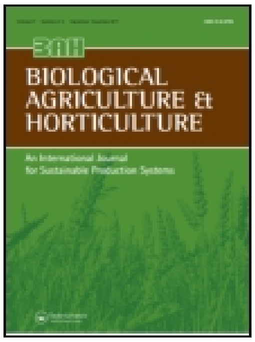

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Greater Mitigation of Climate Change by Organic than Conventional Agriculture: A Review

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ABSTRACT

Organic agriculture is an alternative production system that avoids the use of synthetic pesticides and fertilizers, and relies on biological pest control and on crop rotation, green manure and composts to maintain soil fertility. Although many comparisons have been made between organic and conventional agriculture in terms of crop yields, economic returns and other factors, only a few studies have compared their effects on mitigating climate change. The present review compares the effectiveness of organic and conventional agriculture in mitigating climate change. The review reveals that organic agriculture has a greater potential for mitigating climate change, largely due to its greater ability in reducing emissions of greenhouse gases (GHGs) including carbon dioxide, nitrous oxide (N_2O) and methane (CH_4). It also increases carbon sequestration in soils compared with that of conventional agriculture. In addition, many farming practices commonly adopted in organic agriculture such as rotation with leguminous crops, minimum or no tillage, and the return of crop residues favour the reduction of GHGs and the enhancement of soil carbon sequestration. The certification of farming practices as required in organic agriculture provides a transparent guarantee of organic principles and standards. This also allows the enforced adoption of new and effective practices aimed at improving the mitigation of climate change. Furthermore, organic agriculture is highly adaptable to climate change compared with conventional agriculture. However, greater recognition of the potential of organic agriculture for mitigating climate change is needed. At present, this recognition depends on the ability of organic yields to out-perform conventional yields, which has been shown to occur in developing countries. More research is needed to improve organic yields in developed countries and to improve the potential of mitigating climate change by organic agriculture. Future strategies for improving the effectiveness of organic agriculture in mitigating climate change are presented and discussed.

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REVIEW

Introduction

Organic agriculture is an alternative production system that relies on biological pest control and on crop rotation, green manure and composts to maintain soil fertility, and excludes the use of synthetic pesticides and fertilizers (IFOAM, 1998; USDA, 2007). In recent years, many comparisons have been made between organic and conventional agriculture in terms of crop yields, economic returns and other factors (e.g. Lampkin, 1990; Pimentel *et al.*, 2005; Akinyemi, 2007; Connor, 2007). Only a few studies compared their effects on mitigating climate change (Stolze *et al.*, 2000; Kotschi & Müller-Sämann, 2004; Pimentel, 2006; IFOAM, 2008). The present study reviews the relative effectiveness of organic and conventional agriculture in mitigating climate change.

According to the Intergovernmental Panel on Climate Change (IPCC, 2007) global warming causing climate change is due to anthropogenic GHGs, which include CO_2, CH_4, N_2O, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. Agriculture is the main contributor to CH_4 and N_2O emissions, and also, to a lesser extent to CO_2 emissions.

Carbon dioxide accounts for about 50% of the warming effect of all climate-impact-gases (IPCC, 2001). Concentrations of GHGs in the atmosphere have increased by about 30% over the last two centuries. Emissions of GHGs increased on average by 3.1% per annum between 2000 and 2006, compared with 1.1% per annum in the previous decade. It is predicted to continue to increase rapidly due to economic growth and lack of effective mitigation strategies (Garnaut Climate Change Review, 2008). The average global temperature has risen 0.8°C in the past century and 0.6°C in the past three decades (Hansen *et al.*, 2006), largely due to human-induced activities. If no action is taken to reduce GHG emissions, an increase in global warming of 1.4 to 5.8°C over the 1990 level is projected to occur by 2100 and sea level rises by 90 to 880 mm (IPCC, 2001). Glaciers will continue to retreat, permafrost and sea ice are expected, especially in the Arctic and Antarctic regions. The amount and patterns of precipitation will change, causing extreme weather events including droughts and floods, and changes in agricultural yields, loss of biodiversity and species extinctions.

Food security, agricultural productivity, and climate change are related because climate directly affects the ability of a country to feed its people. On a global scale, in order to increase food production to meet the need of the ever increasing world population, climate change is the most serious long-term challenge facing the world today. The solution of climate change caused by agriculture lies in selecting the best form of agriculture and farming practices aimed at cost-effective production with minimum adverse effects on the environment and climate.

Relationships between agriculture and climate

Agriculture and climate are inextricably linked. Agriculture is both a victim and a cause of climate change. Agricultural production relies fundamentally on the weather. Increasing severe weather patterns such as droughts, floods, desertification and disruption of the growing seasons in many parts of the world have resulted in negative impact on agricultural production. This negative impact is region-specific and is more severe in developing regions such as Africa, Latin America and India, which are already facing food security problems, than in developed countries (William, 2007). According to the Food and Agriculture Organisation (FAO, 2008), an increase of 2–4°C in the average global temperature above the pre-industrial levels could reduce crop yields by 15-35% in Africa and western Asia, and by 25–35% in the Middle East. The impact has also adversely affected the ecosystems and biodiversity (WWF, 2006).

Agriculture practices exacerbate climate change. Agriculture is a major contributor to the emissions of CH_4, CO_2 and N_2O. A considerable amount of CO_2 has been released to the atmosphere from the combustion of fossil fuels, agricultural and forestry activities, deforestation, and other land use changes (Lal *et al.*, 1997, Goh, 2004). Rice production in flooded paddy fields, lagoon storage of farmyard manure, and ruminant digestion of pasture herbage result in the production of CH_4 while N_2O originates from the microbial transformation of nitrogen (N) from fertilizers, manure and soil organic matter. Per unit mass of gas, CH_4 and N_2O cause considerably greater global warming potential (GWP) (21 and 310 times, respectively) than CO_2.

According to IPCC (IPCC, 2004) agriculture contributes 13.5% of GHG emissions. When direct and indirect (land use, transportation, packaging and processing) sources are included, the contribution could be as high as 32% (Greenpeace, 2008). Greenpeace (2008) reported that the largest sources of total non-CO_2 emissions in 2005 were from soil N_2O (32%) and CH_4 (27%) from enteric fermentation of cattle. Emissions of N_2O arose from N fertilizers and manure applied to soils and during manure storage. The livestock sector in agriculture has been identified as a major contributor to global GHG emissions. The FAO (FAO, 2006) report on the 'livestock's long shadow' indicated that 18% of global GHG emissions were from livestock, including one third of this from deforestation. This exceeded that from global transport.

The total annual amount of GHGs emitted by the agricultural sector in 2005 was estimated to be between 5.1 and 6.1 Gt. CO_2 equivalents (CO_2-eq) (Barker *et al.*, 2007). This estimate showed that CH_4, N_2O and CO_2 accounted for 3.3, 2.8 and 0.04 Gt CO_2-eq, respectively. According to current projections, total GHG emissions are expected to reach 8.3 Gt CO_2-eq per year in 2030 (Smith *et al.*, 2007). However, agriculture also has a significant mitigation potential for climate change (Greenpeace, 2008), and could be improved from being the second largest global GHG emitter to a much less important emitter or even a net sink for GHGs. Thus, the solution to present-day climate change problems caused by agriculture lies in changing the farming practices of agriculture.

The potential of organic agriculture in mitigating climate change

There is considerable world-wide support at present in advocating organic agriculture for mitigating climate change (e.g. Kotschi & Müller-Sämann, 2004; ITC, 2007; IFOAM, 2008; Ellis, 2008; Smith, 2009). The potential of organic agriculture in mitigating climate change depends on its ability to reduce emissions of GHGs, nitrous oxide, and methane, increase soil carbon sequestration, and enhance effects of organic farming practices which favour the above two processes.

Reduction of greenhouse gas emissions

Recent experimental results suggest that organic agriculture can significantly reduced GHG emissions. For example, two long-term experiments in Switzerland showed that the GWP of all organic crops was reduced by 18% (Mäder *et al.*, 2002; Nemecek *et al.*, 2005). This was also reported in some Dutch dairy farms and some vegetable crops (ITC, 2007). In general, the GWP of organic farms is considerably smaller that that of conventional or integrated systems based on per land area. The difference declines when calculated on a per product basis due to higher conventional yields (Badgley *et al.*, 2007). This also occurs when the net carbon stock changes, i.e. gains and losses of carbon, are considered (Robertson *et al.*, 2000; Küstermann *et al.*, 2007). As both N_2O and CH_4 are more potent than CO_2, their emissions will have considerable impact on global warming than CO_2. Thus, these gases should be included in assessing the effects of any farming practice on global warming by using carbon footprint measurements. Recently, Hillier *et al.* (2009) reported that organic farms showed a significantly lower carbon footprint than conventional and integrated farms, due to N fertilizer use on the latter two.

Reduction of nitrous oxide emissions

Nitrous oxide emissions are directly linked to the concentration of available mineral N (ammonium and nitrate) in soils arising from the nitrification and denitrification of available soil and added fertilizer N (Alexander, 1977; Firestone & Davidson, 1989; Wrage & Velthop, 2001). High emissions rates are detected directly after mineral fertilizer additions and are very variable

(Bouwman, 1995). The banning of mineral N fertilizer use and the reduced livestock units per hectare in organic farms are expected to reduce the concentration of easily available mineral N in soils resulting in decreased N_2O emissions. In addition, organically managed soils are better aerated due to the improved soil organic matter levels resulting in better soil structure and physical conditions than that of conventionally managed soils. This leads to less denitrification occurring in organically managed soils causing the release of N_2O.

Zeddies (2002) found that farms in southern Germany gave 50% lower N_2O emissions without mineral N fertilizer inputs and also with minimum inputs of animal feed from outside the farm. Petersen *et al.* (2005) reported lower N_2O emissions from organic than conventional farms in five European countries while Flessa *et al.* (2002) reported decreased N_2O emission rates in organic farms only when yield-related emissions were not considered. Earlier studies found either no difference or slightly higher N_2O emissions in the organic variant (Stolze *et al.*, 2000; Kotschi & Müller-Sämann, 2004).

According to Olesen *et al.* (2006), GHG emissions at the farm level may be related to the farm's N surplus or its N efficiency. Since organic cropping systems are limited by N availability with the aim of balancing N inputs and outputs and N efficiency, GHG emissions in organic farms are lower than those of the conventional farms.

Reduction of methane emissions

The reduction or avoidance of CH_4 emissions is of special importance in global warming from the agricultural sector because two thirds of global CH_4 emissions are of anthropogenic origin, mainly from enteric ruminant fermentation in animals (FAO, 2006) and in paddy rice production (Smith & Conan, 2004). In general, the CH_4 emissions from ruminants and rice production are not significantly different between organic and conventional agriculture. Differences are due largely to the extent and intensity of various farming practices and their improvement used within different forms of agriculture.

For example, the amount of CH_4 emitted by animals is directly related to the number of animals (IPCC, 2007), the type of animals, manure management, and diet fed to animals. Intensive conventional farms with higher animal number than less intensive organic farms will have higher emissions although the emissions per unit of product, e.g. meat and milk, might be lower (IPCC, 2007). Chicken and pigs produce much less GHG emissions than dairy cattle and sheep (US-EPA, 1998). Pigs produce the largest amount of manure followed by dairy (Steinfeld *et al.*, 2006). However, if pig manure is used for biogas production to replace fossil fuels, the net effect on GHG emissions could be significantly less.

Methane is released when manure is stored in liquid forms in lagoon or holding tanks, or stored wet as a collection method to handle the large quantity of manure produced in intensive livestock systems (Reid *et al.*, 2004). However, the CH_4 released from the stored manure can be reduced by cooling, use of solid covers, mechanically separating solids from slurry or capturing the CH_4 released (Clemens & Ahlgrimm, 2001; Paustian *et al.*, 2004; Amon *et al.*, 2006; Monteny *et al.*, 2006). Storing manure in solid form such as composting can suppress CH_4 emissions but may result in more N_2O emissions (Paustian *et al.*, 2004).

Efficient and direct recycling of manure and slurry is the best option to reduce GHG emissions as this practice avoids long-distance transport (ITC, 2007). In organic farming systems, cropping depends on nutrient supply from livestock and the combination of cropping and livestock provides an efficient means of mitigating GHG emissions especially CH_4. High energy products fed to animals produce manure with more volatile solids emitting more CH_4 (Greenpeace, 2008). However, CH_4 emissions per kg-feed intake and per kg-product are invariably reduced by feeding more concentrates and replacing forages (Blaxter & Claperton, 1965; Lovett *et al.*, 2003; Beauchemin & McGinn, 2005).

Kotschi & Müller-Sämann (2004) reported that animal longevity is greater in organic cattle farms and this contributed to a reduction in CH_4 emissions. However, milk yields were lower in organic cows due to higher roughage in the diet and this might increase CH_4 emissions per unit milk yield

Although research on CH_4 emissions in organic and conventional paddy rice production is still in its infancy, employing better rice production techniques such as using low CH_4-emitting varieties (Yagi *et al.*, 1997; Aulakh *et al.*, 2001), composted manures with low C/N ratio (Singh *et al.*, 2003), adjusting the timing of organic residue additions (Xu *et al.*, 2000; Cai & Xu, 2004) and using mid-season drainage or avoiding continuous flooding have been shown to reduce CH_4 emissions (Smith & Conan, 2004). However, Akiyama *et al.* (2005) reported that the benefit of draining wetland rice may be offset by increased N_2O emissions.

Increases in soil carbon sequestration

Soil carbon sequestration refers to the storage of carbon in the terrestrial soil in the medium to long term (15 to 50 years) (Goh, 2004). Mechanisms of soil carbon sequestration have been presented by Goh (2004). Soils contain about 1500 Gt of organic carbon (Batjes, 1996) which is about three times that in the vegetation and twice that in the atmosphere (Schlesinger, 1995; IPCC, 2000). Thus a small change per unit area in the soil carbon pool can have important implications in the global carbon balance and climate change.

Organic farming practices such as the use of green manure, animal manure, composts and rotation with intercropping and cover crops enhance soil carbon sequestration and reduce soil carbon losses by soil erosion in addition to increasing soil fertility and physical conditions for plant growth (Reganold *et al.*, 1987; Goh, 2004). Although soil carbon sequestration varies considerably, results from long-term farm comparison and field trials showed that organically managed soil have higher soil organic matter content than those of conventional systems (Table 1, ITC, 2007).

Many long-term field trials have also shown that regular additions of organic materials maintained or increased soil organic carbon and soil productivity (e.g. Powlson *et al.*, 1998, Nyamangara *et al.*, 2001). For example, results of long-term trials comparing organic and standard conventional cropping systems in the United States showed that organic amendments and cover crops resulted in greater accumulation of soil organic carbon than either N fertilizer or conventional practices (LaSalle *et al.*, 2008; Sainju *et al.*, 2008). The Long-term Rodale Institute Farming Systems Trial showed that composting enhances soil carbon accumulation. Other trials also reported that compost recycled

TABLE 1

Carbon sequestration rates in organic farms[a]

Trial	Variant	Result
DOK trial, Switzerland, data for 1978–1998 ((Fließbach *et al.*, 2007)	Biodynamic with composted farmyard manure	Level of soil organic matter remains stable
	Conventional stockless (mineral fertilizer only)	Decrease in soil organic matter: 191 kg ha^{-1} compared to the biodynamic variant (= −13%)
Bavarian farms, Germany (Küstermann, *et al.*, 2007)		Sequestration rates of 110–396 kg ha^{-1} $year^{-1}$
		Lost 249 and 55 kg C in fields managed with integrated pest control
Rodale experiments (Pimentel *et al.*, 2005)	Manure-based organic system	Soil C increase 981 kg ha^{-1} $year^{-1}$
	Legume-based system	Soil C increase 574 kg ha^{-1} $year^{-1}$
United States farming trials (Marriott and Wander, 2006)		14% higher soil organic C in organic than in conventional systems

[a]Source: ITC (2007).

nutrients to plants (Poudel *et al.*, 2002; Pimentel *et al.*, 2005; Miller *et al.*, 2008). Recently, Nayak *et al.* (2009) reported that long-term applications of compost invariability led to increases in soil organic carbon, even when it was applied once a year.

Under permanent organic cropping systems, higher organic carbon accumulation was obtained from the addition of organic manures, plant residues, mixed cropping, legume-based pastures in crop rotation or agroforestry (Drinkwater *et al.*, 1998; Kumar & Goh, 2000; Goh, 2001; 2002). On the other hand, the use of mineral fertilizers in conventional agriculture contributes to increasing oxidation of soil organic matter and thus increased soil carbon losses (Bellamy *et al.*, 2005; Khan *et al.*, 2007; Lal, 2009; Schipper *et al.*, 2009). Bellamy *et al.* (2005) reported 92% of soil carbon losses in 6000 soil samples in Wales and England between 1978 and 2003. Annual CO_2 emissions from intensively cropped soils could be as much as 8% of national industrial CO_2 emissions (Bellamy *et al.*, 2005).

Effects of organic farming practices on reducing greenhouse gas emissions, and enhancing soil carbon sequestration

Effects of major organic farming practices which reduce GHG emissions and enhance soil carbon sequestration are related to the following: (1) less fossil fuel consumption and energy inputs, (2) using organic biomass as a substitute for fossil fuel, (3) enhancement of soil carbon sequestration in organic farms compared with conventional no-till or minimum tillage cropping systems, (4) less carbon losses due to soil erosion, and (5) enforcing certification and monitoring of organic farming practices.

Reduction of fossil fuel consumption and energy inputs

Both conventional and organic agriculture relies on solar and fossil fuel energy for food production. The use of fossil fuels in agriculture produces globally the second major source of GHG emissions and thus any reduction in fossil fuel use mitigates climate change. According to Pimentel (2006) the conversion to organic farming systems can reduce the dependence of farmers on energy and increase the efficiency of energy use per unit of production. Results from Rodale Institute Farming Systems Trials (21 years, 1981 to 2002) showed that fossil fuel energy inputs for organic corn production were about 30% lower than that for conventionally produced corn (Pimentel *et al.*, 2005; Pimentel, 2006). Topp *et al.* (2007) reported that the energy inputs per unit area required for organic grown crops are typically 50% of those in conventional crops due to the lower or no fertilizer and pesticide input in organic agriculture, although this is partially offset by mechanical cultivation in organic farms.

Leake (2000) showed that three times more machine energy was required to produce an organic than a conventional crop. However, when the external energy inputs of fertilizer and pesticide production were taken into account, organic farming systems required only half the energy input of the conventional system (Topp *et al.*, 2007). Using data from a long-term silage experiment in Scotland, Topp *et al.* (2007) showed that in spite of comparable outputs of energy in the biomass of conventional and organic systems, higher output/input energy ratio was obtained for organic than for conventional systems (Table 2).

TABLE 2

A comparison of energy use in the production of silage from a conventionally managed grass ley and one under organic management[a].

	Conventional		Organic	
	Nutrient input/ grass yield (kg ha^{-1})	Energy (MJ ha^{-1})	Nutrient input/ grass yield (kg ha^{-1})	Energy (MJ ha^{-1})
Nitrogen	125	7692	168	none
Phosphorus	40	469	35	none
Potassium	60	452	20	none
Machinery field work		2570		2570
Field work fuel		3530		3530
Sprays, etc.		418		none
Total		15131		6100
Grass yield	4400	27720	5350	33705
Energy output/input		1.83		5.53

[a]Source: Topp *et al.* (2007).

The difference was attributed to the energy required for N fertilizer manufacture which is not needed in organic agriculture. Organic farming systems are generally self-sufficient in N requirements relying on the recycling of manures from livestock, composts and crop residues especially N-fixing residues. Thus, N fixation by legumes plays a critical and important role in mitigating climate change. The biological N fixation by forage legumes is a major N input in Australasian arable farming systems (Haynes *et al.*, 1993, Nguyen *et al.*, 1995; Goh & Williams, 1999). Badgley *et al.* (2007) estimated that as much as 154 million tonnes of N can be obtained from biologically fixed N, which exceeds N fertilizer production from fossil fuel. This source of N should be exploited for agriculture to mitigate climate change.

The energy required for off-farm agriculture practices such as the production and use of fertilizers and pesticides (Table 2) is regarded as indirect energy causing indirect GHG emissions (Greenpeace, 2008). Indirect GHG emissions should be included in estimating total GHG emissions from agriculture.

According to Greenpeace (2008), the production of fertilizer is the largest single emitter, followed by the use of farm machinery, irrigation and pesticide production.

The overall efficiency of organic livestock farms tends to be higher than that of conventional farms because of higher production from organic systems and also the absence of dedicated fertility-building crops which utilize energy without a saleable product in the organic systems (ADAS Consulting Ltd., 2000). In addition, energy consumption in organic livestock farms is 70% lower due to reduced imports of feed (Lampkin, 1997).

Organic biomass as a substitute for fossil fuel

The use of plant biomass as a substitute for fossil fuel provides a high potential for the avoidance of GHG emissions. According to Lal (2002), a real mitigation using this technique is only achievable if the biomass production does not generate additional GHG emissions due to the need of fertilizers input and the removal of large quantities of nutrients from the soil by biofuel plants. Organic agriculture is well positioned for this technique as N fertilizers are not applied (Kotschi & Müller-Sämann, 2004). However, the organic biofuel production system also needs to be not on the same land used for organic food production so as to avoid competition for land.

Enhancement of soil carbon sequestration in organic farms compared with conventional no-till and minimum tillage cropping systems

There is scepticism as to whether organic farming systems can improve soil carbon sequestration compared with conventional minimum tillage or no-till systems because tillage is required in organic farming to control weeds since herbicides are not permitted. In conventional agriculture, the conversion of till to no-till has been reported to enhance soil carbon sequestration in the topsoil (0–5 cm) (Lal & Kimble, 1997; Paustian *et al.*, 1997; Sainju *et al.*, 2008) although this may not occur below 7.5 cm soil depth as higher carbon below the topsoil in tilled areas has been reported depending on soil texture due to residue incorporation at greater soil depths (Jastrow, 1996; Clapp *et al.*, 2000; Sainju *et al.*, 2008). Six *et al.* (2000), reported that the gains in soil organic carbon in minimum tillage systems were offset by the increases in N_2O emissions from mineral N fertilizers applied. Many of the improvements in no-till cropping systems are due to increases in soil organic carbon resulting in improvements in soil aggregation, water-holding capacity, and nutrient cycling (Weil & Magdoff, 2004; Grandy *et al.*, 2006).

Teasdale *et al.* (2007) recently reported that a nine-year comparison of organic corn production system which included the use of tillage with selected conventional tillage systems showed that in spite of the use of tillage in the organic system, soil carbon concentrations were higher at all depths to 30 cm in the organic system than in the other systems (Table 3). The higher accumulation of soil organic carbon in the organic system was attributed to the incorporation of high amounts of organic inputs from manure, composts and cover crops in organic systems. Teasdale *et al.* (2007) concluded that if adequate weed control could be achieved in the reduced tillage organic system, this system would provide improved soil quality and yield-enhancing benefits compared with no-till conventional systems.

TABLE 3

Total soil carbon averaged over 2001 and 2002 at the conclusion of the cropping systems comparison[a].

System	Soil C (g kg^{-1})		
	0–7.5 cm	7.5–15 cm	15–30 cm
No-tillage	15.5 c†	11.1 c	7.1 b
Cover crop	17.3 b	12.4 b	7.8 b
Crown vetch	14.4 c	11.1 c	7.4 b
Organic	19.2 a	15.9 a	10.3 a

†Values within a soil depth range followed by the same letter are not different at $p < 0.05$.
[a]Source: Teasdale *et al.* (2007).

Reduction of soil carbon losses due to soil erosion

Soil erosion is the major cause of soil organic carbon loss, affecting climate change. It has been estimated that in the United States alone, water and wind erosion remove about 1.5 to 2.5 billion tonnes of soil annually (Wojick, 1999). The application of improved agricultural techniques in organic agriculture such as the addition of crop residues, green and animal manures, and composts together with the use of rotation, intercropping and cover crops converts soil carbon losses into gains (Goh, 2001, 2004). In addition, this leads to improved soil structure, increases in soil water infiltration and storage (Goh 2001, Lotter *et al.*, 2003), and reduces soil erosion and carbon loss. Under organic farming, the soil organic matter captures and stores more water in the crop root zone and can be 100% higher in organic than in conventional fields (Lotter *et al.*, 2003).

Certification of organic agriculture provides an assurance strategy for mitigating climate change

Unlike conventional agriculture, organic agriculture follows detailed standards of production and processing, which are enforced by inspection and certification (IFOAM, 1998). Thus, organic agriculture provides a strategy to ensure that farming practices which result in mitigating climate change are favoured and enforced. This also allows organic agriculture to be extended to meet the standards of the Clean Development Mechanism (CDM) of the Kyoto Protocol (IPCC, 2000). The CDM is a compensation scheme, which allows industrial countries to obtain carbon emission reduction credits with emission reduction projects in developing countries (IPCC, 2000).

Unconfirmed benefits of organic agriculture in mitigating climate change

Two major benefits of organic agriculture in mitigating climate change require further research and confirmation. These are related to composting and biogas production, and direct effects of N fertilizers on CH_4 emissions.

Composting and biogas production for mitigating climate change

Although organic agriculture has been in the forefront of biogas production for many decades, this option is not restricted to organic agriculture only. In addition, in the context of climate change, the benefits of aerobic fermentation of manure by composting are ambiguous because a shift from anaerobic to aerobic storage of manure can reduce CH_4 emissions but will increase N_2O emissions by a factor of 10 (Kotschi & Müller-Sämann, 2004), thus resulting in no beneficial mitigation in climate change.

Direct effects of nitrogen fertilizer applications on methane emissions

The consumption of CH_4 by CH_4-oxidizing (methanotrophic) micro-organisms in oxic or well drained soils determines whether a particular soil is a net source or sink of atmospheric CH_4. Under anoxic conditions as in waterlogged paddy rice soils, methanogenic bacteria produce CH_4, which is released to the atmosphere as a GHG. It has generally been accepted that N fertilizer applications inhibit CH_4 consumption and led to enhanced CH_4 emissions (Steudler *et al.*, 1989; Hütsch, 2001; Le Mer & Roger, 2001). However, recently, it was found that ammonium-based fertilizers stimulated the growth and activity of methotrophic bacteria in the rhizosphere of rice, enhancing CH_4 emissions (Bodelier *et al.*, 2000a, 2000b). Thus, further research is needed to elucidate the regulatory effects of N fertilizer application on CH_4 emissions (Bodelier & Laanbroek, 2004).

Adapting organic agriculture to mitigate climate change

Organic farming systems are generally regarded as highly adaptable to climate change compared to conventional agriculture due to (1) higher resilience and adaptation under extremely wet or dry weather conditions, (2) greater application of traditional farmers' skill and knowledge, and (3) higher diversity.

Adaptation to extreme climate conditions

The higher organic matter content in organically managed soils than in conventional agricultural soils has been shown to lead to increased soil water use efficiency in organic systems. During torrential rains, it has been shown that organic fields captured 100% more water that conventional fields (Lotter *et al.*, 2003). In addition, it has been found that organic fields are less prone to soil erosion and carbon loss (Mäder *et al.*, 2002; Pimentel, 2006).

Organically-grown corn and soyabeans have been shown to be more resistant to drought, out-performing conventional crops by 30, and 50–100%, respectively in the Rodale Long-term Field Trial (Delate & Cambardella, 2004; Pimentel *et al.*, 2005; LaSalle *et al.*, 2008). Thus, organic agriculture has the capability of creating more food security in areas with erratic and extreme weather conditions.

Application of traditional skills and knowledge

Organic agriculture has always been based on the application of traditional skills and knowledge to manipulate complex agro-ecosystems to produce food (IFOAM, 1998). This reduces the reliance on external inputs and provides the key to adaption to mitigate climate change. Organic agriculture has been described as the 'reservoir of adaptations' by Tengö & Belfrages (2004).

Enhancement of diversity

Organic agriculture provides a diversity of crops, rotations, landscapes and farming activities (ITC, 2007). This high degree of diversity enhances farm resilience (Mäder *et al.*, 2002; Bengtsson *et al.*, 2005; Hole *et al.*, 2005) and positive effects on pest prevention (Pfiffner & Luka, 2003; Zehnder *et al.*, 2007) and better utilization of soil water and nutrients (Altieri *et al.*, 2005).

Future strategies for improving the effectiveness of organic agriculture in mitigating climate change

A number of strategies are needed to improve the effectiveness of organic agriculture in mitigating climate change. These include (1) greater recognition and acceptance by IPCC and the public, (2) better accounting measures of climate change mitigation potential related to carbon footprint and resource use, (3) better technology transfer to improve organic yields, (4) adopting the application of biochars as a farming practice for improving climate change mitigation potential, and (6) more research in improving organic yields and climate change mitigation potential.

Greater acceptance and recognition of organic agriculture

Although IPCC recognizes the benefits of soil carbon sequestration for mitigating climate change (SRLUCF, 2000; Goh, 2004) the sequestration of carbon in soils is not included in the CDM of Kyoto Protocol (ITC, 2007) nor in the 'gold standard' of the World Wide Fund for Nature (WWF, 2006). This was attributed to the temporary nature of the carbon being sequestered as it will be released back to the atmosphere when a change in land use occurs. However, not all the carbon stored in soils is released when a land use change occurs as some of the carbon is stored in stable forms and is not easily released to the atmosphere (Fließbach & Mäder, 2000; Goh, 2001; 2004; Ellis, 2008). In addition, soil carbon sequestration provides a means of buying time for the development of renewable energy methods to reduce GHG. Kotschi & Müller-Sämann (2004) recommended that initiatives should be lobbied in various countries to include organic agriculture in their national GHG inventories.

According to Stern (2007), organic agriculture is generally regarded as a valuable niche market opportunity and not a major agricultural policy measure. A wider promotion of organic agriculture including its benefits in mitigating climate change should be implemented.

Better measures of climate change potential

Organic farming generally supports the development of a localized food economy and the transport of farms produce is less important than in exportoriented conventional agriculture (Stern, 2007). However, the expansion of organic farming will inevitably result in the export and trade of organic food. The contribution of food transport leads to increased fossil fuels consumption and therefore enhances GHG emissions and exacerbates climate change (Ludi *et al.*, 2007).

The globalization of food flows and its environmental implications requires attention. The use of 'food miles' (Paxton, 1994) is flawed by the fact that GHG emissions by transportation and packaging are minimal compared to the energy consumption in the production of the food especially for food produced in unsuitable region or climate. The environmental impact of international-traded food commodity can frequently be less than that of locally produced food (Ludi *et al.*, 2007). For example, Saunders & Barber (2007) found that there was less energy consumption involved in the importation of lamb from New Zealand to the United Kingdom than in the local produced United Kingdom lamb, in spite of transport savings. This was due to the higher energy intensity of animal feeds, and machinery fuel consumption together with greater use of N fertilizers in the United Kingdom than in New Zealand

Pretty *et al.* (2005) measured the full costs of weekly United Kingdom food basket (12 commodities) from farms to consumer's plate including food production, farm externalities, domestic road transport, government subsidies and shopping transport. Their results indicated that organic farming, localized food systems and sustainable transport reduced the environmental costs of the United Kingdom food system.

Several attempts have been made using life cycle analysis to assess environmental impact of plant (e.g. Matsson, 1999; Payraudeau *et al.*, 2005) and animal production (e.g. Haas *et al.*, 2001; Payraudeau *et al.*, 2005). The life cycle analysis involves a holistic assessment of raw material production, manufacture or processing, distribution, packaging, use and disposal including all the intervening steps in the transportation or cause of the existence of the product (Wikipedia, 2008). Most of the recent studies on these aspects focussed on nutrient use efficiency and less on energy and water use (Topp *et al.*, 2007).

Future studies involving the potential of organic agriculture in mitigating climate change, especially in comparing with that of conventional agriculture, should measure the 'carbon footprint' of the product which includes the total GHG emissions and related energy use throughout the whole life cycle of the product. Both direct and indirect GHG emissions produced in production methods, packaging, storage, disposal and transportation should be taken into account. Applications of the life cycle analysis method for comparing organic and conventional agriculture will provide more accurate assessments of their relative impact on the environment.

Better measures of resource use

Opinions differ with regard to the amounts of energy used in organic and conventional agriculture (Pimental, 2005; 2006; Topp *et al.*, 2007; Greenpeace, 2008). Climate related criteria are not included in the organic standards (IFOAM, 1998). According to Topp *et al.* (2007), in the assessments of the environmental impact of agriculture, reliable energy use data on cultivation and management practices have major impacts on both energy use and nutrient losses (Lobb *et al.* 2007). Care must be taken in defining the spatial and temporal boundaries of the system as the results can be expressed on either an output or an area basis.

Because of generally lower productivity in organic agriculture than in conventional agriculture, energy consumption based on per land area favours organic agriculture while that based on per crop or livestock yield favours conventional agriculture. There is also interest in developing environmental impact indicators which take into account improved soil quality, biodiversity and eco-system quality in the organic system compared to conventional agriculture (Halberg *et al.*, 2005).

Better technology transfer to improve organic yields

Yields of organic agriculture are generally reported to be lower than those of conventional agriculture (Goh & Nguyen, 1992, Nguyen *et al.*, 1995; Badgley *et al.*, 2007; Connor, 2007). The key question that is often being asked is whether organic agriculture is productive enough to meet the world's food needs (Vasilikiotis, 2000; Connor, 2007). This hinders the adoption of organic agriculture for mitigating climate change (Trewavas, 2001). The productivity of organic agriculture is often under-estimated by scientists and policy makers. The United Nation Environmental Programme (UNEP, 2008) analysed 114 farms in 24 African countries and concluded that in terms of yields, organic farms out-performed industrial, chemical-intensive conventional farms in addition to providing environmental benefits.

A group of scientists from University of Michigan (2007) recently reported that a change to organic farming will not reduce the world's food supply but could even enhance food security in developing countries. Badgley *et al.* (2007) modelled the yields of 293 farms in developed and developing world and concluded that average yields of organic crop and livestock production are 92% of those in conventional agriculture. In wheat, organic yields varied between 58 and 98% compared with those of conventional yields (ITC, 2007). Furthermore, a wide range of yields were obtained in organic farms. The surveys showed that organic yields could be improved by better technology transfers from research to farming practices.

Adopting the application of 'biochars' as a farming practice in organic agriculture for improving climate change mitigation potential

Recently, it has been proposed that 'biochars' (charcoals from pyrolysis 400-600°C in the absence of oxygen) produced from biomass (wood, plants, plant waste) when applied to soils can enhance not only crop yields but also increase soil carbon sequestration in mitigating climate change (Glasser, *et al.*, 2002; Lehmann *et al.*, 2003; 2006; Steiner *et al.*, 2007; Novak *et al.*, 2009). This practice was used by ancient agriculturists to produce food in the Amazon basin in the form of 'slash and char' agriculture, resulting in the formation of the black soils known as 'Terra Preta'.

Applications of composts, manures and plant residues to soils are standard farming practices in organic agriculture (IFOAM, 1998). If the above practices include adding charcoals and biochars to soils in organic agriculture, it can result in longer term storage of soil carbon, thereby enhancing the mitigation of climate change. Biochar carbon is more recalcitrant than biogenic soil organic carbon (Sombroek *et al.*, 2003; Goh, 2004; Liang *et al.*, 2006). This is more important under tropical environments where added organic matter is rapidly oxidized and added bases are readily leached (Tiessen *et al.*, 1994).

Furthermore, one of the major difficulties of using soil organic carbon for mitigating climate change is the difficulty of measuring and verifying the small changes in soil carbon with time owing to its temporal and spatial heterogeneity (Goh, 2004). Another difficulty is that soil organic matter carbon accumulation does not continue to increase with time but reaches a steady state or carbon saturation level which governs the limit of the soil carbon sink. The addition of biochars to soils overcomes these difficulties because substantial amounts of carbon are added to soils when biochars are applied (Novak *et al.*, 2009), thus improving the accuracy of monitoring soil carbon changes with time and overcomes soil carbon saturation.

More research in improving organic yields and climate change mitigation potential

Most of the present global research in agriculture is mainly confined to conventional agriculture and very little research is conducted on organic agriculture. For example, almost all (99%) of the present European public and private research funding is for improving conventional farming systems (ITC, 2007). More research funding is needed for organic agriculture on aspects related to improving organic yields, especially in developed countries, and also in improving the mitigating potential of organic agriculture in climate change.

It is widely recognized that GHG emissions are expected to increase in most regions of the world and more research is needed to counteract these increases (Müller, 2009). The IPCC (IPCC, 2007) proposed that increases in agricultural research and development together with increased knowledge and technology transfer are needed.

CONCLUSIONS

The solution to global warming and present-day climate change problems caused by agriculture lies in changing farming practices in agriculture, and adopting the best form of agriculture to provide cost-effective high-yielding agricultural production with minimum adverse effects on the environment and climate. This review shows that organic agriculture has a greater potential in mitigating climate change than conventional agriculture. However, the world-wide acceptance and adoption of organic agriculture for agricultural production and mitigating climate change at present depends on its ability to 'feed the world'. Although it has not been shown widely in developed countries, organic farms were reported to out-perform conventional farms in terms of yields in developing countries. It has also been shown that the negative impact of climate on agricultural production is region-specific, and is more severe in developing countries. Thus, organic agriculture is the best form of agriculture for agricultural production in developing countries, and at the same time, provides mitigation for climate change.

In both developed and developing countries, organic agriculture has considerable potential in mitigating climate change due largely to its ability to reduce GHG emissions and in enhancing carbon sequestration in soils. Furthermore, its functioning mechanism of certification and inspection guarantees transparency and compliance of principles and standards. This approach allows the enforcement of adopting new and improved farming practices aim at mitigating climate change. In addition, organic agriculture is highly adaptable to climate change and it also provides a high degree of diversity in the eco-system. More research is needed for improving this potential and also in increasing organic yields especially in developed countries.

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