

Organic agriculture and climate change

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Review Article

Abstract

This article discusses the mitigation and adaptation potential of organic agricultural systems along three main features: farming system design, cropland management and grassland and livestock management. An important potential contribution of organically managed systems to climate change mitigation is identified in the careful management of nutrients and, hence, the reduction of N₂O emissions from soils. Another high mitigation potential of organic agriculture lies in carbon sequestration in soils. In a first estimate, the emission reduction potential by abstention from mineral fertilizers is calculated to be about 20% and the compensation potential by carbon sequestration to be about 40–72% of the world's current annual agricultural greenhouse gas (GHG) emissions, but further research is needed to consolidate these numbers. On the adaptation side, organic agriculture systems have a strong potential for building resilient food systems in the face of uncertainties, through farm diversification and building soil fertility with organic matter. Additionally, organic agriculture offers alternatives to energy-intensive production inputs such as synthetic fertilizers which are likely to be further limited for poor rural populations by rising energy prices. In developing countries, organic agricultural systems achieve equal or even higher yields, as compared to the current conventional practices, which translate into a potentially important option for food security and sustainable livelihoods for the rural poor in times of climate change. Certified organic products cater for higher income options for farmers and, therefore, can serve as promoters for climate-friendly farming practices worldwide.

Key words: organic agriculture, climate change, mitigation, adaptation, carbon sequestration, diversification, resilience

Introduction

According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), greenhouse gas (GHG) emissions from the agricultural sector account for 10–12% or 5.1–6.1 Gt of the total anthropogenic annual emissions of CO₂-equivalents¹. However, this accounting includes only direct agricultural emissions; emissions due to the production of agricultural inputs such as nitrogen fertilizers, synthetic pesticides and fossil fuels used for agricultural machinery and irrigation are not calculated. Furthermore, land changes in carbon stocks caused by some agricultural practices are not taken into account, e.g., clearing of primary forests. Emissions by deforestation due to land conversion to agriculture, which account for an additional 12%² of the global GHG emissions, can be additionally allocated to agriculture. Thus, agriculture production practices emit at least one-quarter of global anthropogenic GHG emissions and, if food handling and processing activities were to be accounted for, the total share of emissions from the agriculture and food sector would be at least one-third of total emissions. Considering the high contribution of agriculture to anthropogenic GHG

emissions, the choice of food production practices can be a problem or a solution in addressing climate change.

Clearly, agriculture is highly dependent on climate conditions and is therefore subject to change and variability, with obvious impacts on food security. Changing environmental conditions such as rising temperatures, changing precipitation patterns and an increase of extreme weather events seriously affect agricultural productivity, as vulnerability increases and even farming viability³. Until 2030, adverse agricultural impacts are expected mainly in tropical areas, where agriculture provides the primary source of livelihood for more than 60% of the population in sub-Saharan Africa⁴ and about 40–50% in Asia and the Pacific⁵. While a temperature rise of around 2 °C is already inevitable¹, agro-ecosystems designed to cope with stress and adapt to change are strongly needed to facilitate food security and sustainable livelihoods in these regions. By 2050, all agroecosystems of the world—including those in temperate areas—are expected to be affected by climate change¹. Therefore, the quest for climate-proof food systems is of interest to all.

This article discusses the mitigation and adaptation potential of organic agricultural systems along three main

features: farming system design, cropland management and grassland and livestock management. The objective is to draw a case where good agricultural management can compensate today for most of the sector GHG emissions, while providing food and livelihoods.

Definition of Organic Agriculture

According to the Codex Alimentarius Commission, '*organic agriculture is a holistic production management system that avoids use of synthetic fertilizers, pesticides and genetically modified organisms, minimizes pollution of air, soil and water, and optimizes the health and productivity of interdependent communities of plants, animals and people*'⁶. To meet these objectives, organic agriculture farmers need to implement a series of practices that optimize nutrient and energy flows and minimize risk, such as crop rotations and enhanced crop diversity, different combinations of livestock and plants, symbiotic nitrogen fixation with legumes, application of organic manure and biological pest control. All these strategies seek to make the best use of local resources. Hence, organic systems are inherently adapted to site-specific endowments and limitations^{7,8}.

In this article, we refer to all agricultural systems that implement the practices described above, and not only to systems that are certified as organic. Organic certification is required for market purposes, especially when distance is great from producers to consumers and there is a need to verify the organic claim. In developing countries, a huge number of uncertified farms apply organic agriculture practices for their own subsistence purposes. It is to be highlighted that refraining from the use of synthetic inputs does not qualify an operation as organic, as far as it is not accompanied by a proper farm design and management that preserves natural resources from degradation. In 2007, certified organic lands were of 32 million hectares, involving 1.2 million farmers⁹.

Farming System Design

Limited external inputs

The use of external inputs is limited in organic farming systems. Synthetic inputs like mineral fertilizers and chemical pesticides are banned. The energy used for the chemical synthesis of nitrogen fertilizers, which are totally excluded in organic systems, represent up to 0.4–0.6 Gt CO₂ emissions^{10–12}. This is as much as 10% of direct global agricultural emissions and around 1% of total anthropogenic GHG emissions. Williams et al. calculated the total primary energy burden of conventional wheat production in the UK to be allocated by 56% to mineral fertilizers and by 11% to pesticides¹². Pimentel calculated similar results for corn in USA, 30–40% for fertilization and 9–11% for plant protection for wheat and corn¹³. These emissions are avoided by organic agriculture.

However, where labor is not available and conditions allow it, organic management might require more fossil

fuel energy for machinery due to the use of mechanical weed control. A comparison of seven organic and conventional crops carried out in the UK showed a higher energy demand for machinery for all organic products. However, the higher energy demand for machinery did not outweigh the energy savings from foregoing synthetic fertilizers and pesticides¹⁴. The total energy use per product unit was lower for organic systems in all cases except for carrots, where a high energy demand for flame weeding was assumed. On average, the total energy demand for organic products was 15% lower¹⁴.

The reduced dependency on energy inputs in organic agriculture reduces vulnerability to rising energy prices, and hence volatility of agricultural input prices. Nitrogen fertilizer prices rose by 160% during the first quarter of 2008¹⁵, and price hikes are expected to recur with peak oil and climate change, further limiting the access for poor rural populations to agricultural inputs. Organic agriculture can be a promising approach to sustain food security by supplying alternatives to agricultural inputs.

An additional effect of the ban on nitrogen fertilizer input is to give an incentive to enhance nutrient use efficiency and therefore, reduce the risk of nitrous oxide emissions. Between 1960 and 2000, while agricultural productivity increased substantially with increased utilization of fertilizers, the global efficiency of nitrogen use for cereal production decreased from 80 to 30%, while the risk of nitrogen emissions increased¹⁶.

Should all farming be managed organically, the current annual production of 100 megatons of nitrogen in mineral fertilizers and the corresponding N₂O emissions would fall off; using an emission factor of 1.3% for the mineral fertilizer nitrogen, these emissions account for 10% of the anthropogenic GHG emissions from agriculture^{10,17}. Hence, the organic ban on the use of mineral fertilizers, reducing both energy demand for fertilizer manufacturing and nitrous oxide emissions from fertilizer application, could lower the direct global agricultural GHG emissions by about 20%.

Reduced use of synthetic fertilizers is believed to result in lower yields per land unit, depending on the level of intensity of the previous management system. A review by Badgley et al.¹⁸ calculated average yield losses under organic management for developed countries of 0–20% and, in the case of developing countries, an increase of yield or hardly any yield reduction. In low external input systems, and especially in arid and semi-arid areas where most of the food-insecure live, organic yields generally improve up to 180%^{19,20}. Higher yields in low-input systems are mainly achieved by the application of manure from integrated livestock production, composting and diversification. In humid areas, where traditionally less livestock is integrated into the farming system and hence no livestock manure is available, organic yields depend on the availability of other organic nitrogen sources. In paddy rice, nitrogen is supplied by nitrogen-fixing organisms like *Azolla*^{21,22}, with yields comparable to conventional

systems¹⁸. In perennial cropping, such as coffee or banana, high yield reductions are more likely, even though in some cases higher yields were measured^{18,23–27}. However, in an appropriate agroforestry system, lower yields for the main crop are compensated by producing other foodstuff and goods^{28,29}. Agroforestry systems are encouraged by different standards for organic agriculture^{30–32}.

Crop diversification

By abstaining from synthetic input use, organic agricultural systems cannot but adapt to local environmental conditions. Therefore, species and varieties are chosen for their adaptability to the local soil and climate and their resistance to local pests and diseases. Organic farmers prefer not to use uniform crops and breeds and opt for more robust traditional species, which they tend to conserve and develop. Additionally, growing different assemblages of crops in time and space seeks to enhance the agro-ecosystem resilience to external shocks such as extreme weather events or price variation³³, which are all risks most likely to increase as the climate changes³⁴. Diverse cropping systems in developing countries do not only rely on cash crops but also on food crops for household consumption. Currently, most small-scale farmers are net buyers of food and, thus, highly vulnerable to volatile food prices¹⁵. An independence from uniform commercial seeds and imported food increases self-reliance and promotes food sovereignty.

The diversification of cropping systems also make more efficient use of available nutrients, with improved productivity and economic performance, which is of high importance in times of limited nutrients and financial constraints³⁵.

Integrated livestock production

To be successful, organic agriculture must integrate plant and livestock production to the extent possible to optimize nutrient use and recycling. Currently, half of the world's pork production originates from industrial landless systems, and for poultry meat this share amounts to over 70%.³⁶ These confined and intensive livestock systems lead to high nutrient excess on the farm level. For the USA, a comprehensive study carried out by the USDA in 1997 calculated a total farm-level excess of about 60% of the recoverable manure nitrogen and 65% of the recoverable manure phosphorus³⁷.

Landless livestock production systems can rarely be found in organic agricultural systems. According to the EU regulations on organic production, livestock units must not exceed 2 units per hectare, which is equivalent to approximately 170 kg N³⁸. Therefore, manure input is tailored to plant uptake capacities, an aspect which is recommended as a mitigation strategy by the IPCC in order to reduce N₂O emissions and leaching³⁴. But, this aspect of organic standards of other regions needs to be further developed to meet the International Federation of Organic Agricultural Movements (IFOAM) principle of a

harmonious balance between crop production and animal husbandry.

A nutrient excess on the farm does not only lead to a high N₂O emission risk but also to an inefficient use of the world's limited resources. Where manure has to be transported over great distance for application, high energy costs occur.

On pastures, limited livestock density avoids overgrazing. Overgrazing is a risk factor for land degradation and leads to high soil carbon losses^{39–41}.

The limitation of livestock units per hectare and the lower production intensity are incentives for multi-use livestock systems. Case study calculations showed that the methane emissions from milk and beef production can be reduced more than 20% by keeping double-use breeds⁴² (i.e., for milk and meat production). Double-use breeds are normally not kept in conventional systems because of their lower milk yields, but in roughage-based organic systems, double-use breeds do not imply further yield losses and hence are more likely to be used.

Maintenance and restoration of multi-functional landscapes

The integration of landscape features for the establishment of eco-functional landscapes is an important asset of organic management. According to IFOAM, operators shall take measures to maintain and improve landscape and enhance biodiversity³⁰. This may include extensive field margins, hedges, trees or bushes, woodlands, waterways, wetlands and extensive grasslands.

The integration of landscape elements is mentioned as an effective mitigation strategy by the IPCC³⁴, due to its multiple adaptation effects. For example, hedges and trees are useful to reduce erosion, which is expected to be aggravated by climate change¹. Reduced erosion goes along with reduced losses of soil organic matter and, hence, increased soil fertility. In organic systems, the water retention and drainage capacity of the ecosystem is enhanced and the risk of floods or droughts is reduced. Meanwhile, carbon is sequestered in soil and plant biomass. While in conventional systems, landscape elements are cleared because they hinder mechanization and chemical control of pests and weeds⁴³, landscape elements in organic systems are purposely created in order to provide habitats for wildlife that work synergistically with the cropping system; for example, predators keep pests under check and hedges protect from winds^{44,45}.

The adaptation effects of landscape features are particularly important in those areas where the strongest impacts of climate change are expected. An analysis of climate risks identified southern Africa and South Asia as the regions where climate change will cause the most severe impacts for a large food-insecure human population⁴⁶. The organic standards of these regions already include regulations concerning landscape elements. According to the East African Standard, trees shall be present and hedges should

be encouraged³¹. The Pacific Organic Standard contains the most specific climate-related standards, which requests properties over 5 ha to set aside a minimum of 5% of the certified area for wildlife, unless the property is following a traditional agroforestry or polyculture approach³².

Agroforestry systems have similar effects, even to a higher degree. They are recommended as mitigation strategy by the IPCC³⁴ and are encouraged by different standards for organic agriculture^{30–32}.

Biomass burning and deforestation

CH₄ and N₂O from biomass burning account for 12% of the agricultural GHG emissions. Additionally, the carbon sequestered in the burned biomass is lost to the atmosphere. In organic agriculture, preparation of land by burning vegetation is restricted to a minimum^{30–32}.

IFOAM organic standards ban the certification of primary ecosystems, which have recently been cleared or altered^{31,32}. Organic agriculture thus contributes to halting deforestation resulting from forest conversion to croplands (12% of global GHG emissions²) and thus highly contributes to mitigating climate change. However, further development of organic standards is needed.

Restoration of degraded land

Organic farming practices such as crop rotation, cover crops, manuring and application of organic amendments are recommended strategies to restore degraded soils⁴⁷ and hence improve the livelihoods of rural populations affected by climate change; 70% of the land in dry areas is assumed to be degraded⁴⁸. In the Tigray Province, one of the most degraded parts of Ethiopia, agricultural productivity was doubled by soil fertility techniques over 1 million hectares through agroforestry, application of compost and introduction of leguminous plants into the crop sequence⁴⁹. By restoring soil fertility, yields were increased to a much greater extent at both farm and regional levels than by using purchased mineral fertilizers.

Restoration of degraded land not only offers income opportunities for rural populations but also has a huge mitigation potential by increasing soil carbon sequestration. The total mitigation potential by restoration of degraded land is estimated as 0.15 Gt (technical potential up to USD 20 per t of carbon) and up to 0.7 Gt (physical potential)⁵⁰. As degraded lands usually host market-marginalized populations, organic land management may be the only opportunity to improve food security through an organized use of local labor to rehabilitate degraded land and increase productivity and soil carbon sequestration.

Cropland Management

As nitrogen is far more limited in organic systems, there is a strong incentive to avoid losses and enhance soil fertility⁵¹. Furthermore, there is a need to reduce the risk of pest and diseases by preventive measures. The most important

instrument for achieving these aims is a diverse crop rotation, including catch and cover crops and intercropping.

N₂O emissions from soils

N₂O emissions are the most important source of agricultural emissions: 38% of agricultural GHG emissions³⁴. The IPCC attributes a default value of 1% to applied fertilizer nitrogen as direct N₂O emissions¹⁷. In other publications, emission factors of up to 3–5 kg N₂O-N per 100 kg N-input can be found⁵². These higher values for global N₂O budget are due to the consideration of both direct and indirect emissions, including also livestock production, NH₃ and NO₃ emissions, nitrogen leakage into rivers and coastal zones, etc.

In organic systems, the nitrogen input to soils, and hence the potential nitrous oxide emissions, are reduced. Mineral fertilizers, which currently cause direct N₂O emissions in the range of 10% of agricultural GHG emissions, are totally avoided (see the above section, ‘Limited external inputs’).

Catch and cover crops extract plant-available nitrogen unused by the preceding crop and keep it in the system. Therefore, they further reduce the level of reactive nitrogen in the topsoil, which is the main driving factor for N₂O emissions^{53,54}. A study from The Netherlands comparing 13 organically and conventionally managed farms showed lower levels of soluble nitrogen in the organically managed soils⁵⁵.

N₂O emissions show a very high variability over time and are therefore difficult to determine⁵⁶. The share of reactive nitrogen that is emitted as N₂O depends on a broad range of soil and weather conditions and management practices, which could partly foil the positive effect of lower nitrogen levels in topsoil. Effects of different soil conditions are not yet well understood. Comparisons between soils receiving manure versus mineral fertilizers found higher N₂O emissions after manure application compared to mineral fertilizer applications, but not for all soil types^{57,58}. One study from Brittany found no significant differences between mineral and organic fertilization⁵⁹. The higher nitrous oxide emissions after incorporation of manure and plant residues are explained by the high oxygen consumption for decomposition of the organic matter^{60–62}. These peaks in N₂O can be mitigated by enhanced aeration of the top soil. In compacted soils, the risk of nitrous oxide emissions is higher^{63,64}. Organic management practices facilitate a lower bulk density, enhancing soil aeration^{65,66}. Low aeration is also a reason for partly higher risk of N₂O emissions in no-tillage systems⁶⁷.

The highest risk for N₂O emissions in organic farms is the incorporation of legumes, which are the main nitrogen source for organic farms⁶⁸. For Germany, emissions of 9 kg N₂O ha⁻¹ were measured after incorporation of legumes. But the average of N₂O emissions over the whole crop rotation was lower for the organic farm, as compared to the conventional system (4 kg N₂O per hectare for the organic and 5 kg for the conventional system)⁶⁹.

To sum up, while there are some indicators for higher N₂O emissions per kg nitrogen applied, there is no clear evidence for higher emission factors in organic systems. Regarding the lower fertilization intensity and the higher nitrogen use efficiency in low-input systems, both leading to lower concentrations of reactive nitrogen in top soils, a lower overall risk of N₂O emission from organic cultivated soils can be assumed. However, as there is high uncertainty in N₂O emission factors, further research is recommended.

Carbon sequestration in cropland and soil organic matter

A second mitigation effect of cash and cover crops, intercropping and manure is an increased carbon sequestration in the soil^{34,70,71}. Several field studies have proved the positive effect of organic farming practice on soil carbon pools^{72–74}. In Switzerland, a long-term trial biodynamic system showed a stable carbon content, while a carbon loss of 15% in 21 years was measured for the compared conventional system. In the USA, a field trial showed a fivefold higher carbon sequestration in the organic system (i.e., 1218 kg of carbon per hectare per year) in comparison with conventional management^{74,75}. The potential of carbon sequestration rate by organic farming for European agricultural soils has been estimated at 0–0.5 t C per hectare per year⁷¹.

Niggli et al.⁷⁶ calculated the sequestration potential of organic croplands to be 0.9–2.4 Gt CO₂ per year (which is equivalent to an average sequestration potential of about 0.2–0.4 t C per hectare and year for all croplands), which represents 15–47% of total annual agricultural GHG emissions^{10,34,76}.

But some practices currently discussed for their high sequestration potential, such as no-tillage, are so far poorly applicable in organic systems. No-tillage is difficult in organic agricultural systems because the accompanied insurgence of weeds cannot be faced with herbicides, as in conventional systems, but only by mechanical weed control, if affordable⁷⁷. The estimated technical potential carbon sequestration rate of conventional zero-tillage is 0.4 t C per hectare per year for Europe, which is slightly higher than the sequestration potential of organic farming practices. However, Freibauer et al. argued that the realistically achievable mitigation potential for organic agriculture is higher (i.e., 3.8 Gt as compared to less than 2.5 Gt for the European Union) due to price premium incentives in organic management⁷¹. Furthermore, recent studies question the sequestration potential of no-tillage systems. A review carried out in 2007 found no positive effect of no-tillage on the total soil carbon stock when samples are taken deeper than 30 cm⁷⁸. One study found even higher concentrations of combustible C and N in the topsoil of organic systems, as compared to no-till systems⁷⁷.

One important factor to consider in assessing soil management impact on GHG emissions is the trade-off

between carbon sequestration and N₂O. Conventional no-tillage systems perform well in terms of carbon sequestration but can increase N₂O emissions^{79–82}. Although not yet well analyzed, in some cases no-tillage can lead to much higher N₂O emissions⁶⁷. For developing countries, there are still few research data available concerning soil carbon sequestration rates and N₂O emissions.

In the long term, the removal of GHGs from the atmosphere through soil carbon sequestration is limited. The level of soil organic matter does not increase indefinitely in any soil, but reaches a certain equilibrium, depending on the soil and climatic conditions and management practices⁸³. Lal estimates the carbon sink capacity of the world's agricultural soils by enhanced management practices to be 21–51 Gt carbon, which is equivalent to all anthropogenic GHG emissions over 2–3 years, referring to 2004 emissions⁸⁴. Thus, carbon sequestration in soils is not sufficient to achieve a climate neutral agriculture in the long run, but in the medium term, it can compensate inevitable agricultural emissions until more neutral production practices are developed and widely used.

Additionally, it must be considered that carbon sequestration has a mitigation effect only if the sequestration is permanent. There are scientific results showing that the carbon stored by no-tillage systems is released by a single ploughing, presumably because of its labile quality⁸⁵.

Most of the soil-sequestered carbon is stored as soil organic matter⁸⁴. In different long-term field trials, organic matter content in organically managed soils was higher^{86–88}. Soil organic matter has positive effects on the water-capturing capacity of the soil. A higher water-capturing capacity strengthens the resilience to droughts and reduces the risk of floods⁸⁹, which are both more likely to increase with climate change. The need for irrigation is lowered, which has an additional adaptation and mitigation effect⁹⁰. Furthermore, soil organic matter enhances the nutrient buffer capacity and the microbial activity, both strengthening soil fertility.

Paddy production

Another agricultural GHG source influenced by cropping systems is methane from paddy rice fields, which accounts for 11% of the global agricultural GHG emissions. The main influencing factors are cultivars, organic amendments and drainage⁹¹. While organic amendments increase emissions, drainage reduces emissions⁹². Organic systems add more organic amendments but adding amendments in times of drainage could avoid higher emissions^{93,94}. As organic systems do not use herbicides, aquatic weeds tend to be present in organic rice paddies—and weeds have an additional decreasing effect on methane emissions⁹⁵. The yields in organic and conventional rice production do not differ significantly^{18,96,97}. Generally, there are adverse effects of organic paddy production on methane emissions due to organic fertilization, while emission compensation measures (such as drainage) are not mandatory. Further

research is needed to quantify and recommend organic practices conducive to climate mitigation. One promising approach could be the combination of organic practices with resource-saving systems as the 'system of rice intensification' (SRI), where soils are kept un-flooded most of the growing period and hence methane emissions are significantly reduced^{98–100}.

Pasture, Livestock and Manure Management

Methane emissions from enteric fermentation

One of the most important sources of GHG emissions from agriculture are the methane emissions from enteric fermentation, which account for 4–5% of the global anthropogenic GHG emissions^{1,34}. The quantity of methane emitted per product unit depends on the animal diet and the cow breed's performance.

High milk yields per cow reduce emissions per product unit. High energy feedstuff (e.g., grains and soya) can reduce emissions because methane emissions mainly derive from the digestion of fiber from roughage¹⁰¹. In developed countries, organic management usually achieves lower milk yields per cow than conventional production¹⁸; the main reason is a more roughage-based ration with low concentrate supply. However in developing countries, where two-thirds of the enteric methane emissions occur, organic systems achieve higher milk yields, as more careful management improves the relatively low performance of traditional systems¹⁰².

In organic systems, ruminants are kept to make productive use of fodder legumes, which play an important role as nitrogen source in organic crop rotations. Also, many grasslands are not suitable for cropping due to topography, climate and soils, and the best productive use of these lands is to keep ruminants on them. High livestock performance is generally achieved by feeding high-energy crops, which neglects the unique ability of ruminants to digest roughage. Using crops for feed rather than food poses substantial challenges to food security; currently, one-third of the world's cropland is used to produce animal feed³⁶, let alone all the inherent environmental problems that intensive cropping systems pose in terms of high N-fertilizer use, soil degradation and further land clearing. Furthermore, high energy concentration in animal diets, if not managed very carefully, can lead to rumen acidification and secondary inflammations, which is a cause of animal illness¹⁰³. Therefore, from an organic perspective, there are severe constraints to mitigating methane emissions from enteric fermentation by shifting to a high-energy diet by feeding higher amounts of concentrates. Organic principles view livestock systems as part of a whole, including the process through which feed is supplied. The objective of organic livestock management, though not yet achieved, is to create a nearly closed nutrient cycle whereby feed is supplied on-farm. While integration and disintensification

are attempted (to different degrees) everywhere in organic livestock systems, there is an increasing awareness of the need to optimize the productivity of roughage with more research and development.

Methane emissions from organic livestock systems can be reduced by about 10% (under European conditions) through reduced animal replacement rates¹⁰⁴, as a low replacement rate is more likely in systems with lower performance per cow since these are not pushed beyond their limit. Also, stress resistance (an important factor under climate change conditions) and longevity are among the most important traits of organic breeding¹⁰⁵.

Manure management

Methane and N₂O from manure account for about 7% of the agricultural GHG emissions³⁴. Methane emissions predominantly occur in liquid manure systems, while N₂O emissions are higher in solid manure systems and on pastures³⁴. There is a very high variance for both gaseous emissions, depending on composition, coverage, temperature and moisture of the manure. Measures leading to a reduction of methane emissions from manure often increase emissions of N₂O and vice versa¹⁰⁶. Methane emissions from liquid manure can be reduced nearly to zero by fermenting the slurry in biogas plants, which would have the positive side effect of generating renewable energy and is in line with organic principles. For N₂O, there is limited mitigation potential for most animals worldwide³⁴.

Carbon sequestration in grasslands

Pastures are the favored feeding strategy for organic cattle. Therefore, organic livestock management is an option for maintaining grasslands, which have a high carbon sequestration potential^{34,107}. Combined with a limited livestock density to prevent overgrazing, organic grassland farming could be a way to optimize carbon sequestration in grasslands^{108,109}.

The global carbon sequestration potential by improved pasture management practices was calculated to be 0.22 tC per ha per year¹¹⁰. Assuming 0.2 tC per ha per year for organic farming practices, the total carbon sequestration potential of the world's grassland would be 1.4 Gt per year at the current state, which is equivalent to about 25% of the annual GHG emissions from agriculture^{10,34,76}.

Organic Supply Chains and Lifestyle

GHG emissions from energy use in the food chain are normally not counted as agricultural emissions. In inventory reports, they appear as emissions from energy supply, industries and transport. There are no comprehensive data available for the GHG emissions of the food sector on a global scale. In the USA, 19% of the fossil energy is used in the food sector¹³. A comparison of seven organic and conventional crops in the UK showed a higher ($n = 6$) or the same ($n = 1$) energy demand for collection, transport and

Table 1. Mitigation potential of organic agriculture.

| Source of GHG | Share of total anthropogenic GHG emissions | Impacts of optimized organic management | Remarks |
|--|--|---|--|
| Direct emissions from agriculture | 10–12% | | |
| N ₂ O from soils | 4.2% | Reduction | Higher nitrogen use efficiency |
| CH ₄ from enteric fermentation | 3.5% | Opposed effects | Increased by lower performance and lower energy concentration in the diet but reduced by lower replacement rate and multi-use breeds |
| Biomass burning | 1.3% | Reduction | Burning avoided according to organic standards |
| Paddy rice | 1.2% | Opposed effects | Increased by organic amendments but lowered by drainage and aquatic weeds |
| Manure handling | 0.8% | Equal | Reduced methane emissions but no effect on N ₂ O emissions |
| Direct emissions from forest clearing for agriculture | 12% | Reduction | Clearing of primary ecosystems restricted |
| Indirect emissions | | | |
| Mineral fertilizers | 1% | Totally avoided | Prohibited use of mineral fertilizers |
| Food chain | ? | (Reduction) | Inherent energy saving but still inefficient distribution systems |
| Carbon sequestration | | | |
| Arable lands | | Enhanced | Increased soil organic matter |
| Grasslands | | Enhanced | Increased soil organic matter |

distribution of organic products. The disadvantage of the organic products is due to the still small economy of scale of organic agriculture (i.e., <2% of global food retail⁹), leading to lower energy efficiency of collection and distribution. This disadvantage could be compensated by supplying products to local wholesalers and food shops¹⁴, as well as by direct supply to consumers (e.g., box schemes) and by larger economies of scale.

Additionally, organic standards tend to support low-energy technologies for packaging. IFOAM standards already cover packaging by advising processors of organic food to avoid unnecessary packaging materials and to use reusable, recycled, recyclable or biodegradable packaging, whenever possible. This includes an intrinsic potential for energy saving.

Certified organic agriculture is linked to consumption patterns that seek locally adapted, healthy and ecologically friendly foods and goods. From a consumer's point of view, the organic philosophy of adaptation to local conditions involves a preference for seasonal and local food. A recent study from Germany has shown that both seasonal and regional consumption has remarkable effects on energy saving¹¹. For example, for apples, a threefold higher energy demand was calculated for intercontinental selling (i.e., from New Zealand to Germany), as compared to an average German production system that involves 6 months of cold storage (i.e., 5.1 MJ kg⁻¹, as compared to 1.6 MJ kg⁻¹). Apples produced in traditional orchard meadows showed the lowest total energy demand (i.e., 0.6 MJ kg⁻¹). Orchard meadows can be seen as an example

for agroforestry in temperate Europe and comply with the organic aim of diversified multifunctional landscapes.

Global food trade is energy efficient only when a production process is energy competitive as compared to local production, either due to favorable climate (e.g., coffee or bananas are best produced in tropical countries) or seasonality (e.g., vegetables). Transportation means (air, sea or road) is another determining factor in calculating the carbon footprint of a traded product. Regional production does not offer advantages when heating is needed. The Swiss organic standard already includes a strict limitation for greenhouse heating and air shipping of organic food¹².

Despite the trend of the past decade of conventionalization of organic food systems, including highly processed and functional foods, sophisticated packaging and global retailing, organic consumers are currently reverting to less energy demanding and decreased carbon footprint commodities. Currently, the organic community is developing adequate carbon labels to be included within the organic standards and labels¹³.

Conclusions

Organic agricultural systems have an inherent potential to both reduce GHG emissions and to enhance carbon sequestration in the soil (Table 1).

An important potential contribution of organically managed systems is the careful management of nutrients, and hence the reduction of N₂O emissions from soils,

Table 2. Adaptation potential of organic agriculture.

| Objectives | Means | Impacts |
|---|---|---|
| Alternative to industrial production inputs (i.e., mineral fertilizers and agrochemicals) to decrease pollution | Improvement of natural resources processes and environmental services (e.g., soil formation, predation) | Reliance on local resources and independence from volatile prices of agricultural inputs (e.g., mineral fertilizers) that accompany fossil fuel hikes |
| <i>In situ</i> conservation and development of agrobiodiversity | Farm diversification (e.g., polycropping, agroforestry and integrated crop/livestock) and use of local varieties and breeds | Risk splitting (e.g., pests and diseases), enhanced use of nutrient and energy flows, resilience to climate variability and savings on capital-intensive seeds and breeds |
| Landscaping | Creation of micro-habitats (e.g., hedges), permanent vegetative cover and wildlife corridors | Enhanced ecosystem balance (e.g., pest prevention), protection of wild biodiversity and better resistance to wind and heat waves |
| Soil fertility | Nutrient management (e.g., rotations, coralling, cover crops and manuring) | Increased yields, enhanced soil water retention/drainage (better response to droughts and floods), decreased irrigation needs and avoided land degradation |

which are the most relevant single source of direct GHG emissions from agriculture. More research is needed to quantify and improve the effects of organic paddy rice production and to develop strategies to reduce methane emissions from enteric fermentation (e.g., by promoting double-use breeds). Indirect GHG emissions are reduced in organic systems by avoidance of mineral fertilizers.

With the current organic consumers' demand, further emission reductions are expected when organic standards include specific climate standards that consider, *inter alia*, reduced energy consumption in the organic food chain (e.g., limitations on greenhouse heating/cooling, processing and packaging, food miles combined with life cycle assessment). The advantage of organic systems is that they are driven by aware consumers and that they already carry a guarantee system of verification and labeling which is consonant with climate labeling¹¹³.

The highest mitigation potential of organic agriculture lies in carbon sequestration in soils and in reduced clearing of primary ecosystems. The total amount of mitigation is difficult to quantify, because it is highly dependent on local environmental conditions and management practices. Should all agricultural systems be managed organically, the omission of mineral fertilizer production and application is estimated to reduce the agricultural GHG emissions by about 20% — 10% caused by reduced N₂O emissions and about 10% by lower energy demand. These avoided emissions are supplemented by an emission compensation potential through carbon sequestration in croplands and grasslands of about 40–72% of the current annual agricultural GHG emissions⁷⁶. However, further research is needed to confirm these figures, as long-term scientific studies are limited and do not apply to different kinds of soils, climates and practices. To date, most of the research on the mitigation potential of agricultural practices has been carried out in developed countries; dedicated investigations are needed to assess and understand the

mitigation potential in tropical and subtropical areas and under the predominant management practices of developing countries.

More importantly, the adaptation aspects of organic agricultural practices must be the focus of public policies and research. One of the main effects of climate change is an increase of uncertainties, both for weather events and global food markets. Organic agriculture has a strong potential for building resilience in the face of climate variability (Table 2).

The total abstention from synthetic inputs in organic agriculture has been a strong incentive to develop agricultural management practices that optimize the natural production potential of specific agro-ecosystems, based on traditional knowledge and modern research. These strategies can be used to enhance agricultural communities that have no access to purchased inputs, which is the case of the majority of the rural poor. The main organic strategies are diversification and an increase of soil organic matter, which both could enhance resilience against extreme weather events and are recommended by the IPCC. These strategies have, in particular, a high potential to enhance the productivity of degraded soils, especially in marginal areas, while enhancing soil carbon sequestration. The adaptive approach inherent to organic agriculture offers simultaneous climate mitigation benefits.

Finally, certified organic products cater for higher income options for producers and hence a market-based incentive for environmental stewardship. The scaling-up of organic agriculture would promote and support climate-friendly farming practices worldwide. However, investments in research and development of organic agriculture are needed to better unlock its potential and application on a large scale.

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References

- 1 IPCC (Intergovernmental Panel on Climate Change). 2007. Synthesis report. In O.R.D. Metz, P.R. Bosch, R. Dave, and L.A. Meyer (eds). Fourth Assessment Report: Climate Change 2007. Cambridge University Press, Cambridge, UK.
- 2 Andrasko, K., Benitez-Ponce, P., Boer, R., Dutschke, M., Elsiddig, E., Ford-Robertson, J., Frumhoff, P., Karjalainen, T., Krankina, O., Kurz, W., Matsumoto, M., Oyhantcabal, W., Ravindranath, N.H., Sanz Sanchez, M.J., and Zhang, X. 2007. Forestry. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer, (eds). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- 3 Food and Agriculture Organisation of the United Nations (FAO). 2007. Adaptation to Climate Change in Agriculture, Forestry and Fisheries: Perspective, Framework and Priorities. FAO, Rome, Italy.
- 4 IPCC (Intergovernmental Panel on Climate Change). 2007. Summary for policymakers. In M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van derLinden, and C.E. Hanson (eds). Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK. p. 7–22.
- 5 ILO. 2007. Employment by sector. In: Key Indicators of the Labour Market (KILM). 5th ed. International Labour Organisation (ILO), Geneva, Switzerland. Available at Web site <http://www.ilo.org/public/english/employment/strat/kilm/download/kilm04.pdf> (verified 15 October 2009).
- 6 Codex Alimentarius Commission. 2001. Guidelines for the Production, Processing, Labelling and Marketing of Organically Produced Foods. First Revision. Joint Food and Agriculture Organisation (FAO) and World Health Organisation (WHO) Food Standards Program, Rome, Italy. Available at Web site http://www.codexalimentarius.net/download/standards/360/CXG_032e.pdf (verified 15 October 2009).
- 7 Köpke, U. 1997. Ökologischer Landbau. In E.R. Keller, H. Hanus and K.-U. Heyland, (eds). Grundlagen der landwirtschaftlichen Pflanzenproduktion. Eugen Ulmer Verlag, Stuttgart, Germany. p. 625–628.
- 8 Vogt, G. 2000. Entstehung und Entwicklung des ökologischen Landbaus. Reihe Ökologische Konzepte 99. Stiftung Ökologie und Landbau, Bad Dürkheim, Germany.
- 9 Willer, H. and Kilcher, L. (eds). 2009. The World of Organic Agriculture. Statistics and Emerging Trends 2009. IFOAM, Bonn, Germany, FiBL, Frick, Switzerland and ITC, Geneva, Switzerland.
- 10 FAOSTAT. 2009. FAO Statistical Database Domain on Fertilizers: ResourceSTAT-Fertilizers. Food and Agriculture Organisation of the United Nations (FAO) Rome, Italy. Available at Web site <http://faostat.fao.org/site/575/default.aspx#anchor> (accessed 7 October 2009).
- 11 European Fertilizer Manufactures Association (EFMA). 2005. Understanding Nitrogen and Its Use in Agriculture. EFMA, Brussels, Belgium.
- 12 Williams, A.G., Audsley, E., and Sandars, D.L. 2006. Determining the Environmental Burdens and Resource Use in the Production of Agricultural and Horticultural Commodities. Main Report. Defra Research Project IS0205. Cranfield University, Bedford, and the Department for Environment, Food and Rural Affairs (Defra) of the United Kingdom Government, London. Available at Web site <http://www.silsoe.cranfield.ac.uk>, and www.defra.gov.uk (verified 15 October 2009).
- 13 Pimentel, D. 2006. Impacts of Organic Farming on the Efficiency of Energy Use in Agriculture. The Organic Center, Cornell University, Ithaca, NY.
- 14 Ministry of Agriculture, Fisheries and Food of the United Kingdom. 2000. Energy Use in Organic Farming Systems. MAFF Project Code OF0182, London, UK.
- 15 Food and Agriculture Organisation of the United Nations (FAO). 2008. Soaring Food Prices: Facts, Perspectives, Impacts and Actions Required. HLC/08/INF/1. FAO, Rome, Italy.
- 16 Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Y., and Winiwarter, W. 2008. How a century of ammonia synthesis changed the world. *Nature Geoscience* 1:636–639.
- 17 Eggleston, S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (eds). 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Prepared by the National Greenhouse Gas Inventories Programme (IGES), Hayama, Japan.
- 18 Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Chappell, M.J., Avilés-Vázquez, K., Samulon, A., and Perfecto, I. 2007. Organic agriculture and the global food supply. *Renewable Agriculture and Food Systems* 22:86–108.
- 19 Pretty, J. 2002. Lessons from certified and non certified organic projects in developing countries. In N. El-Hage Scialabba and C. Hattam (eds). Organic Agriculture, Environment and Food Security. FAO, Rome, Italy. p. 139–162.
- 20 Blaise, D. 2006. Yield, boll distribution and fibre quality of hybrid cotton as influenced by organic and modern methods of distribution. *Journal of Agronomy and Crop Science* 1992:248–256.
- 21 Augstburger, F., Berger, J., Censkowsky, U., Heid, P., Milz, J., Streit, Ch., Panyakul, V., den Braber, K., and Naturland. 2002. Organic Farming in the Tropics and Subtropics. Exemplary Description of 20 Crops—Rice. Naturland e.V., with support of German Agency for Technical Cooperation. Gräfelfing, Germany.
- 22 Cassman, K.G., Peng, S., Olk, D.C., Ladha, J.K., Reichardt, W., Dobermann, A., and Singh, U. 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Research* 56:7–39.
- 23 Pülschen, L. and Lutze, H.J. 1993. Ecological and economic conditions of organic coffee production in Latin America and Papua New Guinea. *Angewandte Botanik* 67:204–208.
- 24 Polius, J. 2000. Brief overview of banana production in St. Lucia. In M. Holderness, S. Sharrock, E. Frison, and M. Kairo (eds). Organic Banana 2000: Towards an Organic Banana Initiative in the Caribbean. Report of the International Workshop on the Production and Marketing of Organic Bananas by Smallholder Farmers. International Network for the Improvement of Banana and Plantain, Montpellier, France. p. 55–60.
- 25 Lyngbaek, A.E., Muschler, R.G., and Sinclair, F.L. 2001. Productivity and profitability of multistrata organic versus

- conventional coffee farms in Costa Rica. *Agroforestry Systems* 53:205–213.
- 26 Lotter, D. 2003. Out of the Ashes of the Coffee Crash, Costa Rica Organic is Born. The New Farm, Rodale Institute, Rodale, PA, USA. Available at Web site: <http://www.newfarm.org> (verified 15 October 2009).
- 27 Van der Vossen, H.A.M. 2005. A critical analysis of the agronomic and economic sustainability of organic coffee production. *Experimental Agriculture* 41:449–473.
- 28 Daniels, S., Mack, R., and Whinney, J. 1999. Considerations for the Sustainable Production of Cocoa. Organic Commodity Project, Cambridge, MA, USA.
- 29 Rice, R.A. and Greenberg, R. 2000. Cacao cultivation and the cultivation of biological diversity. *Ambio* 29(3):167–173.
- 30 International Federation of Organic Agricultural Movements (IFOAM). 2002. Basic Standards for Organic Production and Processing Approved by the IFOAM General Assembly, Victoria, Canada, August 2002.
- 31 East African Community. 2007. East African Organic Products Standard. East African Community, Arusha, Tanzania.
- 32 Secretariat of the Pacific Community. 2008. Pacific Organic Standard. Prepared for publication on behalf of the Regional Organic Task Force at the Secretariat of the Pacific Community's headquarters, Noumea, New Caledonia.
- 33 Smith, J.B. and Lenhart, S.S. 1996. Climate change adaptation policy options. *Climate Research* 6:193–201.
- 34 Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., and Sirotenko, O. 2007. Agriculture. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds). *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- 35 Zhang, F. and Li, L. 2003. Using competitive and facilitative interactions in intercropping systems enhance crop productivity and nutrient use efficiency. *Plant and Soil* 248: 305–312.
- 36 Steinfeld, H., Gerber, P., Wassenaar, T., Rosales, M., and de Haan, C. 2006. *Livestock's Long Shadow: Environmental Issues and Options*. FAO, Rome, Italy.
- 37 Kellogg, R.L., Lander, C.H., Moffitt, D.C., and Gollehon, N. 2000. Manure Nutrients Relative to the Capacity of Cropland and Pastureland to Assimilate Nutrients: Spatial and Temporal Trends for the United States. Publication Number nps00–0579. USDA, Washington, DC, USA.
- 38 European Union. 2007. Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91. European Union, Brussels, Belgium.
- 39 Conant, R.T. and Paustian, K. 2002. Potential soil carbon sequestration in overgrazed grassland ecosystems. *Global Biogeochemical Cycles* 16:90.1–90.9.
- 40 Abril, A. and Bucher, E.H. 2001. Overgrazing and soil carbon dynamics in the western Chaco of Argentina. *Applied Soil Ecology* 16:243–249.
- 41 Zou, Ch., Wang, K., Wang, T., and Xu, W. 2007. Overgrazing and soil carbon dynamics in eastern Inner Mongolia of China. *Ecology Research* 22:135–142.
- 42 Rosenberger, E., Götz, K.-U., Dodenhoff, J., Krogmeier, D., Emmerling, R., Luntz, B., and Anzenberger, H. 2004. Überprüfung der Zuchtstrategie beim Fleckvieh. Bayerische Landesanstalt für Landwirtschaft, Poing, Germany. Available at Web site <http://www.lfl.bayern.de/itz/rind/09285/index.php> (verified 20 October 2009).
- 43 Benton, T.G., Vickery, J.A., and Wilson, J.D. 2003. Farmland biodiversity: is habitat heterogeneity the key? *Trends in Ecology and Evolution* 18:182–188.
- 44 Zehnder, G., Gurr, G.M., Kühne, St., Wade, M.R., Wratten, St. D., and Wyss, E. 2007. Arthropod pest management in organic crops. *Annual Review of Entomology* 52:57–80.
- 45 Smolikowski, B., Puig, H., and Roose, E. 2001. Influence of soil protection techniques on runoff, erosion and plant production on semi-arid hillsides of Cabo Verde. *Agriculture, Ecosystems and Environment* 87:67–80.
- 46 Lobell, D.B., Marshall, B.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., and Naylor, R.L. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science* 319:607–610.
- 47 Blanco, H. and Lal, R. 2008. Chapter 15: Restoration of eroded and degraded soils. In *Principles of Soil Conservation and Management*. Springer, Dordrecht, Netherlands.
- 48 Dregne, H.E. and Chou, N.T. 1994. Global desertification dimensions and costs. In H.E. Dregne (ed.). *Degradation and Restoration of Arid Lands*. Texas Technical University, Lubbock, USA.
- 49 Edwards, S. 2007. The impact of compost use on crop yields in Tigray, Ethiopia. Institute for Sustainable Development (ISD). In *Proceedings of the International Conference on Organic Agriculture and Food Security*. FAO, Rome, Italy. Available at Web site <ftp://ftp.fao.org/paia/organicag/ofs/02-Edwards.pdf> (verified 15 October 2009).
- 50 Smith, P., Martino, D., Cai, Y., Gwary, D., Janzen, J., Kumar, P., McCarl, B., Ogle, St., Howden, M., AcAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., and Smith, J. 2008. Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B* 363:789–813.
- 51 Stolze, M., Pierr, A., Haring, A., and Dabbert, S. 2000. The environmental impacts of organic farming in Europe. In *Organic Farming in Europe: Economics and Policy*. Volume 6. University of Hohenheim, Stuttgart, Germany.
- 52 Crutzen, P.J., Mosier, A.R., Smith, K.A., and Winiwarter, W. 2007. N₂O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics Discussions* 7:11191–11205.
- 53 Ruser, R., Flessa, H., Schilling, R., Beese, F., and Munch, J.C. 2001. Effects of crop-specific field management and N fertilization and N₂O emissions from a fine-loamy soil. *Nutrient Cycling in Agroecosystems* 59:177–191.
- 54 Smith, K.A., McTaggart, I.P., Dobbie, K.E., and Conen, F. 1998. Emissions of N₂O from Scottish agricultural soils, as a function of fertilizer N. *Nutrient Cycling in Agroecosystems* 52:123–130.
- 55 Diepeningen, A.D., de Vos, O.J., Korthals, G.W., and van Bruggen, A.H.C. 2006. Effects of organic versus conventional management on chemical and biological parameters in agricultural soils. *Applied Soil Ecology* 31:120–135.
- 56 Sehy, U. 2004. N₂O-Freisetzung landwirtschaftlich genutzter Böden unter dem Einfluss von Bewirtschaftungs-, Witterungs- und Standortfaktoren. PhD thesis, Institute of Soil Ecology, TU-Munich-Weihenstephan, Freising, Germany.

- 57 Van Groeningen, J.W., Kasper, G.J., Velthof, G.L., van den Pol/van Dasselaar, A., and Kuikman, P.J. 2004. Nitrous oxide emissions from silage maize fields under different mineral fertilizer and slurry application. *Plant and Soil* 263:101–111.
- 58 Rochette, P., Angers, D.A., Chantigny, M.H., Gagnon, B., and Bertrand, N. 2008. N₂O fluxes in soils of contrasting textures fertilized with liquid and solid dairy cattle manure. *Canadian Journal of Soil Science* 88:175–187.
- 59 Dambreville, Ch., Morvan, Th., and German, J.C. 2007. N₂O emission in maize crops fertilized with pig slurry, matured pig manure or ammonia nitrate in Brittany. *Agriculture, Ecosystems and Environment* 123:201–210.
- 60 Flessa, H. and Beese, F. 1995. Effects of sugar beet residues on soil redox potential and nitrous oxide emission. *Soil Science Society of America Journal* 59:1044–1051.
- 61 Flessa, H. and Beese, F. 2000. Laboratory estimates of trace gas emissions following surface application and injection of cattle slurry. *Journal of Environmental Quality* 29:262–268.
- 62 Smith, K.A. 1997. The potential for feedback effects induced by global warming on emissions of nitrous oxide by soils. *Global Change Biology* 3:327–338.
- 63 Ruser, R., Flessa, H., Schilling, R., Steindl, H., and Beese, F. 1998. Effects of soil compaction and fertilization on N₂O and CH₄ fluxes in potato fields. *Soil Science Society of America Journal* 62:1587–1595.
- 64 Sitaula, B.K., Hansen, S., Sitaula, J.I.B., and Bakken, L.R. 2000. Effects of soil compaction on N₂O emission in agricultural soils. *Chemosphere* 2:367–371.
- 65 Glover, J.D., Reganold, J.P., and Andrews, P.K. 1999. Systematic method for rating soil quality of conventional, organic and integrated apple orchards in Washington State. *Agriculture, Ecosystems and Environment* 80(2000):29–45.
- 66 Reganold, J.P., Palmer, A.S., Lockhart, J.C., and MacGregor, A.N. 1993. Soil quality and financial performance of bio-dynamic and conventional farms in New Zealand. *Science* 260:344–349.
- 67 Rochette, P., Angers, D.A., Chantigny, M.H., and Bertrand, N. 2008. Nitrous oxide emissions respond differently to no-till in loam and heavy clay soil. *Soil Science Society of America Journal* 72:1363–1369.
- 68 Baggs, E.M., Rees, R.M., Smith, K.A., and Vinten, A.J.A. 2000. Nitrous oxide emission from soils after incorporating crop residues. *Soil Use and Management* 16:82–87.
- 69 Flessa, H., Ruser, R., Doersch, R., Kamp, T., Jimenez, M.A., Munch, J.C., and Beese, F. 2002. Integrated evaluation of greenhouse gas emissions from two farming systems in southern Germany: special consideration of soil N₂O emissions. *Agriculture, Ecosystems and Environment* 91: 175–189.
- 70 Barthès, B., Azontonde, A., Blanchart, E., Girardin, C., Villenave, C., Lesaint, S., Oliver, R., and Feller, C. 2004. Effect of a legume cover crop (*Mucuna pruriens* var. *utilis*) on soil carbon in an Ultisol under maize cultivation in southern Benin. *Soil Use and Management* 20:231–239.
- 71 Freibauer, A., Rounsevell, M.D.A., Smith, P., and Verhagen, J. 2004. Carbon sequestration in the agricultural soils of Europe. *Geoderma* 122:1–23.
- 72 Küstermann, B., Kainz, M., and Hülsbergen, K.-J. 2008. Modelling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems. *Renewable Agriculture and Food Systems* 23:38–52.
- 73 Fliessbach, A., Oberholzer, H.-R., Gunst, L., and Mäder, P. 2007. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. *Agriculture, Ecosystems and Environment* 118:273–284.
- 74 Pimentel, D., Hepperly, P., Hanson, J., Douds, D., and Seidel, R. 2005. Environmental, energetic and economic comparison of organic and conventional farming systems. *Bioscience* 55:573–582.
- 75 Hepperly, P., Douds, D. Jr, and Seidel, R. 2006. The Rodale farming system trial 1981–2005: long term analysis of organic and conventional maize and soybean cropping systems. In J. Raupp, C. Pekrun, M. Oltmanns, and U. Köpke (eds). *Long-Term Field Experiments in Organic Farming*. International Society of Organic Agricultural Research (ISOFAR), Bonn, Germany. p. 15–32.
- 76 Niggli, U., Fliessbach, A., Hepperly, P., and Scialabba, N. 2009. Low Greenhouse Gas Agriculture: Mitigation and Adaptation Potential of Sustainable Farming Systems. FAO, Rome, Italy. Available at Web site <ftp://ftp.fao.org/docrep/fao/010/ai781e/ai781e00.pdf> (verified 15 October 2009).
- 77 Teasdale, J.R., Coffman, C.B., and Mangum, R.W. 2007. Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement. *Agronomy Journal* 99(5):1297–1305.
- 78 Baker, J.M., Ochsner, T.E., Venterea, R.T., and Griffis, T.J. 2007. Tillage and soil carbon sequestration—what do we really know? *Agriculture, Ecosystems and Environment* 118:1–5.
- 79 Cassman, K., Dobermann, A., Walters, D.T., and Yang, H. 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources* 28:315–358.
- 80 Smith, K.A. and Conen, F. 2004. Impacts of land management on fluxes of trace greenhouse gases. *Soil Use and Management* 20:255–263.
- 81 Helgason, B.L., Janyen, H.H., Chantigny, M.H., Drury, C.F., Ellert, B.H., Gregorich, E.G., Lemke, E., Pattey, E., Rochette, P., and Wagner-Riddle, C. 2005. Toward improved coefficients for predicting direct N₂O emissions from soil in Canadian agroecosystems. *Nutrient Cycling in Agroecosystems* 71:87–99.
- 82 Li, C., Frohling, S., and Butterbach-Bahl, K. 2005. Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. *Climatic Change* 72:321–338.
- 83 Jonston, A.E., Poulton, P.R., and Coleman, K. 2009. Soil organic matter: Its importance in sustainable agriculture and carbon dioxide fluxes. *Advances in Agronomy* 101:1–57.
- 84 Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304:1623–1627.
- 85 Stockfisch, N., Forstreuter, T., and Ehlers, W. 1999. Ploughing effects on soil organic matter after twenty years of conservation tillage in Lower Saxony, Germany. *Soil and Tillage Research* 52:91–101.
- 86 Siegrist, S., Staub, D., Pfiffner, L., and Mäder, P. 1998. Does organic agriculture reduce soil erodibility? The results of a long-term field study on loess in Switzerland. *Agriculture, Ecosystems and Environment* 69:253–264.
- 87 Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U. 2002. Soil fertility and biodiversity in organic farming. *Science* 296:1694–1697.

- 88 Marriott, E.E. and Wander, M.M. 2006. Total and labile soil organic matter in organic and conventional farming systems. *Soil Science Society of America Journal* 70:950–959.
- 89 Lotter, D., Seidel, R., and Liebhardt, W. 2003. The performance of organic and conventional cropping systems in an extreme climate year. *American Journal of Alternative Agriculture* 18:146–154.
- 90 Fan, T., Stewart, B.A., Payne, W., Yong, W., Luo, J., and Gao, Y. 2005. Long-term fertilizer and water availability effects on cereal yield and soil chemical properties in northwest China. *Soil Science of America Journal* 69:842–855.
- 91 Neue, H.U., Wassmann, R., Lantin, R.S., Alberto, M.C.R., Aduna, J.B., and Javellana, A.M. 1996. Factors affecting methane emission from rice fields. *Atmospheric Environment* 30:1751–1754.
- 92 Yang, S.S. and Chang, H.L. 2001. Effect of green manure amendment and flooding on methane emission from paddy fields. *Chemosphere—Global Change Science* 3:41–49.
- 93 Xu, H., Cai, Z.C., Jia, Z.J., and Tsuruta, H. 2000. Effect of land management in winter crop season on CH₄ emission during the following flooded and rice growing period. *Nutrient Cycling in Agroecosystems* 58:327–332.
- 94 Cai, Z.C. and Xu, H. 2004. Options for mitigating CH₄ emissions from rice fields in China. In Y. Hayashi (ed.). *Material Circulation through Agro-Ecosystems in East Asia and Assessment of Its Environmental Impact*. NIAES Series 5, Tsukuba, Japan. p. 45–55.
- 95 Inubushi, K., Sugii, H., Nishino, S., and Nishino, E. 2001. Effect of aquatic weeds on methane emission from submerged paddy soil. *American Journal of Botany* 88(6): 975–979.
- 96 Rasul, G. and Thapa, G.B. 2004. Sustainability of ecological and conventional agricultural systems in Bangladesh: an assessment based on environmental, economic and social perspectives. *Agricultural Systems* 70:327–351.
- 97 Lina, M., Gatchalian, D., and Galapan, F. 1999. KALIKASAN: Aiming at Integrated Organic Agriculture. ILEIA Center for Learning on Sustainable Agriculture, Newsletter 20: September 1999. Amersfoort, The Netherlands.
- 98 Uphoff, N. 2002. Changes and evolution in SRI methods. In N. Uphoff, E.C.M. Fernandes, L.P. Yuan, J.M. Peng, S. Rafaralahy, and J. Rabenandrasana (eds). *Assessment of the System for Rice Intensification*. Cornell International Institute for Food, Agriculture and Development, Ithaca, NY, USA. p. 8–14.
- 99 Dobermann, A. 2004. A critical assessment of the system of rice intensification (SRI). *Agricultural Systems* 79:261–281.
- 100 Stoop, W.A. and Kassam, A.H. 2005. The SRI controversy: a response. *Field Crop Research* 91:357–360.
- 101 Pelchen, A. 1996. Dynamik von Methanemissionen landwirtschaftlicher Nutztiere unter dem Einfluss verschiedener Fütterungssysteme—eine Modellbetrachtung zum Treibhauseffekt. PhD thesis, Humbolt-University, Berlin, Germany.
- 102 Pretty, J. and Hine, R. 2001. *Reducing Food Poverty with Sustainable Agriculture: A Summary of New Evidence*. Final Report from the ‘SAFE World’ Research Project, University of Essex, Colchester, UK.
- 103 Plaizier, J.C., Krause, D.O., Gozho, G.N., and McBride, B.W. 2009. Subacute ruminal acidosis in dairy cows: The physiological causes, incidence and consequences. *The Veterinary Journal* 176:21–31.
- 104 Müller-Lindenlauf, M. 2009. *Umweltwirkungen ökologisch wirtschaftender Milchviehbetriebe unterschiedlicher Fütterungsintensität und Produktionsstruktur*. PhD thesis, University of Bonn, Dr. Köster, Berlin, Germany.
- 105 Van Diepen, P., McLean, B., and Frost, D. 2007. *Livestock Breeds and Organic Farming Systems*. ADAS Pwllpeiran and Organic Centre Wales, Aberystwyth, UK.
- 106 Paustian, K., Babcock, B.A., Hatfield, J., Lal, R., McCarl, B.A., McLaughlin, C., Mosier, A., Rice, C., Robertson, G.P., Rosenberg, N.J., Rosenzweig, C., Schlesinger, W.H., and Zilberman, D. 2004. *Agricultural Mitigation of Greenhouse Gases: Science and Policy Options*. CAST (Council on Agricultural Science and Technology) Report R141. Ames, IA, USA.
- 107 Neill, Ch., Melillo, J.M., Steudler, P.A., Cerri, C.C., de Moraes, J.F.L., Piccolo, M.C., and Brito, M. 1997. Soil carbon and nitrogen stocks following forest clearing for pasture in the south western Brazilian Amazon. *Ecological Applications* 7(4):1216–1225.
- 108 Rice, C.W. and Owensby, C.E. 2001. Effects of fire and grazing on soil carbon in rangelands. In R. Follet, M.M. Kimble, and R. Lal (eds). *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect*. Lewis Publishers, Boca Raton, FL, USA. p. 323–342.
- 109 Liebig, M.A., Morgan, J.A., Reeder, J.D., Ellert, B.H., Gollany, H.T., and Schuman, G.E. 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil and Tillage Research* 83:25–52.
- 110 Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J., and Dokken, D.J. (eds). 2000. *Land Use, Land Use Change and Forestry*. Cambridge University Press, Cambridge, UK.
- 111 Reinhardt, G., Gärtner, S., Münch, J.I., and Häfele, S. 2009. *Ökologische Optimierung regional erzeugter Lebensmittel: Energie und Klimagasbilanzen*. Institut für Energie und Umweltforschung, Heidelberg, Germany.
- 112 Bioswiss: Richtlinien für die Erzeugung, Verarbeitung und den Handel von Knospe-Produkten. Fassung vom 1. Januar 2009. Bioswiss, Basel, Switzerland.
- 113 KRAV. 2008. Project Description for the Project ‘Standards for Climate Marking of Foods’. Version 2.0, 15 February 2008. Available at Web site http://www.krav.se/Global/projektbeskrivning%202.0_EN.pdf (verified 20 October 2009).