural land to bioenergy cropping.

Mitigation options are often not applied in isolation and some of these options may be mutually exclusive or otherwise affect each other. Such interactions between individual mitigation options are often highly local and context specific. This may result in biases in the estimates of both biophysical and economic potentials of the mitigation options. A study on incrementally applying the least-cost mitigation strategies by sequentially redefining the biophysical state following the application of each

Table 1. *Biofuel production (Million ton oil equivalents (Mtoe)) in 2007 by country (Fischer* et al. *2009)*

	Bioethanol		Biodiesel		Total
	Mtoe	Feedstock	Mtoe	Feedstock	Mtoe
USA	14·55	Maize	1·25	Soybean	15·8
Brazil	10·44	Sugar cane	0·17	Soybean	10·6
EU	1·24	Wheat, maize, sugar beet	4·52	Rapeseed	5·8
China	1·01	Maize, wheat	0·08	Used oils	1·1
Canada	0·55	Wheat	0·07		0·6
India	0·22	Sugar cane	0·03		0·3
Indonesia	0·00		0·30	Palm oil	0·3
Malaysia	0·00		0·24	Palm oil	0·2
World	28·57		7·56		36·13

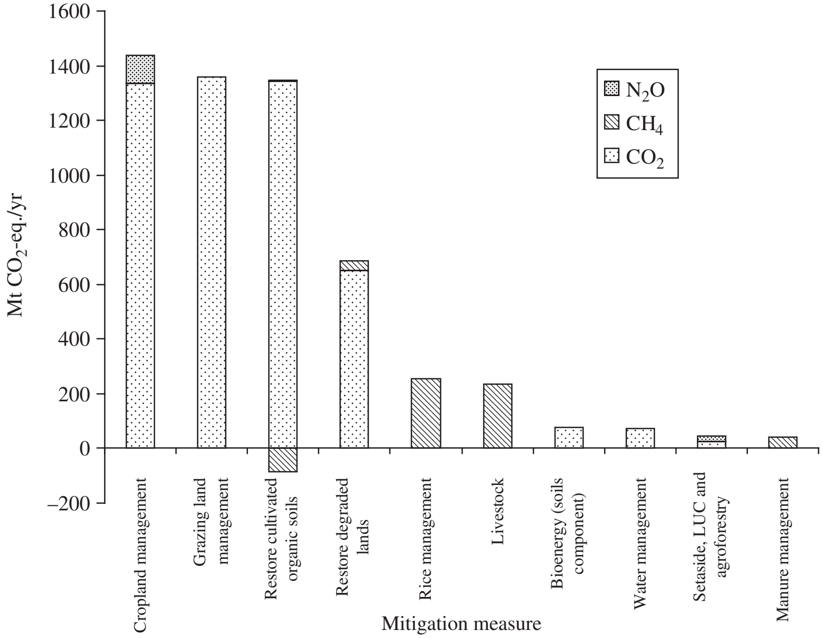

Fig. 1. Global biophysical mitigation potential (Mt CO_2-equiv/yr) by 2030 for each agricultural management practice showing the impacts of each practice on each GHG (Smith *et al.* 2008).

mitigation option has shown that the abatement potential with incremental responses is greater than the abatement potential estimated using typical conservative ad hoc adjustments for dealing with technologies that are not independent, while the abatement under incremental responses is less than the estimates that ignore interactions between technologies (Rose *et al.* 2009). This shows the importance of considering interactions between technologies in future studies on GHG mitigation in agriculture. However, such interactions depend on the structure of the farming systems and on current management systems and will therefore be highly region-specific (Sommer *et al.* 2009).

COST-EFFECTIVENESS OF AGRICULTURAL GHG MITIGATION MEASURES

Governments worldwide recognize the need to achieve emission reductions in an economically efficient manner. In theory, this means that some

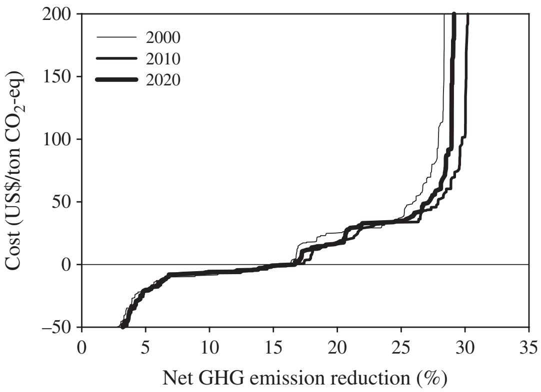

Fig. 2. Global MACC for soil management for three time-slices (Beach *et al.* 2008).

attempts should be made to equalize the marginal abatement costs across different sectors. In other words, the cheapest units of GHG should be abated first. This suggests a requirement for information on abatement schedules or marginal abatement cost curves (MACCs) which show the relative cost of GHG mitigation by alternative mitigation methods and technologies.

There have been several attempts to construct MACCs for agriculture (e.g. Smith *et al.* 2007*a*, *b*; Beach *et al.* 2008). An example of a global MACC for soil management is illustrated in Fig. 2, which shows that there is quite a large potential for reducing emissions (up to 15% reduction) associated with negative costs of emissions, so that adopting these practices would seemingly increase profitability. This indicates that there may be costs and adoption barriers that are not captured in these economic analyses. Figure 2 also shows that emission reductions greater than *c.* 30% for soil management would be associated with excessive costs. The potential changes slightly over time due to the dynamic effects of the measures on soil carbon contents.

National studies on estimating MACC have also been performed, and a recent study for the UK is among the most comprehensive of such studies (Moran *et al.* 2008). In that study, a range of specific abatement measures were identified from a variety of published and unpublished sources, and the relevance and applicability was then derived from expert opinion which was also used to estimate the abatement potentials and the extent to which measures would be additional to a business as usual baseline. To a large extent, relevant information on implementation costs was also based on expert input. The resulting abatement potentials are clearly influenced by the levels of expected adoption of these measures. In the UK, significant potentials for abatement were found in crop and soil management and in livestock management.

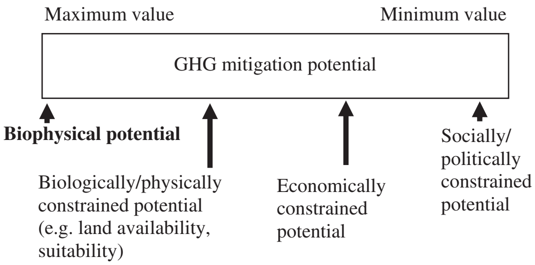

Fig. 3. Impacts of different constraints on reducing GHG mitigation potential from its theoretical biophysical maximum to the lower achievable potential (Smith *et al.* 2007*b*).

However, such MACCs will differ considerably regionally depending on the agricultural structure as well as on soils, climate and current regulatory frameworks.

In addition to the differing levels of abatement related to adoption, MACC variants can be created using private or social costs or a hybrid of both. The key distinctions here are the different discounting assumptions and whether the analysis reflects private or social costs or not. A number of caveats need to be stressed on the results of most of the published MACCs. The first is that the results often do not include a quantitative assessment of ancillary benefits and costs, i.e. other positive and negative external impacts likely to arise when implementing some GHG abatement measures. Reduced water pollution related to more efficient use of the N fertilizer is a classic example. A similar caveat applies to the need to extend the consideration of costs to the life cycle impact of some measures.

In the most recent global assessment of agricultural GHG mitigation potential (Smith *et al.* 2007*a*, *b*, 2008), there is a very significant cost effective GHG mitigation potential in agriculture. The yearly mitigation potential in agriculture is estimated to be 4200, 2600 and 1600 Mt CO_2 equiv/yr at C prices of 100, 50 and 20 US$/t CO_2 equiv, respectively. The value of GHG mitigated each year is equivalent to 420 000, 130 000 and 32 000 million US$/yr for C prices of 100, 50 and 20 US$/t CO_2 equiv, respectively.

BARRIERS TO THE IMPLEMENTATION OF AGRICULTURAL GHG MITIGATION MEASURES

Analyses of GHG mitigation options have clearly shown that there is considerable potential for reducing GHG emissions with very low costs or in many cases even with a net profit. The reason why such mitigation options are not readily being implemented must therefore largely be associated with a range of barriers and constraints for their adoption (Fig. 3). However, there are a few studies on the types and extents of such barriers (Smith *et al.* 2007*a*, *b*). These barriers are also likely to be highly regional and often even farm-specific depending on the local bio-physical, social and economic conditions.

From a policy perspective, the most commonly mentioned barriers to the adoption of C sequestration activities on agricultural lands include (Smith *et al.* 2007*b*):

- *Permanence*. Carbon sequestration in soil only removes C until a new equilibrium is reached, which may take 2–4 decades depending on the climate and management system. A subsequent change in management can even reverse the gains in soil C storage.
- *Additionality*. The GHG emission reductions need to be additional to what would have happened in the absence of a C market or other policy measures. Many of the options are already well known and some of them are already implemented to some extent; so, an obstacle becomes how much is actually additional to what would otherwise have been implemented.
- *Uncertainty*. There are several uncertainties associated with the complex biological and ecological processes affecting soil C storage and other agricultural trace gases, and this makes potential investors more wary of these options compared with many industrial mitigation activities. There is also often an inter-annual variation in emission reductions, which can complicate matters if such variation is included in mitigation commitments.
- *Leakage*. The adoption of certain mitigation options may lead to reduced production in the implementing region (e.g. reduced fertilizer use or taking land out of production). Since demand can often be considered constant, such options may lead to agricultural expansion or intensification elsewhere, resulting in no net effect on emissions. From a global perspective, the regional or national accounting of mitigation in agriculture should therefore be corrected for such leakage effects.

There are a number of additional problems related to the implementation of mitigation options (Smith *et al.* 2007*b*):

- *Transaction costs*. Farmers will not adopt unprofitable mitigation practices in the absence of regulations or incentives. Under an incentive-based system, such as a carbon market, the amount of money that the farmer receives is not the market price, but the market price less transaction costs associated with getting the commodity to the market.
- *Measurement and monitoring costs*. There are large uncertainties associated with the estimation of measurement and monitoring costs, and in reality it depends on the strictness to which various indirect methods for assessing changes in soil carbon and emissions of other biogenic GHGs are accepted.

From a farming or farm level perspective, the following categories of barriers and constraints to the implementation of new technologies and management options to reduce GHG emissions can be identified:

- *Lack of resources*. Some of the measures to increase soil carbon contents require an addition of more organic materials. However, in many regions – especially in developing countries – such organic matter is a scarce resource as it is also used for other purposes including fuel.
- *Lack of information and education*. Many of the GHG mitigation options are identical to measures that should otherwise be taken to obtain an optimized and sustainable agricultural production. In many cases, such options are not implemented due to the lack of knowledge and skill at the local farm level. Therefore, the development and expansion of current educational and extension schemes should be promoted, and education and advice should also include the concern for reducing GHG emissions.
- *Interference with other regulations*. In some cases, the implementation of mitigation options may interfere with other regulations. An example could be the establishment of large biogas facilities, where the odour from such a facility could cause concern among the local community and delay or prevent the establishment. Another example is the use of growth hormones or genetically modified organism crops which is under strict regulation in some countries.
- *Property rights*. Both property rights and the lack of a clear single-party land ownership in certain areas may inhibit the implementation of management changes.
- *Financial constraints*. Some mitigation options carry large investment costs (in particular for new animal housing and manure management systems) and obtaining finance for this may be difficult, if the revenue obtained is uncertain.

BIOENERGY – OPPORTUNITIES AND TRADE-OFFS

Bioenergy is derived from biomass from agricultural energy crops; forestry- and wood-based industries; farm, municipal and industrial organic waste; and marine sources (e.g. seaweed). Biomass can be used in the generation of electricity, heat and biofuels. Using bioenergy can be beneficial to achieve environmental objectives, reduce CO_2 emissions compared to fossil fuels and support rural development efforts, but there are also some risks and negative impacts linked to extensive use.

Current production processes for liquid biofuels follow the first generation conversion technologies relying on sugar, starch or vegetable oil components of crops. These are extensively used in Brazil (sugar cane for bioethanol), the USA (cereals, mainly maize for bioethanol) and the EU (oilseeds, mainly rapeseed for biodiesel) (Table 1). Feedstocks utilized for these first-generation technologies are primarily food and feed plants, and there is thus a direct competition with land required for food production. These technologies generate both fuel and various by-products that are used for livestock feed or in the industry.

A substantial expansion of biofuel production will require an expansion of the range of feedstocks and introduction of advanced (so-called second generation) conversion technologies. Second generation biofuels will be based on lignocellulosic biomass comprising cellulose, hemicelluloses and lignin. Such feedstock sources exist in agriculture and forestry residues (straw, maize stover and wood) and dedicated energy crops (e.g. miscanthus (*Miscanthus* spp.) switchgrass (*Panicum virgatum*) and willow (*Salix* spp.)). Such perennial energy crops can potentially be grown on land that is not suitable for intensive agriculture, thus reducing competition with food production, and the environmental impacts as well as input intensity are also lower in these crops compared with first generation feedstocks.

Biomass from agricultural residues or dedicated crops can be an important biomass feedstock, but its contribution to mitigation depends on the demand for bioenergy from transport and energy supply, on water availability and on requirements of land for food and fibre production. A widespread use of agricultural land for biomass production may compete with other land uses and have other environmental impacts. The economic mitigation potential for agricultural bioenergy in 2030 is estimated to be 70–1260, 560–2320 and 2720 Mt CO_2 equiv/yr at prices up to 20, 50 and above 100 US$/t CO_2 equiv, respectively. These potentials represent mitigation of 0·50–0·90 of all other agricultural mitigation measures combined (Smith *et al*. 2007*a*, *b*, 2008).

Based on the current state-of-the-art analyses, which take the key sustainability criteria into account, the upper boundary of the global biomass resource potential by 2050 can amount to over 400 exajoules (1 EJ = 10^{18} joules) (Dornburg *et al*. 2008). The global primary energy demand in 2050 is projected to be *c*. 600–1040 EJ/yr. Thus, biomass has the potential to meet a substantial share of the world's energy demand. The larger part of the potential biomass resource base is interlinked with improvements in agricultural management, investment in infrastructure, good governance of land use and the introduction of strong sustainability frameworks.

A simulation of the combined environmental and land use effects of bioenergy production has recently been performed by Popp & Lotze-Campen (2009), and covered the most important food and feed, livestock and bioenergy production types in 10 economic regions worldwide. It showed that increasing demand for bioenergy until 2055 enhances global non-CO_2 emissions greatly compared to baseline conditions, due to increases in N_2O emissions from the soil. Here, the largest share of additional N_2O emissions from the soil is associated with the direct fertilization of bioenergy crops. A lesser part refers to increased fertilization of food and feed crops, due to the intensification of agricultural production. This shows the importance of including all GHG emissions, including N_2O from the soil, in a comprehensive assessment for the net benefit of bioenergy for climate change mitigation.

Most studies on substituting biofuels for gasoline have found that this will reduce GHG emissions, because biofuels sequester carbon through the growth of the feedstock. However, many analyses have failed to count the emissions that occur as farmers worldwide respond to higher prices and convert forests and grasslands to new croplands for growing feedstock for first-generation biofuels. Simulations with a global agricultural model have recently shown that maize-based ethanol in the US, instead of reducing emissions by 20 %, nearly doubles GHG emissions over 30 years (Searchinger *et al*. 2008). Biofuels from switchgrass, if grown on the US maize lands, increase emissions by 50 %. This highlights the value of the increased use of agricultural wastes for bioenergy, or alternatively substantially increasing productivity of bioenergy crops to avoid substantial land use changes.

Carbon losses due to land use change occur at the time of land conversion, but GHG from biofuels substituting fossil oil accumulate only gradually over time (Fargione *et al*. 2008). As a consequence, the net GHG savings, resulting from rapid expansion of first-generation biofuels, will only be reached after several decades.

POLICY OPTIONS FOR ENCOURAGING ADAPTATION AND IMPLEMENTATION

The adaptation actions of farmers are mainly driven by short- to mid-term productivity or economic considerations. Barriers to adaptation (e.g. social acceptance, work load, biodiversity and many others) may also present barriers to mitigation. Smith *et al*. (2007*b*) provided a discussion at a table, detailing the synergies and trade-offs between adaptation and mitigation actions.

An important but frequently overlooked issue in developing guidelines for the inclusion of agriculture in national and international climate change mitigation policies is the specific mechanisms through which mitigation is achieved. For instance, whether these sectors are allocated allowances under a cap-and-trade system or provide mitigation through an offset market will potentially have significant implications for agricultural mitigation, land use and commodity production and prices. This may be particularly important in the case of bioenergy, where the use of agricultural feedstocks would reduce emissions from the regulated sectors and would fall under the market for allowances rather than the market for offsets. Because the market prices for allowances and offsets are expected to diverge over time under some policies being proposed, the design of GHG mitigation policy has important implications for farmer incentives to adopt GHG mitigating practices across time. A recent analysis of the US forestry and agricultural sector shows that the land use and allocation and mitigation potential is quite sensitive to how such policies are implemented in practice (Daigneault *et al.* 2009).

Besides the overall policies related to how agricultural emissions should be included in the overall GHG regulation scheme, there is a need to consider how the most promising mitigation measures could be promoted. Overall, the following categories of incentives and regulation can be considered:

- *Support*. Some of the mitigation options are not profitable for the farmers, and additional economic support will be needed for farmers to adopt these practices. Such support may be provided either through a carbon market or dedicated agro-environmental support for certain practices. However, there are also other types of support that society can provide to the farmers to increase adoptions, including education, demonstration and advice.
- *Taxation*. Taxing GHG emissions may be another incentive to reduce them. In those cases, where emissions are directly related to the use of inputs (e.g. N fertilizer), such taxation may be imposed directly on input use. In other cases, more complex schemes may have to be employed to provide the necessary basis for taxation, such that it is legally justifiable.
- *Prescription*. Some farming practices are associated with very high GHG emissions (e.g. cultivation of peatland soils). In such cases, society may choose to ban these polluting practices. This will in some cases require financial compensation, since some prescribed changes can be seen as violation of property rights. In other cases, it may make sense to prescribe the use of certain practices (e.g. use of nitrification inhibitors in N fertilizers). To be effective, such regulations require effective control schemes and substantial fines in case of violation.

SYNERGIES BETWEEN MITIGATION AND ADAPTATION IN AGRICULTURE

Climate change significantly adds to the challenge of feeding a continuously larger world population by reducing the quality of soil and availability of water in many regions and by increasing the variability of temperature and rainfall (Tubiello *et al.* 2007). With the growth in world food demand, the already large contribution of agriculture to global GHG emissions will increase in importance, unless more effective and climate-friendly farming systems are adopted. The challenge of agriculture within the climate change context is therefore two-fold, both to reduce emissions and to adapt to a changing and more variable climate.

For dry croplands, the most important GHGs are N_2O and CO_2 (Six *et al.* 2004), and management practices greatly affect the emissions. The CO_2 fluxes are affected through the carbon inputs and through tillage, which affect the soil carbon turnover rate by influencing soil organic matter protection. The N_2O fluxes are primarily affected through N inputs. Measures for reducing GHG emissions therefore largely focus on enhancing C input and retention in soils and at the same time aim to reduce N_2O emissions through avoiding periods of excessive N contents in soils and by minimizing N losses from the system. For paddy rice areas, which dominate large areas of Asia, CH_4, produced through anaerobic decomposition, is the dominant GHG.

The primary aim of the mitigation options is to reduce emissions of CH_4 or N_2O or to increase soil C storage. Increasing organic matter in the soil can also enhance crop yield and improve yield stability (Pan *et al.* 2009) and also enhance the adaptive capacity of soils, so is a 'win–win–win' option. Therefore, the mitigation options all affect the C and/or N cycle of the agroecosystem in some way. Often, this not only affects GHG emissions but also the soil properties and nutrient cycling. One of the main challenges under climate change is related to the intensification of the hydrological cycle, leading to more intensive rainfall and longer dry periods. The result is that more rainy conditions and higher risk of soil erosion and nutrient leaching in currently wet temperate climates, where rainfall in general will increase in the wet part of the season (Christensen *et al.* 2007). Such measures will influence C and N cycling and thus emissions of CO_2, CH_4 and N_2O (Olesen *et al.* 2004).

Although changes in precipitation patterns are hard to predict, rainfall in some currently arid/semi-arid areas may very well be reduced leading to more frequent droughts and higher dependency on stored soil moisture for supporting crop growth and yield. This might increase the dependency on soil moisture storage and conservation, although the seasonality of the preciptation will be critical. This will influence soil

C storage and possibly N_2O emissions. Adaptation to the increased variability of temperature and rainfall involves increasing the resilience of the production systems. This may be done by improving soil water holding capacities through adding crop residues and manure to arable soils or by adding diversity to the crop rotations (Mäder *et al.* 2002), e.g. by selecting crops that follow better in a rotation and adding legumes to cereal-based systems. The effects of extremely high temperatures on some crops may be reduced through modifying the microclimate, e.g. by adding shade and shelter as in agroforestry systems (Cannell *et al.* 1996). An example of microclimate modification is that of growing coffee under shade, which increases the resilience of coffee growing under climate change by lowering maximum temperatures and improving moisture retension (Lin *et al.* 2008).

Most categories of adaptation options for climate change affecting the mitigation options include: (1) measures that reduce soil degradation, (2) measures that reduce leaching of N and phosphorus (P), (3) measures for conserving soil moisture, (4) increasing the diversity of crop rotations by choices of species or varieties, (5) modification of microclimate to reduce temperature extremes and provide shelter, (6) land use change involving the abandonment or extensification of existing agricultural land or avoidance of cultivation of new land. These adaptation measures will in general, if properly applied, reduce GHG emissions, by improving N use efficiencies and improving soil C storage.

Some mitigation measures may also have negative effects in relation to adaptation. Examples could be catch crops that besides reducing nutrient leakages and adding carbon to soils also consume water. In situations of water scarcity, this water consumption of the catch crop may reduce available soil water for the cash crops and thus negatively affect yields. Other examples of negative effects are the establishment of soil covers from crop residues or permanent understories in orchards that act as insulating materials for heat transfer to and from the soil. This insulation will increase the risk of low temperatures (frost) for the crops during night and of extremely high temperatures during daytime.

There is a particularly large risk of negative effects of mitigation measures related to the increased removal of crop residues from cropping systems for use in bioenergy, if this means that soil C contents are being depleted. With increasing temperatures in regions with sufficient soil moisture, soil C turnover will be enhanced, which further stresses the need for a sufficient return of crop residues to maintain soil fertility and soil structure that can sustain plant production in a more variable climate. This may severely limit the long-term possibilities for removing crop residues for bioenergy in cropping systems based on annual crops.

There is a large potential for synergies between mitigation and adaptation within agriculture. This needs to be incorporated into economic analyses of the mitigation costs. The inter-linkages between mitigation and adaptation are, however, not very well explored and further studies are warranted to better quantify short- and long-term effects on suitability for mitigation and adaptation to climate change.

INTEGRATING BIOENERGY WITH FOOD AND FEED PRODUCTION

The challenges facing agriculture are three-fold: to increase production, to reduce emissions and to adapt to a warmer and more variable climate. There is a particular need to increase agricultural productivity, reduce GHG emissions and adapt to climate change in developing countries (Mertz *et al.* 2009). These challenges require an urgent and substantial increase in the focus of research, innovation, transformation of knowledge and education at all levels across all sectors related to agriculture. To do so, calls for capacity building in many cases, which requires the focus not only of national and local governments but also of international donors and the international research community. There is a further need internationally to promote the development of cropping systems and technologies that deliver highly productive systems for combined food, feed and bioenergy production (FAO 2006). Such actions require a collaborative effort across private and public research institutes, and many research disciplines.

Since there is potential conflict between land for food and land for fuel (Searchinger *et al.* 2008), the challenge within the area of bioenergy is to integrate into it a biomass conversion concept, so that it can contribute to the global efforts of developing alternatives to the entire spectrum of products currently obtained from oil and natural gas. Biomass conversion in biorefineries can not only provide bioenergy but also produce biomaterials, biochemicals, biofertilizer, food and feed ingredients, etc. The conceptual frame for such an integrated approach to technologies for a fossil-free society is the biorefinery. The two basic elements in a biorefinery are the feedstock and the agents for converting the biomass polymers into the products needed. The sustainable feedstock resources, consisting primarily of lignocellulosic materials from plant cell walls, will come from crop residues, from side-streams from the agro-industry and from municipality waste. The agents that make the biomass conversion into valuable and value-added products possible are micro-organisms and microbial products, primarily enzymes. With such an approach, the biorefinery technologies can be developed without threatening the production of food and feed.

Compared with most current food and feed crops, feedstock for biorefineries can be produced in perennial cropping systems that have a much lower input intensity in terms of energy use, fertilizer input and pesticides. Since there is no soil tillage and a permanent crop cover, these systems will also accumulate soil carbon and protect against erosion and nutrient leakage. In many areas, such systems are likely candidates for cropping systems in environmentally sensitive areas and for reclaiming degraded lands. Nevertheless, the optimal use and performance of biomass production is regionally specific. Policies therefore need to take regionally specific conditions into account, and need to incorporate the agricultural and livestock sector as part of good governance of land-use and rural development, interlinked with developing bioenergy.

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