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Organic agriculture and climate change

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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 N_2O 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 CO_2-equivalents[1]. 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 viability[3]. 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 Africa[4] and about 40–50% in Asia and the Pacific[5]. While a temperature rise of around 2 °C is already inevitable[1], 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 change[1]. 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 farmers[9].

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 CO_2 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 pesticides[12]. Pimentel calculated similar results for corn in USA, 30–40% for fertilization and 9–11% for plant protection for wheat and corn[13]. 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 pesticides[14]. 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% lower[14].

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 2008[15], 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 increased[16].

Should all farming be managed organically, the current annual production of 100 megatons of nitrogen in mineral fertilizers and the corresponding N_2O 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 systems[18]. 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 variation[33], which are all risks most likely to increase as the climate changes[34]. 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 prices[15]. 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 constraints[35].

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 phosphorus[37].

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 N[38]. 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 N_2O emissions and leaching[34]. 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 N_2O 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 breeds[42] (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 biodiversity[30]. 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 IPCC[34], due to its multiple adaptation effects. For example, hedges and trees are useful to reduce erosion, which is expected to be aggravated by climate change[1]. 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 weeds[43], 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 population[46]. 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 encouraged[31]. 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 approach[32].

Agroforestry systems have similar effects, even to a higher degree. They are recommended as mitigation strategy by the IPCC[34] and are encouraged by different standards for organic agriculture[30–32].

Biomass burning and deforestation

CH_4 and N_2O 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 emissions[2]) 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 soils[47] and hence improve the livelihoods of rural populations affected by climate change; 70% of the land in dry areas is assumed to be degraded[48]. 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 sequence[49]. 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 fertility[51]. 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.

N_2O emissions from soils

N_2O emissions are the most important source of agricultural emissions: 38% of agricultural GHG emissions[34]. The IPCC attributes a default value of 1% to applied fertilizer nitrogen as direct N_2O emissions[17]. In other publications, emission factors of up to 3–5 kg N_2O-N per 100 kg N-input can be found[52]. These higher values for global N_2O budget are due to the consideration of both direct and indirect emissions, including also livestock production, NH_3 and NO_3 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 N_2O 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 N_2O 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 soils[55].

N_2O emissions show a very high variability over time and are therefore difficult to determine[56]. The share of reactive nitrogen that is emitted as N_2O 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 N_2O 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 fertilization[59]. 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 N_2O 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 N_2O emissions in no-tillage systems[67].

The highest risk for N_2O emissions in organic farms is the incorporation of legumes, which are the main nitrogen source for organic farms[68]. For Germany, emissions of $9\,\mathrm{kg}\,N_2O\,\mathrm{ha}^{-1}$ were measured after incorporation of legumes. But the average of N_2O emissions over the whole crop rotation was lower for the organic farm, as compared to the conventional system (4 kg N_2O per hectare for the organic and 5 kg for the conventional system)[69].

To sum up, while there are some indicators for higher N_2O 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 N_2O emission from organic cultivated soils can be assumed. However, as there is high uncertainty in N_2O 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 year[71].

Niggli et al.[76] calculated the sequestration potential of organic croplands to be 0.9–2.4 Gt CO_2 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 affordable[77]. 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 management[71]. 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 cm[78]. One study found even higher concentrations of combustible C and N in the topsoil of organic systems, as compared to no-till systems[77].

One important factor to consider in assessing soil management impact on GHG emissions is the trade-off between carbon sequestration and N_2O. Conventional no-tillage systems perform well in terms of carbon sequestration but can increase N_2O emissions[79–82]. Although not yet well analyzed, in some cases no-tillage can lead to much higher N_2O emissions[67]. For developing countries, there are still few research data available concerning soil carbon sequestration rates and N_2O 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 practices[83]. 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 emissions[84]. 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 quality[85].

Most of the soil-sequestered carbon is stored as soil organic matter[84]. 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 floods[89], which are both more likely to increase with climate change. The need for irrigation is lowered, which has an additional adaptation and mitigation effect[90]. 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 drainage[91]. While organic amendments increase emissions, drainage reduces emissions[92]. 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 emissions[95]. 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 roughage[101]. In developed countries, organic management usually achieves lower milk yields per cow than conventional production[18]; 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 systems[102].

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 feed[36], 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 illness[103]. Therefore, from an organic perspective, there are severe constrains 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 rates[104], 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 breeding[105].

Manure management

Methane and N_2O from manure account for about 7% of the agricultural GHG emissions[34]. Methane emissions predominantly occur in liquid manure systems, while N_2O emissions are higher in solid manure systems and on pastures[34]. 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 N_2O and vice versa[106]. 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 N_2O, there is limited mitigation potential for most animals worldwide[34].

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 t C per ha per year[110]. Assuming 0.2 t C 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 sector[13]. 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_2O 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_2O 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 retail[9]), leading to lower energy efficiency of collection and distribution. This disadvantage could be compensated by supplying products to local wholesalers and food shops[14], 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 saving[111]. 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., $5.1\,\mathrm{MJ\,kg^{-1}}$, as compared to $1.6\,\mathrm{MJ\,kg^{-1}}$). Apples produced in traditional orchard meadows showed the lowest total energy demand (i.e., $0.6\,\mathrm{MJ\,kg^{-1}}$). 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 food[112].

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 labels[113].

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 N_2O 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
In situ 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 labeling[113].

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 N_2O 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 emissions[76]. 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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