Effects of industrial agriculture on climate change and the mitigation potential of small-scale agro-ecological farms

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Abstract

According to the Intergovernmental Panel on Climate Change (IPCC), agriculture is responsible for 10–12% of total global anthropogenic emissions and almost a quarter of the continuing increase of greenhouse gas (GHG) emissions. Not all forms of agriculture, however, have equivalent impacts on global warming. Industrial agriculture contributes significantly to global warming, representing a large majority of total agriculture-related GHG emissions. Alternatively, ecologically based methods for agricultural production, predominantly used on small-scale farms, are far less energy-consumptive and release fewer GHGs than industrial agricultural production. Besides generating fewer direct emissions, agro-ecological management techniques have the potential to sequester more GHGs than industrial agriculture. Here, we review the literature on the contributions of agriculture to climate change and show the extent of GHG contributions from the industrial agricultural system and the potential of agro-ecological smallholder agriculture to help reduce GHG emissions. These reductions are achieved in three broad areas when compared with the industrial agricultural system: (1) a decrease in materials used and fluxes involved in the release of GHGs based on agricultural crop management choices; (2) a decrease in fluxes involved in livestock production and pasture management; and (3) a reduction in the transportation of agricultural inputs, outputs and products through an increased emphasis on local food systems. Although there are a number of barriers and challenges towards adopting small-scale agro-ecological methods on the large scale, appropriate incentives can lead to incremental steps towards agro-ecological management that may be able to reduce and mitigate GHG emissions from the agricultural sector.

Keywords: Industrial agriculture, Agro-ecology, Small-scale agriculture, Greenhouse gases, Land conversion, Mitigation, Climate change, Global warming, Adaptation

Review Methodology: We searched the following databases: Web of Science and Google Scholar. In addition, we used the references from the articles obtained by this method to check for additional relevant material.

Introduction

Global modes of production, consumption and trade have generated enormous problems for the Earth, including the transcendental problem of global warming. According to the Intergovernmental Panel on Climate Change (IPCC), agriculture is responsible for 10–12% of global anthropogenic greenhouse gas (GHG) emissions, and $\sim$24% of the increases in atmospheric GHG emissions [1]. Not all types of agriculture, however, have equivalent impacts on global warming. Industrial or conventional agricultural practices make use of high-yielding plant and animal varieties, large-scale monocrops, high stocking densities, decreased or absent fallow periods, high levels of agrochemicals and high degrees of mechanization [2]. These practices are made possible through the corresponding use of fossil fuels to power the production of synthetic fertilizers and pesticides, agricultural machinery and increased levels of irrigation. The general practices of industrial-style agriculture, therefore, contribute significantly to GHG emissions [3].

Agro-ecological methods for production, primarily used on small-scale farms, on the other hand, are potentially far less energy-consumptive than industrial agricultural production methods and may produce far fewer GHGs per unit of land and per unit of product [4, 5]. Agro-ecological systems are often based on species diversity, not only from a variety of crops but also from companion plants, insect populations, soil microbial and fungal diversity, birds and other vertebrate wildlife that can cohabit with crops and provide ecosystem services to the agricultural system [6]. Agro-ecological methods not only depend on fewer external inputs and less petroleum-dependent infrastructure, but also restore soils and in some cases may sequester more carbon (C) in microbial biomass and better support nitrogen-fixing bacteria populations [7]. Common practices in agro-ecological agriculture include cover cropping, lengthened fallows, fertilization with animal manure, crop rotation, intercropping, alley cropping, biological pest control and other methods that seek to minimize or eliminate the use of external and synthetic inputs, including fossil fuels, by replacing them with ecologically driven processes [8]. Furthermore, such practices are typically sensitive to nature's ecological variations and increasingly emphasize production for and within local systems, thereby minimizing the GHG emissions resulting from the transport of goods [9]. By incorporating sustainable agro-ecological management options into the structure and function of agricultural production in general, significant reductions in levels of GHG emissions can be achieved in this sector [10].

In this review, we compare the differences in GHG contributions between the management systems of industrial and agro-ecological production systems and also discuss potential solutions for mitigating emissions from agriculture. Although it is evident that these two systems represent extremes on a continuum of agricultural practices, we frame the argument as a dichotomy for heuristic purposes. We present first an overview of GHG fluxes in industrial cropping and livestock systems. In the second part, we examine the potential mitigation methods drawn from agro-ecological systems. In the third part, we examine the challenges to the increased adoption of agro-ecological management techniques.

Industrial Agriculture, Livestock Production and GHG fluxes

Industrial agricultural production emits three important GHGs at significant levels: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). CO_2 is the most abundant GHG and is responsible for most human-induced climate change, but N_2O and CH_4 are also significant contributors and more potent than CO_2 in terms of the global warming potential [11]. Agricultural activities are responsible for approximately 50% of global atmospheric inputs of CH_4, and agricultural soils are responsible for 75% of global N_2O emissions [12]. There are a variety of potential sources of GHGs from industrial agricultural systems including soil management, land use and the application of inputs (Table 1). Agricultural management practices can alter the emission or sequestration rates of these three gases (Table 2, [13–16]).

C and N Fluxes in Industrial Agricultural Cropping Systems

CO_2 is emitted from agricultural systems through a variety of mechanisms, including plant respiration, soil efflux, through the use of fossil fuels in machinery and the production of agricultural inputs (e.g. fertilizers and pesticides). CO_2 efflux or soil respiration is a combination of microbial and root processes that transfer the C in soil organic matter (SOM) back to gaseous CO_2. Soil respiration rates are governed by factors similar to other soil functions: temperature, water content, microbial density, diversity and structure, and the biochemical composition of plant material decomposing in the soils.

Worldwide, soils contain about 70% of terrestrial organic C [17], and it is estimated that agriculture systems have lost more than 50 Pg C [1]. Soil C content is closely linked to the soil microbial community structure and function, and in particular, fungal biomass [18]. Excessive nitrogen (N) fertilization decreases fungal abundance and favours bacterial domination [19]. This microbial community shift is one mechanism by which industrial agriculture decreases the capacity of soil to sequester C and ultimately transforms it into a net source of C [7].

Carbon inputs to agro-ecosystems occur through photosynthesis as well as through the accumulation of SOM from the decomposition of plant, root and animal matter. These processes are highly dependent on

Table 1 Potential sources of GHGs emissions (CO_2, CH_4 and N_2O) from agricultural systems

CO_2 emissions	CH_4 emissions	N_2O emissions
• N fertilizer production • On farm fossil fuel, feed • On farm fossil fuel, livestock related • Deforestation • Cultivated soils, tillage • Desertification of pasture • Processing • Supply chain operations: packaging, cold chain and transport	• Enteric fermentation • Manure management • Methanogenesis from water logged soils • Agricultural waste burning	• N fertilizer application • Indirect fertilizer application • Leguminous feed cropping • Manure management • Manure application/deposition • Indirect manure emissions

Adapted from [39].

Table 2 Selected agricultural practices and their potential for climate change mitigation with industrial or agro-ecological techniques. Adapted from [4], with additional data from [14, 60, 61]

Mitigative effects					
Practice	CO_2	CH_4	N_2O	Agro-ecology	Industrial
Agronomy					
Cover crops/avoiding bare fallows	+		+/−	X	1
Eliminate/very limited use of external inputs (synthetic pesticides and fertilizers)	+			X	
Nutrient management					
N-fixing plants	+		+/−	X	2
Crop–livestock integration	+		+	X	3
Improve nutrient-use efficiency	+		+	X[4]	X
Tillage/residue management					
No-till	+		+/−	X	X
Reduced till organic	+		+/−	X	
Agro-forestry	+		+/−	X	
Livestock grazing intensity	+/−	+/−	+/−	X	5
Grazing land nutrient management	+		+/−	X	X
Restoration of degraded lands					
Erosion control	+			X	X[6]
Addition of measures or composts	+		+/−	X	7
Improved manure storage and handling		+	+/−	X	X
Manure anaerobic digestion		+	+/−	X	X
More efficient use of manure as a nutrient source	+		+	X	X

+ Indicates reduced emission or increased removal (positive effect on mitigation).
− Indicates increased emission or decreased removal (negative effect on mitigation).
[1] Although there is little systematic research on the frequency of use of cover crops, three sources indicate it to be far more common among organic/agro-ecological farmers than industrial farmers [13, 15, 16]. Ridgley's survey of ~100 California farmers indicated that 70–100% of organic farmers used cover cropping; only 8% of conventional farmers self-reported as using it. Singer *et al.*'s survey of 3500 US Corn Belt farmers found that only ~10% of farmers had recently used cover crops. Although they did not split the data by organic or conventional farming, cover crop use was significantly correlated with two agro-ecological norms: greater crop diversity (although the magnitude difference in number of crops was low; mean of 3.12 versus 2.51) and raising of both crops and livestock (52% versus 38%).
[2] N-fixing plants are most often used as cover crops (see Note 1), but may also be used in relay or intercropping schemes, while cover crops may also be non-leguminous.
[3] Industrial systems are usually definitionally considered to not include integration (see [41]), but the relevant empirical data rarely includes specific characteristics of production systems. Agro-ecological systems encourage, and in some cases require such integration [61].
[4] Agro-ecological systems may have a much greater relative potential to increase use efficiency as compared with other mitigative practices [67].
[5] Grazing intensity is projected to increase in coming years [14], but cultural, practical and sometimes regulatory restrictions limit livestock intensity in many agro-ecological systems in ways not typically reflected in industrial systems (see [61]).
[6] A variety of erosion control strategies is nominally practical in both industrial and agro-ecological systems. Agro-ecological agriculture, however, arguably has a larger range of such practices already in use, available or common to it, such as hedgerows, agroforestry, cover cropping and other strategies involving structural complexity [14, 60, 61]
[7] Additional use of manures or compost is possible in either system, but as with other practices reviewed here, may be more common or practicable in agro-ecological systems.

agricultural management methods, and many systems do not sequester C [20]. Several practices associated with industrial agriculture, such as inorganic fertilization and intensive tillage, reduce SOM, thus potentially increasing GHG emissions [3]. For example, symbiotic arbuscular mycorrhizal fungi, found in the roots of most arable crops and about 80% of plants worldwide, are thought to contribute to C sequestration in soils and make-up significant portions of SOM [21]. However, in large-scale industrial agricultural systems, frequent tillage and intensive application of inorganic N and pesticides decrease the diversity, abundance and functioning of these beneficial microbes (e.g. [22, 23]). Since these fungi have also been shown to act synergistically with N-fixing bacteria and other soil microbes that facilitate SOM accumulation; these methods of industrial agriculture result in a further depletion of soil C and N, and a greater need for fertilizer application [24]. Together, these cascading effects lead to greater GHG emissions and a net C loss from industrial agricultural systems.

Nitrous oxide (N_2O) emissions represent the major share of agriculture's contribution to GHGs. The global warming potential of N_2O is 298 times stronger than CO_2 per unit weight in trapping atmospheric heat, and agriculture is its most significant anthropogenic source [1]. The dominant and most direct way N enters Earth's biological systems is through the action of N-fixing bacteria, which convert molecular nitrogen (N_2, which makes up around 78% of the atmosphere) to ammonia (NH_3). Many leguminous plants (and a few non-legumes), such as soybeans and alfalfa (lucerne), contain nodules in their roots to house these N-fixing bacteria. As terrestrial plants are often limited by N, plants that grow with N-fixing bacteria in their roots have an advantage in nutrient-poor soils.

Industrial agriculture has significantly altered the quantities of biologically available N through the mass production and the application of synthetic N fertilizers [25]. In the production of fertilizer, the Haber–Bosch process, the N cycle is short-circuited to force the conversion of N_2 to biologically usable compounds such as NH_3, ammonium nitrate and urea. Besides producing more biologically available N, the process of breaking the strong triple bonds of N_2 requires high-energy inputs and temperatures of around 500°C. Consequently, synthetic fertilizer production consumes 3–5% of the world's natural gas and 1–2% of the world's annual energy supply [1].

The key N cycling processes of nitrification and denitrification have been shown to increase with synthetic N fertilization and greater tillage intensity, which changes the bacterial and fungal communities involved in N cycling [26]. Nitrification, the process by which ammonium (NH_4^+) is oxidized to nitrate (NO_3^-), is conducted by two sets of micro-organisms: NH_3-oxidizing bacteria and Archaea [27]. Denitrification completes the N cycle by converting NO_3^- back to N_2. Denitrification is a source of soil-derived N_2O, which is produced as an intermediary compound and can be released in significant quantities to the atmosphere. Inorganic N fertilization is one of the main factors that contributes to N_2O emission from agriculture [3], particularly when over-fertilization of crops occurs (can occur with organic fertilizers as well), increasing rates of nitrification and denitrification and releasing significant quantities of N_2O [28]. Denitrification is accomplished by a wide range of bacterial species, and the specific composition of denitrifying bacteria can determine the rate at which N_2O is released back into the atmosphere [29]. Alterations in microbial communities can have surprisingly long-lasting effects with examples of long-abandoned industrial agricultural sites continuing to harbour increased abundance of nitrifier bacteria [30].

Tropical ecosystems that are generally limited by phosphorus, may be especially prone to increases in N_2O release with N fertilization because N fertilizer in phosphorus-limited systems generates 10–100 times more NO and N_2O than in N-limited systems, as they seem to be already naturally N-saturated [31]. While the impact of N fertilization on the microbial communities is not completely understood, it is clear that large-scale industrial management leads to N saturation in the system, which generates more substrate (i.e. NH_4^+ for nitrification, followed by NO_3^-) for denitrification and facilitates rapid production of N_2O [32, 33].

Practices that reduce the porosity of the soil and increase anoxic conditions also increase N_2O emission by increasing denitrification [34, 35]. However, the magnitude of N_2O fluxes from soils depends on a set of complex interactions between the microbial communities, the plant litter entering SOM, climate and soil properties such as temperature, porosity, water content and pH [36, 37].

GHG Fluxes in Industrial Livestock Production

Global trade in livestock products is rapidly growing as changes in food preferences increase the demand for meat and milk [38]. This trend creates pressure to raise cows, pigs and chickens in large-scale confined spaces and to feed them industrially raised grains, soybeans or residues. The total impact of livestock on GHG emissions includes a variety of production-related activities such as overgrazing, enteric CH_4 production by ruminants and feed-crop production with fertilizers (Table 1).

Most of the world's swine and poultry are raised in intensive (concentrated) industrial systems, and most US beef is finished in feedlots, resulting in significantly increased GHG production. Industrial-scale livestock operations are potent sources of CH_4 and N_2O when manure is stored in liquid form, promoting anaerobic breakdown, with gases diffusing directly from reservoirs of liquid manure. Of all CH_4 emissions, 37% are attributable to livestock, especially grain-fed animals [39]. This figure includes emissions from liquid storage of manure, enteric fermentation by ruminants and burning of fossil fuel to make and transport fertilizers for feed crops. Enteric foregut fermentation of fibrous food and exhalation of gas by the world's ruminants (cattle, sheep, goats and camels) may emit 80 million metric tonnes of CH_4 per year, representing 80% of agricultural CH_4 emissions [39–41]. Emissions, however, vary with the mass of the animal and feed type [42]. CH_4 emissions from decomposition of pig and dairy manure in anaerobic holding reservoirs constitute 4% of global CH_4 emissions or about 10 million metric tonnes [40, 43].

Livestock contribute 65% of N_2O as well as 30 million tonnes of NH_3 annually [44], primarily through manure and use of feeds grown with synthetic fertilizers. Davidson [45] estimates that 2% of manure N and 2.5% of synthetic fertilizer N were converted to N_2O between 1860 and 2005, and the highest rates of N_2O emissions occur where N availability to nitrifying and denitrifying microorganisms exceeds C availability. N_2O emissions from applications of slurred manure to fields can be reduced if the manure is previously stored or digested anaerobically [46].

Transportation of Agricultural Inputs, Outputs and Products

According to the IPCC [1], 13.1% of total GHG emissions derive from transport, but discerning just what fraction of this transport total is associated with the industrial agricultural system is problematic. It is estimated that 28% of all UK road transport is devoted to agricultural activities [47] (approximately 5% of all UK emissions [48]). In addition, one life-cycle study in the USA noted that agricultural transport as a whole contributes 11% of all agricultural GHG emissions from agriculture (excluding an unknown amount of emissions from the transportation of agricultural inputs) [49]. Thus, reductions in transportation and distance associated with the movement of agricultural inputs, outputs and products may have a significant impact in reducing GHG contributions from the agricultural sector.

Many studies have focused on the concept of 'food miles' to refer to the total distance food has to travel from the original production site to the place where it is consumed. The GHG emissions from air transport are considered particularly high, with estimates at 1.093 CO_2 equivalent/t/km [50]. Truck transport was estimated to contribute 0.15 CO_2 equivalent/t/km, while rail transport was estimated to contribute 0.01 CO_2 equivalent/t/km [51].

One study of the environmental cost of major food items consumed in the UK [47] concluded that domestic transport accounted for the highest level of environmental cost, given the high volumes of domestic movement compared with air or sea transport. Another major review in the UK suggested that, in addition to air transport, urban food transport (i.e. people going to buy food or having food delivered), heavy goods vehicle delivery and shipping all need to be considered to fully assess the GHG emissions from transport [4]. The study noted that air transport of food, which has the highest GHG emissions, has more than doubled in a decade (1992–2002).

The use of food miles as a substitute for complete calculation of energy cost or GHG emissions has been criticized as being simplistic because it does not take into account differences in energy use within the production system and other aspects of the life-cycle analysis. Differences in GHG contributions from agricultural management intensity and inefficiencies in production systems may outweigh energy costs associated with transportation. For example, Saunders *et al.* [52] argued that transporting milk solids from New Zealand to the UK was a reasonable transport decision because the UK uses twice as much energy per tonne of milk solids produced as New Zealand does, even including the energy associated with transport. Saunders *et al.* [52] suggest this conclusion is important because it emphasizes the efficiency of 'less intensive' production systems. Obviously, however, were the UK to convert its dairy system to something more energy-rational, such as that in New Zealand, this would reduce the energy cost per litre of milk even more than shipping the dairy products from New Zealand.

Emissions from cold storage of fruits and vegetables may also be factored into the equation. A comparison in Germany of locally grown apples to imported New Zealand apples showed 27% higher C emissions in the imported produce when emissions from longer cold storage were taken into account [53]. Another life-cycle assessment comparing organic and conventional wheat concluded that the global warming potential of one loaf of bread using conventional wheat flour (1 kg bread loaf) without transport is 190 g CO_2 equivalent, while one organic loaf of bread resulted in 160 g CO_2 equivalent. But this reduction in global warming potential is lost if the organic loaf is shipped from a location 420 km further away than for the conventional loaf [51].

The same patterns exist for animal feed. CO_2 emissions from fossil fuel used for production and transport of fertilizers for feed crops in concentrated animal feeding operations (CAFOs) and confinement dairies probably exceed analogous transportation costs for pasture-fed animals. Shipment of soybean cakes from Brazil to Swedish dairies, for example, costs 32 000 tonnes of CO_2 emissions per year for transportation by ship [54], thereby significantly increase the global warming potential of transported feed.

On-farm transportation and energy use are large contributors of CO_2 emissions from industrial agriculture systems as well [1]. Diesel used in industrial agriculture systems of the USA amount to 59 000 million litres and is estimated to release 10.8 million metric tonnes of C per year. Estimates of CO_2 emissions from agricultural machinery used in conventional, reduced and no-tillage systems were 72, 45 and 23 kg C/ha/yr, respectively, showing that reduced tillage can decrease on-farm machinery operations and C emissions from fuel [55]. Data of fuel records from farmers estimate that crops under no-till management used 45 litres of diesel/ha/yr, whereas other more field-intensive crops may use up to 84 litres of diesel/ha/yr [56].

One report looking at the 'cradle to plate' life cycle of butter found that C emissions for direct inputs on-farm, including electricity, agricultural machinery and lubricants, accounted for 190–200 g CO_2/MJ of C emissions [52]. Diesel and petrol used for tractors, trucks, utilities and cars required 36.4 and 22.4 litres/ha, with a total energy use of 2483 MJ/ha or 3032 MJ/tonne of milk solids. CO_2 emissions from all liquid fuels were 230 kg CO_2/ha or 280.4 kg CO_2/tonne of milk solids, about 22% of all direct, indirect and capital on-farm energy based CO_2 emissions.

Mitigation Potential of Small-Scale Agro-ecological Management

Although there is potential to reduce GHG emissions within the industrial system by increasing N use efficiency, reducing tillage, practicing integrated pest management, etc. [4, 57], the large-scale, mechanized, monocultural characteristics of this system limits its mitigation potential and contribute to other environmental impacts [2, 58]. Agricultural intensification (in the industrial mode) and monocultures frequently lead to declines in the diversity of the soil biota and can have profound effects on the biological regulation of decomposition and nutrient availability in soil [59], leading to a greater need for mechanization and external inputs. The implementation of agro-ecological practices with increased crop and microbial diversity may have a large impact in reducing the outward fluxes of GHG emissions from these agricultural systems, as well as making them more resilient to the changing conditions associated with global climate change [60, 61] (Figure 1). The following sections review management options from agro-ecological systems that have the potential to mitigate GHG emissions from the agricultural sector.

Management and Mitigation Options in Agro-ecological Systems

Agro-ecological systems are generally defined as systems that attempt to follow ecological principles in the production of food, fuel, fibre and encompass a broad range of management approaches to achieve this goal. In maintaining the ecological principles of a natural system, agro-ecological systems try to maintain the diversity within the system to sustain the many ecological processes that provide ecosystem services useful to production, including pest control, pollination and restoration of soil nutrients [6, 59, 62, 63]. Additionally, there are a number of management options that can potentially mitigate GHG emissions from the agricultural system.

One potential mitigation option often used in agro-ecological systems is increasing plant diversity to enhance soil ecosystem processes within the agro-ecosystem. For example, the rate of loss of limiting nutrients from terrestrial ecosystems has been found to be lower under high plant diversity and is impacted by plant species composition and rotational practices [62, 64]. Likewise, the rebuilding of soil C and N stocks in highly degraded soils can be accelerated if fields are planted with a high-diversity mixture of appropriate plant species [65]. Given this, it is not surprising that diverse agro-ecosystems have been shown to sequester more C in soil than those with reduced biodiversity [66].

The transformation of diverse landscape mosaics and diverse agricultural systems to large-scale monocultures not only reduces the GHG sequestration potential of the soil but also increases the need for fertilizer application. More diverse farming systems, because they promote higher total productivity and stability, may reduce the necessity for synthetic fertilizer application, therefore reducing N_2O emissions from its application as well as CO_2 emissions from its production [67]. For example, studies of GHG fluxes in the US Corn Belt showed that continuous corn (maize) cropped rotations contributed significantly to N_2O emissions (upwards of 3–8 kg/ha/yr), driven by pulse emissions following N fertilization in concurrence with major rainfall events. More complex systems, such as maize–soybean rotations and restored prairies showed diminished N_2O emissions and contributed to global warming mitigation [60, 68].

Management options such as no-till cropping and reduced-till organic cropping have been shown to enhance C storage, soil aggregation and associated environmental processes with no significant ecological or yield trade-offs. Although conservation tillage is generally found in agro-ecological systems, no-till is also commonly found in some industrial agricultural systems to great benefit for soil health (Table 2). No-till agriculture in maize–soybean–wheat rotations in Michigan showed an accumulation of 26 g C/m^2/yr over 12 years in 0–5 cm soil depth [69]. In a long-term analysis, looking at a range of cropped and unmanaged lands, Robertson *et al.* [3] found that conventional (industrialized) systems were net emitters of GHGs, while other types of less intensively disrupted systems were able to accumulate soil C over the decade following establishment. No-till was shown to accumulate 30 g soil C/m^2/yr, while cover crop organic agriculture was shown to accumulate 8–11 g soil C/m^2/yr in 0–7.5 cm soil depths; both types of management showing a mitigating effect. N_2O fluxes were also three times higher in the industrial agricultural sites versus the non-industrially managed sites [3].

Reviewing several long-term field trials, Niggli *et al.* [10] found similar sequestration potential, concluding that organic farming with reduced tillage techniques could sequester 50 g soil C/m^2/yr, a finding in line with Lal [70]. Lal estimates that agro-ecological practices could mitigate 23–86% of agriculture's GHG emissions (1.4–4.4 Gt CO_2 equivalents/year) depending on the management practices adopted, while Niggli *et al.* [10] report a potential of 40–65% mitigation, along with a possible 20% reduction in

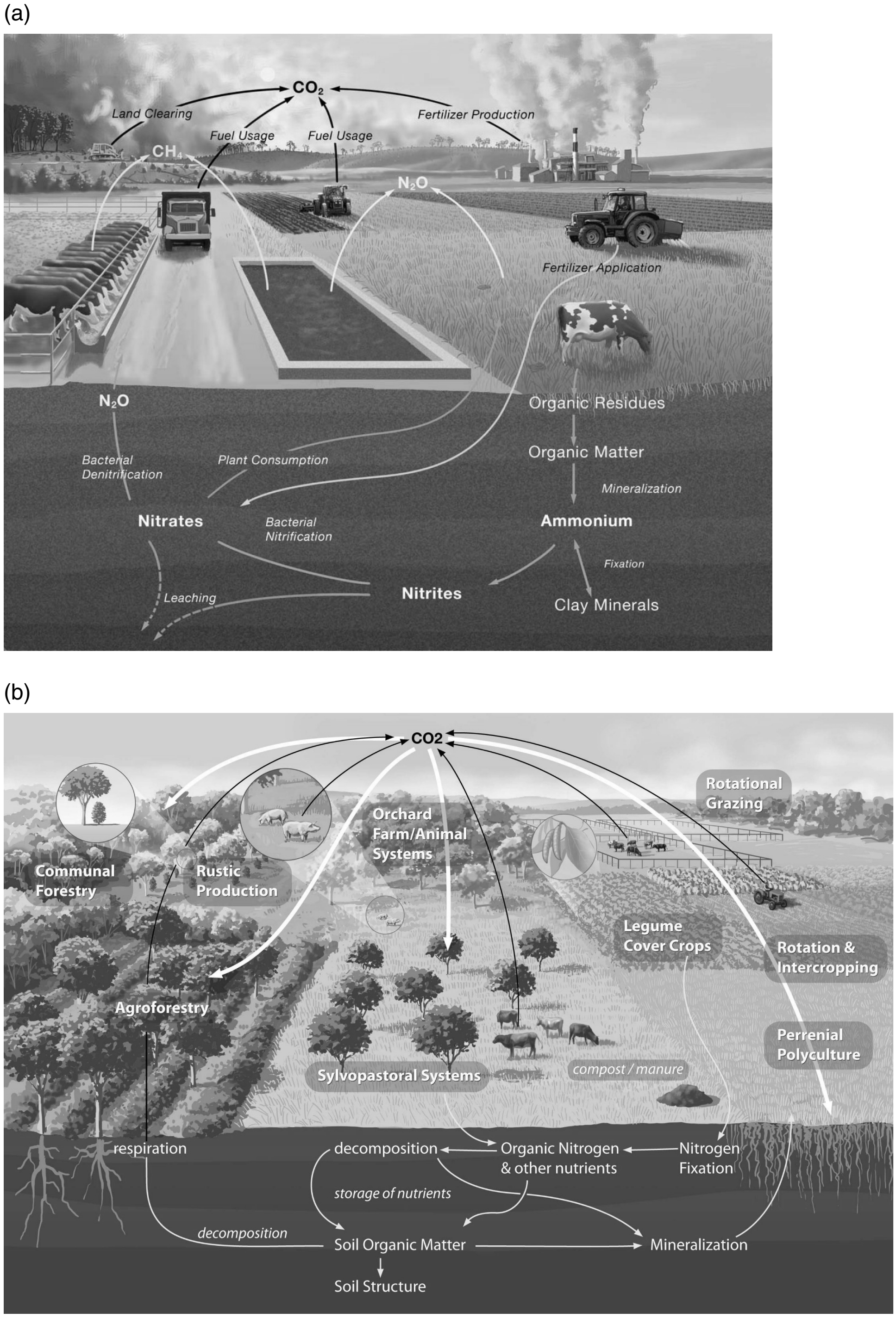

Figure 1 GHG sources and sinks in industrial versus agro-ecological Systems. (a) Large-scale industrial agriculture (b) Small-scale agro-ecological agriculture

emissions by abandoning industrially produced N fertilizers.[1]

To achieve these mitigations, Niggli *et al.* and Lal estimate contributions from a variety of practices, similar to those outlined in Table 2. Each study breaks mitigation potential down by land type, with Lal estimating improved C sequestration on the estimated 1350 Mha of cropland soil through conservation tillage, cover cropping, manuring, integrated farming and agroforestry contributing 1.4–2.9 Gt CO_2/yr of potential mitigation. Restoration of the 1100 Mha of global soils degraded or desertified through erosion control, afforestation and water

[1]Lal gives his findings in Gt C, which is approximately equal to Gt CO_2 divided by 3.67.

Table 3. Comparative GHG emissions from various types of agricultural and forested systems

Land-use system	N_2O emissions (μg N/m^2/h)	CH_4 flux (μg C/m^2/h)	CO_2 emissions (μg C/m^2/h)	Source
Cropping system				
High-input cropping	31.2	15.2	84	[79]
Low-input cropping	15.6	−17.5	66.6	[79]
Cassava/*Imperata*	7.1	−14.8		[78]
Agroforestry systems				
Shifting cultivation	8.6	−23.5	67.5	[79]
Multistate agroforestry	5.8	−23.3	32.6	[79]
Peach palm	9.8	−17	66.4	[79]
Jungle rubber	1	−12		[78]
Rubber agroforests	12.5	−27.5		[78]
Forests				
Forest	9.2	−28.8	73.3	[79]
Forest	5	−31		[78]
Logged forest	7.2	−38.2		[78]

Adapted from [76].

conservation collectively accounts for approximately 0.7–1.5 Gt CO_2/yr (amounts are non-additive). Both Niggli *et al.* and Lal give a large range, as exact sequestration rates and their change through time have high uncertainties; Niggli *et al.*' minimum estimate is based on a sequestration potential of 200 kg/ha/yr for arable and permanent crops; they calculate that a significantly higher amount of sequestration – 500 kg/ha/yr – could be achieved with full adoption of organic farming and reduced tillage.

These and other reviews [60, 70, 71] demonstrate that agro-ecological practices, such as reduced tillage, soil conservation and cover crops, elimination of synthetic pesticides and substituting industrially produced N fixation with biological fixation, can make a large difference in the offsets of GHGs, and that creating agricultural systems that more closely resemble the nutrient cycling mechanisms of natural systems may very well help the agricultural system attain net negative or neutral global warming effects.

Agroforestry is another form of agro-ecological management that may be able to contribute greatly to reducing GHG emissions from the agricultural sector. Agroforestry is a system where livestock or food crops are produced in combination with growing trees, either for timber, firewood or other tree products [72]. Some of these systems, especially the traditional ones, can contain high species diversity within a small area of land [73, 74]. Not only do they provide diversity of crops in time and space, but also they can protect soil from erosion and provide litter for organic material and soil nutrients [75], reducing the need for synthetic fertilizer.

Evidence is emerging that agroforestry systems have great potential for increasing both above- and below-ground C stocks, reducing soil erosion and degradation, and mitigating GHG emissions [76]. In agroforestry systems, the standing stock of the C aboveground is usually higher than the equivalent land use without trees [4]. For example, establishing coffee agroforestry systems maintains 22 times more C stored in aboveground living biomass when compared with traditional maize over a period of 7 years [77]. For smallholder agroforestry in the tropics, potential C sequestration rates range from 1.5 to 3.5 Mg C/ha/yr [72]. Furthermore, in degraded soils in the sub-humid tropics, improved fallow agroforestry practices have been found to increase topsoil C stocks up to 1.6 Mg C/ha/yr above continuous maize cropping. Agroforestry systems with perennial crops, such as coffee and cacao, may be more important C sinks than those that combine trees with annual crops [72].

The potential of agroforestry to curb GHG emissions is not limited to C sequestration. A review of agroforestry practices in the humid tropics shows that the systems were able to mitigate N_2O and CO_2 emissions from the soils and increase the CH_4 sink strength compared with annual cropping systems (Table 3; [76, 78]). In a study of the Peruvian Amazon, a tree-based agroforestry system emitted less than a third of the N_2O of a high (fertilizer) input annual cropping system and half that of the low-input cropping system [79]. Data from several countries strongly suggest that agroforestry systems can partially offset CH_4 emissions, while conventional high-input (industrial) systems exacerbate CH_4 emissions (Table 3). Such strategies of reduced tillage and increased diversity in space and time can have significant effects on GHG emissions coming from the system.

Mitigation of GHGs from Livestock and Manure Management in Agro-ecological Systems

The world's huge livestock population and the inherently high levels of GHG emissions produced by them provide opportunities to influence climate change. Although market forces favour intensification of livestock production [80], the use of agro-ecological methods, along with stocking limitations, may reduce emissions of GHGs and provide richer returns for livelihood and sustainability, while deforestation, feed-crop dependence and land degradation are avoided (Figure 1). Mitigation methods include fewer livestock, conservation tillage, organic farming, crop rotation, cover crops and green manures, reduced compaction and water management to irrigate in ways that prevent erosion and avoid NO_3^- leaching [60, 81].

The world's soils have lost over 42 Gt of C in the past 250 years, but they retain the capacity to recover up to 66% of the amount lost [70]. Rotational grazing that keeps livestock numbers within limits for the healthy growth of grasses and forbs is the primary tool for sustainable agro-ecological livestock production [82]. Well-managed pastures can reduce CH_4 and N_2O contributions and can sequester C when manure is cycled into the soil by arthropods and micro-organisms [83]. For example, pastures on fields thick with grass and leguminous forbs sequester significant amounts of C and N with reduced loss to the atmosphere, and utilizes natural biodiversity to build rich soils.

The full accounting of GHG emissions from the livestock production system must be taken into account to understand which system has a greater capacity to store C. For example, conventional pig production in Denmark had 7–22% lower direct GHG production than organic (free-range) pigs, but grass and clover in the free range system permitted net soil C sequestration [84]. When estimated C sequestration was included in the life-cycle analysis, the free-range systems had lower GHG emissions. On the other hand, yield tradeoffs could offset the reduced emissions of free-range or less intensive animal production [85].

Reduction of synthetically fertilized feeds also effectively reduces GHG pollution [86]. As much as 18 million tonnes of CO_2 per year are emitted in the cultivation of 1.8 million km^2 of maize, soybean and wheat for livestock feed [87], and the problem is rapidly growing. A change to non-fertilized feed stock will therefore have a large impact on overall GHG emissions. The implementation of methods designed to restore degraded soils could potentially sequester 0.3 to over 1 tonne of C/ha/yr [39, 41]. Introducing grass species with higher productivity or C allocation to deeper roots has been shown to increase soil C in savannahs [88]. Introducing legumes in grazing lands and a mixed crop system can also promote soil C storage [89], potentially also reducing N_2O emissions. Slowing degradation and impeding desertification with such alternative grassland management techniques could conserve up to 0.5–1.5 Pg C annually in savannahs [90].

When forested areas are cleared for grazing, C is lost above- and belowground as enormous quantities of organic C bound in plant biomass and SOM are liberated and respired back to the atmosphere as CO_2 [90–92]. Clearing and burning forests for grazing or cropland may release over a billion tonnes of CO_2 per year [1], with 50% of soil C lost in the first decade following forest clearing [93]. In total, livestock production may be responsible for 2.7 billion tonnes of CO_2 emissions per year [41, 94].

On the other hand, throughout the tropics an alternative form of pasture management has been common and is still found in many areas of the tropics: the silvopastoral agroforestry system (the incorporation of trees into pasture systems [95, 96]). From the point of view of C storage it is evident that putting roots deeper into the ground represents a potentially large pool for storage. Indeed, the extensive research showing that deforestation results in C release into the atmosphere simply represents the inverse of what would be expected from the addition of trees to pasture systems. Some recent research has examined this issue directly (e.g. [72, 97]), but certainly further research is required before a convincing quantitative estimate can be proffered. Nevertheless, the fundamental structure of the system strongly implies the potential for an enormous amount of C storage, provided substantial area of pasture could be converted to silvopastoral systems.

In addition to their C storage potential, the addition of trees to pastures may very well increase N cycling [97], thus potentially enhancing the breakdown of manure. Especially in comparison with modern concentrated animal operations, the potential to mitigate the production of CH_4 and N_2O could be large. This aspect of GHG mitigation is complicated and not well understood; involving a large battery of questions associated with soil structure, soil microbiology and N dynamics. However, since most CH_4 and N_2O emissions emerge from anoxic pockets (or the general matrix of slurry so common in CAFOs), aerating the soil with deeper root material should be expected to reduce the emissions of these two GHGs.

Mitigation Potential in Small Scale, Locally Based Food Systems

Transportation accounts for a small but significant amount of GHG emissions that can be attributed primarily to agricultural processes used in industrial agriculture systems. Evidence suggests that a conversion to locally based distribution of products and sourcing of inputs could have a significant impact on reducing global C emissions. The calculation of GHG emissions is a complicated process that has to take into account not only transportation in the industrial system but also transportation in a locally based system that might replace it. Just how much saving would accrue in a transformation from the industrial to an agro-ecological locally based food system is not clear, as we know of no studies that have compared transport emissions from smallholder farming to industrial farming, although it is highly likely that GHG reduction would occur through the consequent change in transportation activities.

For example, it has been convincingly shown that a simple shift to purchasing food that was locally produced may by itself do little to reduce GHG emissions [49, 98], with significant amounts of emissions coming from production, processing and packaging rather than transportation *per se* [99]. Further, local production would not necessarily address the substantial portion of transportation-related emissions generated by consumers' trips to the store [47], and it is worth noting that the possible emissions reductions in local production when the inputs (e.g. fertilizers and pesticides) are sourced locally seem to show limited evidence of local socio-economic benefits [100, 101].

Rather than concluding from this that small-scale local systems have little to offer, the implication of these studies (especially from [47]) is that localized production without alteration of any other of the pertinent institutions and structures will be vastly insufficient. Food policy councils, which range from formal bodies with decision-making power to less formal advisory groups at local, regional and national levels have shown significant successes in addressing fundamental structural problems that might block alternative or comprehensive solutions involving higher-level structural change beyond simple changes in the production origin of foodstuffs (e.g. [102, 103]). For example, changing the available transportation options, locating affordable local food stands at major pedestrian thoroughfares, creating centralizing infrastructure for small producers and retailers to take advantage of economies of scale while remaining local or even simple ideas such as altering the configuration of farm plots relative to each other can all fundamentally affect the feasibility of alternatives [47, 104–107]. In such cases, the difficulty in realizing GHG emission reductions may be associated with socio-political concerns rather than the technical viability of reducing emissions in a locally based system [9]. For example, Pretty *et al.* [47] note the potential environmental savings from increased use of shipping by rail, consumer transportation by bus, bike or foot and other structural changes that would require substantial social (and likely economic) investment, but that may yield substantial long-term social, economic and environmental gains. The possibilities in this area have been, as far as we are aware, little explored, with the current infrastructure and institutional arrangements often taken as fixed. Given, however, that the current arrangements have generated the very problem that we are seeking to address – global climate change – assuming little or no institutional or infrastructural change, in all practicality, precludes the possibility of creating viable solutions.

As has been observed by many (e.g. [102, 108]), there are few if any 'one size fits all' approaches. But effective common-property governance often originates from strong local institutions [109]; small-scale local systems premised on 'food sovereignty' (the right of local people to control their own food systems, including their own markets, resources, food cultures and production models) offer the potential to take advantage of local governance structures to generate socially and ecologically sustainable (i.e. lower GHG-emitting) systems [101, 105, 110, 111].

Challenges to the Adoption of Agro-ecological Management

Adoption of the small-scale agro-ecological systems analysed here faces a number of practical difficulties, as we have described. Fundamentally, institutional and political shifts will have to occur [14, 112, 113]. The requirements for and nature of such changes will vary significantly from place to place, making exact delineation of the challenges facing widespread adoption of agro-ecological practices difficult. But some challenges transcend the institutional particulars of various places and agro-ecological practices in general.

Increasing Patterns of Consolidation and Expansion of Intensive Large-Scale Monocultures

The result of agricultural policies and historically low commodity prices in the USA and other developed countries has led to an increase in farm size, as small-scale farmers are not able to generate enough income to maintain their farms. Furthermore, as land appropriate for agro-industrial commodities becomes scarce in the USA, Western Europe, China and many other countries, agribusinesses are looking to expand in regions with large agricultural frontiers. Latin America, Africa and South and Southeast Asia have experienced exponential increases in deforestation at the expense of cropland expansion since 1950 [1]. The heavy promotion of industrial monoculture plantations and agrofuels as solutions to the current food and energy crises increase the pressure on agricultural land, leading to more deforestation [114] and more GHG emissions [1]. Emissions associated with land use changes averaged over the 1990s are estimated to be 0.5–2.7 Gt C/yr [1]. Converting tropical rainforests into industrial farming systems, which is happening in many tropical regions of the world, has a threefold impact on the CH_4 budget, with the elimination of a CH_4 sink from deforestation, the emission of CH_4 from biomass burning and the emissions of CH_4 from fertilizer-based industrial agriculture, all of which significantly increase the CH_4 emissions from the landscape [1].

Tropical savannahs have been heavily impacted by human activity, with large extensions of land converted from tree–grass mixtures to open pastures and agriculture [115]. For example, the Brazilian *cerrado*, one of the world's biodiversity hotspots [116], is one of the most threatened savannah systems in the world. More than 50% of its original 2 million km^2 has already been transformed into pasture and agricultural lands for cash crops, mainly industrial soybean production [117]. The transformation of the *cerrado* to large-scale soybean plantations has a strong impact on GHG emissions. When this ecosystem or other savannahs are transformed to pastures or annual agriculture, the C stocks are altered, with the degree of the alteration depending on the extent of the modification. In Mato Grosso, the Brazilian state with the highest deforestation rate, 17% of total deforestation during 2001–2004 resulted from direct conversion of forest to large-scale mechanized cropland, primarily soybean [118]. Tropical forest conversion to soybean for biodiesel is estimated to release greater than 280 Mg CO_2/ha and will require 320 years to capture it back into the ecosystem [119].

As soybean producers buy up land from ranchers in the south of Brazil, many of the newly capitalized ranchers move to the north and into the Amazon where land prices are lower and they can expand their herds, extending the agricultural frontier [120]. The advancement of industrial-scale monocultures and extensive cattle ranching for the increasing global meat demands are increasing deforestation in one of the largest C stocks in the world (estimated to represent 38% of the total C stock in the tropics [121]). Large-scale cattle ranching continues to be the pre-eminent force behind deforestation in the Brazilian Amazonia with large- and medium-sized ranches accounting for about 70% of clearing activity [122].

It has been argued that agricultural intensification can mitigate GHG emissions in a cost-effective way by increasing yields and therefore sparing land that would otherwise be put into production in order to produce enough food to feed the growing world population [123]. However, this argument ignores empirical evidence that agricultural intensification in developing countries often leads to more deforestation, not less [114, 124, 125], and that agro-ecological systems can match yields of conventional agriculture in developed countries and significantly increase yields in developing countries [126, 127]. This land-sparing argument can only work if industrial agriculture is the only way to achieve high productivity and if it does not result in increased deforestation. But as noted above, empirical evidence suggests that neither of these conditions is satisfied. The negative relationship between farm size and total production output further suggests that rather than large industrial monocultures, what is needed to increase food production are many small-scale efficient farms. This well-known relationship is known as the 'inverse size–productivity relationship,' first described by Amartya Sen [128, 129] for Indian farms, and further confirmed and explained by other authors [130–133]. Since large farms tend to be less productive, large-scale industrial agriculture programmes often lead to more deforestation and agro-ecological methods can greatly increase total production output, it follows that there is no necessary trade-off between GHG mitigation through small-scale-agro-ecological agriculture and food production.

Institutional Incentives and Barriers

In developing countries, in spite of the expansion of large-scale industrial agriculture, there are still millions of small-scale farmers who can implement agro-ecological practices with potentially significant impacts in GHG mitigation. In developed countries, significant changes in agricultural policies will be required to reverse the land consolidation trend. Although the consolidation trend continues in developed countries a variety of factors are contributing to a new trend in small-scale agro-ecological farms. Such factors include the rising demands for organic and local products, an increase in farmer market development and a growing popularity of community-supported agriculture programmes [134]. However, there still exists a variety of institutional barriers to increasing the growth of small-scale agro-ecological management.

One challenge to the increased adoption of agro-ecological management at the farmer level is the loss of appropriate knowledge and skills within the farming system [135, 136]. Small-scale agro-ecological production is 'knowledge-intensive': fertility, pest control and other agricultural services are generated and maintained by local, traditional (but often still evolving) and indigenous practices, aided in recent decades by significant amounts of academic agro-ecological research [14, 113, 137]. Industrial agriculture, generally speaking, appropriates agricultural knowledge and skill, centralizes it in multinational establishments and research institutes, putting it further out of reach via restrictions on intellectual property – all of which may result in a disruption of the ongoing processes of farmer learning (deskilling) [138–140]. A return to knowledge dissemination through extension will be required to re-learn how to implement many of the agro-ecological management options into modern farm practices [141].

Further complicating the picture is the socio-cultural momentum behind industrial methods, the characteristics of which can sometimes 'lock out' and divert resources from studying and implementing agro-ecological methods [14, 142–144]. In the USA, the economic incentives to intensify production in monoculture systems outweigh the incentives to diversify agriculture systems and increase agro-ecosystems management. Between 1995 and 2002, 89% of the $91.2 billion given out in commodity payments went to five select crops (maize, wheat, soybean, cotton and rice) in order to boost the income of crop and livestock farmers. Soybean and maize alone received 56% of those dollars [145]. The commodity payment system encourages the monocropping of these few crops over large tracts of landscape in order for farmers to receive a greater amount in subsidies. However, with fewer species planted in space and time, there are significant losses of ecosystem services and functions [2, 146]. Additionally, some industrial agricultural systems have been subjected to planned obsolescence where farmers are required to buy new versions of seeds, which formerly represented a self-replicating good [147]. This represents yet another version of the various treadmills created by the industrial system that are difficult for farmers to get off of once they are entrenched in the system [139, 142, 148].

Another commonly perceived challenge for the adoption of agro-ecological methods is the acknowledged possibility of decreased yields (e.g. [60, 126]), especially as it may affect the global food supply. It is widely concluded that yields in the Global North (Developed Countries) would decrease somewhat under agro-ecological methods (Badgley *et al.* [126] review of 160 cases averaged an 8% decrease across ten FAO food categories). However, the weight of recent evidence reinforces Badgley *et al.* findings that the Global South (Developing Countries) would have significant average increases in yield, on the order of 80–100% increases by moving toward agro-ecological practices [149–152]. Although yield may decrease under agro-ecological methods in some cases, it is nonetheless the case that malnutrition (presently, and in many projections of the future) is primarily tied to poverty and not lack of regional or global food supply, and that the most important factor in decreasing malnutrition has repeatedly been found to be women's education and political rights [112, 152, 153].

Because farmers require economic benefits to be willing and able to adopt new practices, economic models that are able to predict threshold prices at which farmers begin to adopt environmental land use practices or payments for ecosystem services can be highly effective in encouraging farmer adoption of agro-ecosystems management options. In one model on the potential of farmers to participate in C sequestration contracts and increase sequestration potential through agroforestry and terracing of fields, the analysis showed that at prices above US $50 per MgC, adoption would increase substantially, and at prices of US $100 per MgC, terrace and agroforestry adoption for C sequestration would have the potential to raise per capita incomes by up to 15% [154]. Incentives that can increase economic productivity of farms by selling ecosystem services, such as C sequestration, have the potential for increasing the adoption of agro-ecological management options such as agroforestry [154].

One payment mechanism that has potential to combat global warming, fund forest conservation and deliver economic benefits to rural populations while promoting C sequestration is the UN Reducing Emissions from Deforestation and Forest Degradation (REDD) Program, part of the Clean Development Mechanism (CDM) included in the Kyoto Protocol. The programme allows for governments and groups to access C payments for the sequestration potential achieved on their lands, and small-scale sinks projects were included into the Kyoto Protocol to assure that low-income communities could benefit from potential projects. Thus, the CDM small-scale sinks programme can help improve the livelihood conditions in developing countries through a market mechanism aimed at mitigating climate change through the sustainable use of natural resources. It has been estimated that cutting global deforestation rates 10% could generate up to US$13.5 billion in C credits under the REDD initiative [155].

However, there has been growing concern regarding issues of equity and sustainable development because projects take place in rural areas where the majority of poor people are concentrated and where conflicts over land and resources are complex [156]. Many environmental groups resisted the inclusion of sinks in the CDM on the grounds that the benefactors of the CDM payments would most-likely be large-scale industries establishing monoculture plantations rather than the indigenous communities traditionally managing the local forests. Additionally, there is a fear that the payment scheme would spur encroachment onto indigenous lands, further marginalizing and displacing local and indigenous populations [157, 158].

Governance issues relating to the rights and ownerships of trees and land will be increasingly important as the C market becomes a potential source of income for local and indigenous populations [159], and the FAO [160] has warned that poor land users are not likely to become the beneficiaries of payments for C sequestration credits without proper institutions and capacity to provide information support. However, several studies have pointed to the options of multi-species community-based reforestation or agroforestry as more likely systems to deliver benefits to marginal populations, as they can be attractive to emerging socially and environmentally responsible markets [161, 162], and transfer of ownership of larger forest common patches over to local communities can lead to better management of forest resources, thereby increasing C storage [163]. Increased agroforestry cover in sustainable perennial systems may be one way that farmers can take advantage of the C markets as a means to increase the economic benefits of maintaining systems with high levels of structurally complex agriculture.

Conclusions

Long-term sustainability of agro-ecosystems and the ecosystem services they generate depend on the conservation of biodiversity at both the farm and the landscape level. Current industrial agricultural systems reduce diversity at the farm level and create structurally simplified landscapes that may contribute significantly to GHG emissions and global warming. On the other hand, small-scale agro-ecological farms, by maintaining diversity at the farm and landscape levels, by conserving soils and by reducing the inputs of pesticides, fertilizers and fossil fuels, contribute to the maintenance of ecosystem processes and services, including the mitigation of GHG emissions.

Environmental services should be considered in all policy initiatives related to the goals of sustainable agriculture. Sequestration of C and N are goals compatible with soil and water management as well as the protection of biodiversity. The world's efforts to reduce emission of global GHGs cannot afford to continue with industrial agricultural 'business as usual', but must support incentives that increase the adoption of small-scale agro-ecological techniques that mitigate atmospheric GHGs. Supporting small-scale family farmers on secure land, and helping them maintain agro-ecological farming on lands that could be taken over by industrial agricultural systems, while protecting forests from giant clear-cutting projects, and abolishing factory livestock feeding operations will contribute to climate change mitigation as well as food sovereignty.

Furthermore, many of the agricultural practices that mitigate GHG emissions, such as soil conservation measures, reduce reliance on inorganic fertilizers and pesticides; and diversification of the farms also increase the resilience of agricultural systems, which, even under the most optimistic future scenarios, will be needed for adaptation to climate change. This synergy between climate-change mitigation and adaptation represents a great opportunity for developing win–win strategies in the agricultural sector. We conclude that agro-ecological systems provide management options to reduce the contributions of GHG emissions from the agricultural sector and provide for management techniques that promote increased C sequestration and mitigate emissions from the system. A more concerted effort to understand the range of agro-ecological techniques that could be used to mitigate GHG emissions in the various regions of the world will increase the ability to implement sustainable agro-ecological farm systems at local and regional scales.

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