Agricultural Influences on Carbon Emissions and Sequestration: A Review of Evidence and the Emerging Trading Options

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Executive Summary

The 1997 Kyoto Protocol to the UN Framework Convention on Climate Change established an international policy context for the reduction of carbon emissions and increases in carbon sinks in order to address climate change. Under the protocol, the principle of financial and technological transfers to land management projects and initiatives was established.

Agricultural systems contribute to carbon emissions through several mechanisms: i) the direct use of fossil fuels in farm operations; ii) the indirect use of embodied energy in inputs that are energy-intensive to manufacture (particularly fertilizers); and iii) the cultivation of soils resulting in the loss of soil organic matter. On the other hand, agriculture is also an accumulator of carbon, offsetting losses when organic matter is accumulated in the soil, or when above-ground woody biomass acts either as a permanent sink or is used as an energy source that substitutes for fossil fuels.

Long-term agricultural experiments in both Europe and North America indicate that soil organic matter and soil carbon are lost during intensive cultivation. But both can be increased to new higher equilibria with sustainable management practices. The greatest dividend comes from conversion of arable to agroforestry as there is a benefit from both increased soil organic matter and the accumulation of above-ground woody biomass. Grasslands within rotations, zero-tillage (or no-till) farming, green manures, and high amendments of straw and manures, also lead to substantial carbon sequestration. There is now good evidence to show that sustainable agricultural systems can lead to the annual accumulation of 0.3-0.6 t C/ha, rising to several tonnes per ha when trees are intercropped in cropping and grazing systems.

Agriculture as an economic sector contributes to carbon emissions through the consumption of direct and indirect fossil fuel. With the increased use of nitrogen fertilizers, pumped irrigation and mechanical power, industrialised agriculture has become progressively less energy efficient. These three sources account for more than 90% of the total energy inputs to farming. We summarise the evidence from both industrialised and developing countries by comparing sustainable with high-input conventional systems of production. Low-input or organic rice in Bangladesh, China, and Latin America is some 15-25 times more energy efficient than irrigated rice grown in the USA. For each tonne of cereal or vegetable from industrialised high-input systems, 3000-10,000 MJ of energy are consumed in its production. But for each tonne of cereal or vegetable from sustainable farming, only 500-1000 MJ are consumed.

It is now known that intensive and continuous cultivation of cereals leads to reductions in soil organic matter and carbon. But recent years have seen an extraordinary growth in adoption of `conservation tillage' and `zero-tillage' systems, particularly in the Americas. These systems of cultivation maintain a permanent or semi-permanent organic cover on the soil. The function is to protect the soil physically from the action of sun, rain and wind, and to feed soil biota. The result is reduced soil erosion and improved soil organic matter and carbon content.

Conservation tillage systems (particularly zero-till) and those using legumes as green manures and/or cover crops contribute to organic matter and carbon accumulation in the soil. Zero till systems also have an additional benefit of requiring less fossil fuel for machinery passes. Intensive arable with zero-tillage results in accumulation of 0.3-0.6 t C /ha/year, but ZT with mixed rotations and cover crops can accumulate 0.66-1.3 t C/ha/year.

The rates are higher in humid-temperate areas (0.5-1.0 t C/ha/yr), lower in the humid tropics (0.2-0.5 t C/ha/yr), and lowest in the semi-arid tropics (0.1-0.2 t C/ha/yr).

Article 17 of the Kyoto Protocol permits countries to produce certified emissions reductions (also known as offsets) and emissions reductions units through joint implementation projects. As it is cheaper at the margin for many countries to abate greenhouse gas emissions, such joint implementation is in theory a cost-effective mechanism for achieving global targets.

For real impacts on climate change to occur, sinks must become permanent. If lands under conservation tillage are ploughed, then all the gains in soil carbon and organic matter are lost. This raises a core challenge for trading systems, as there is no such thing as a permanent emissions reduction nor a permanent sequestered tonne of carbon.

Despite these uncertainties, carbon `boards of trade' or trading systems first emerged during the year 2000. The externalities of carbon have been calculated in Europe to be US$95 per tonne, representing an upper bound of what could be paid in trading systems. The first carbon exchange or trading systems have set credit values from US$1-38 per tonne of carbon, though most commonly in the $2.50-5.00 range.

We use these market prices to plot the potential gains for zero-tillage farmers using three different types of ZT systems. Intensive ZT systems with no rotations yield less income than mixed systems. The best are ZT systems with mixed rotations and leguminous cover crops that accumulate more than 1 t C/ha/yr.

For the UK, we estimate that carbon could bring arable and grassland farmers (not counting rough grazing) between £18m ($27m) and £147m ($220m) per year. This would represent a significant additional source of additional income.

The important policy questions centre on how to establish permanent or indefinite sinks; how to prevent leakage (eg reploughing of zero-tilled fields, deforestation); how to agree measurements; and whether the cost of implementation can be justified through their additional side effects or multifunctionality.

We do not yet know how much carbon would be created in response to monetary incentives for carbon sequestration. The empirical evidence is relatively sparse, and practical experience even more limited. No agreed system of payment levels has yet been established. Another unresolved issue relates to the location for the greatest carbon returns on investments. Investments in creating sustainable systems in the tropics are likely to be cheaper than in temperate regions, where industrialised agriculture prevails. Such transfers from industrialised to developing countries could produce substantial net global benefits as well as benefit poorer developing country farmers.

At current prices, it is clear that farmers are not set to become solely carbon farmers. However, systems accumulating carbon are also delivering many other public goods, such as improved biodiversity and clean water from watersheds, and policy makers may also seek to price these so as to increase the total payment package. Carbon, therefore, represents an important new source of income for farmers, as well as helping to encourage farmers to adopt a wide range of sustainable practices.

1. Introduction

The 1997 Kyoto Protocol to the UN Framework Convention on Climate Change established an international policy context for the reduction of carbon emissions and increases in carbon sinks in order to address the global challenge of anthropogenic interference with the climate system. Under the protocol, the principle was established of financial and technological transfers to land management projects and initiatives (through forestry and farming) that sequester and protect carbon stocks through the Clean Development Mechanism (CDM) and `Land Use, Land-Use Change and Forestry' mechanisms.

The concept of carbon trading is, however, still contested. Under the Kyoto Protocol, industrialised countries and countries in transition undertook to reduce net greenhouse gas emissions by 5.2% below 1990 levels by 2012. To some, this implies the need both to reduce emissions and increase sinks; to others, it suggests that investments in sinks will be sufficient to meet domestic obligations. Importantly, the CDM also offers the opportunity for governments or businesses to invest in carbon sink projects elsewhere, whilst counting the accumulated carbon against their emissions budget. A further area of concern centres on the need for new carbon sinks to be permanent.

Despite the controversy, it is clear to most commentators (cf IPCC, 2000, 2001; FAO, 2000) that both emission reductions and sink growth will be necessary if there is to be any positive effect on mitigation or even reduction of current climate change trends.

Forests are under close scrutiny for their potential as carbon sinks (Bateman and Lovett, 2000; Chomitz, 2000; Pfaff et al., 2000; Smith J et al., 2000). In this paper, we review the latest empirical data on carbon sequestration opportunities in agricultural systems through both soil storage and terrestrial biomass. We re-examine energy studies to assess the direct and indirect energy required to produce cereals and vegetables in conventional industrialised systems compared with sustainable systems.

We then assess experimental evidence from zero-tillage agricultural systems in temperate and tropical regions to assess carbon sequestration potential. We review the emergent carbon-trading systems and the monetary values currently being allocated to carbon, and

draw policy conclusions for agriculture and land management that can contribute to reversing anthropogenically-induced climate change.

2. Sources and Sinks in Agricultural Systems

Under the Framework Convention on Climate Change, a source is any *"process or activity which releases a greenhouse gas, or aerosol or a precursor of a greenhouse gas into the atmosphere"*. A sink is any process, activity or mechanism which removes these from the atmosphere (Articles 1.8 and 1.9). Carbon sequestration is, therefore, defined as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere (FAO, 2000). Agricultural systems contribute to carbon emissions through several mechanisms:

i)   the direct use of fossil fuels in farm operations;

ii)   the indirect use of embodied energy in inputs that are energy-intensive to manufacture (particularly fertilizers);

iii)   the cultivation of soils resulting in the loss of soil organic matter.

On the other hand, agriculture is also an accumulator of carbon, offsetting losses when organic matter is accumulated in the soil, or when above-ground woody biomass acts either as a permanent sink or is used as an energy source that substitutes for fossil fuels. Table 1 contains a summary of the positive contributions that can be made by farmers both to reduce the carbon emitted from farms, and to increase the number and effectiveness of carbon sinks.

Soil organic matter (SOM) comprises the sum of all organic substances in the soil, and is defined as a *"mixture of plant and animal residues at various stages of decomposition, of substances synthesised microbiologically and/or chemically from the breakdown products, and of the bodies of micro-organisms and small animals and their decomposing products"* (Schnitzer, 1991). It has a stabilising effect on soil structure, improves moisture retention, and protects soil against erosion (Reicosky et al., 1995; Fliessbach and Mäder, 2000; Six et al., 2000). A wide range of factors affect levels of SOM, including moisture status, temperature, oxygen supply, drainage, soil acidity, nutrient supply, clay content and mineralogy. SOM accumulates best at low temperatures in acid parent materials and in anaerobic conditions (Batjes and Sombroek, 1997). Large amounts of SOM and carbon are lost from the soil following

deforestation, conversion to grazing land, draining of peatlands, and intensive ploughing (Reicosky and Lindstrom, 1994; Reicosky et al., 1997).

Table 1. Farm-based options for reducing carbon and other greenhouse gas emissions and increasing carbon sinks

Options for reducing carbon and other greenhouse gas emissions from farms	Options for increasing carbon sinks on farms
• conserve fuel and reduce energy use • use conservation tillage to reduce CO_2 emissions from soils • grass-based grazing systems to reduce methane emissions from livestock • composting to reduce manure methane emissions • substitute biofuels for fossil fuels • reduce machinery use • reduce use of inorganic fertilizers • use targeted- and slow-release fertilizers	• reduce ploughing with conservation- and zero-tillage • use mixed rotations using cover crops and green manures • minimise summer fallows and periods with no ground cover • apply composts and manures to soil • improve pasture and rangelands through grazing and vegetation management • use perennial rather than annual grasses, as perennials have 60-80% of biomass below ground compared with 20% for annuals • restore and protect wetlands (provided carbon sequestration is greater than methane production) • convert agricultural land to woodlands • adopt agroforestry in cropping systems • cultivate crops for biofuels (grasses, coppiced trees)

Sources: adapted from Lal et al. (1998), Robertson et al. (2000), USDA (2000)

Long-term agricultural experiments in both Europe and North America indicate that soil organic matter and soil carbon are lost during intensive cultivation, typically showing exponential decline after the first cultivation of virgin soils, but with continuing steady loss over many years (Arrouays and Pélissier, 1994; Reicosky et al., 1995, 1997; RCEP, 1996; Sala and Paruelo, 1997; Rasmussen et al., 1998; Tilman, 1998; Smith, 1999; Robert et al., 2001).

It has also been established that SOM and soil carbon can be increased to new higher equilibria with sustainable management practices. A wide range of long-term comparative studies show that organic and sustainable systems improve soils through accumulation of organic matter and soil carbon, with accompanying increases in microbial activity, in the USA (Lockeretz et al., 1989; Wander et al., 1994, 1995; Petersen et al., 2000), Germany (El Titi,

1999; Tebrügge, 2000), UK (Smith et al., 1998; Tilman, 1998), Scandinavia (Kätterer and Andrén, 1999), Switzerland (FiBL, 2000), and New Zealand (Reganold et al., 1987, 1993)[1].

The IPCC (2000) reviewed the carbon sequestration potential of changing land use management towards more sustainable practices, including complete land use changes (Table 2). They concluded that the greatest dividend comes from conversion of arable to agroforestry as there is a benefit from both increased soil organic matter and above-ground woody biomass. Agroforestry, if used for energy production, has an additional benefit if it substitutes for fossil-fuel energy production.

Table 2. Carbon sequestration in various land use systems (over 50 year period after conversion or adoption)

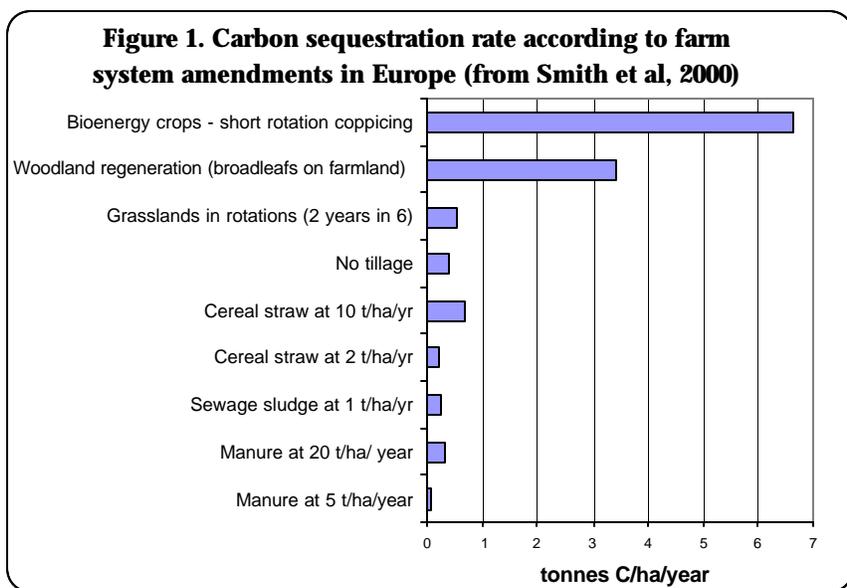| System	Accumulated carbon under improved management within land use (t C/ha/year)	Accumulated carbon with land use change (t C/ha/year)
Forest management	0.4-0.5	-
Cropland management	0.3	-
Grazing land management	0.5-0.7	-
Agroforestry	0.3-0.5	3.1
Rice paddies	0.1	-
Urban land management	0.3	-
Conversion of arable to grassland	-	0.8
Wetland restoration	-	0.4
Degraded land restoration	-	0.3

Source: IPCC, 2000

These data may be conservative. The USDA National Agroforestry Center (2000) suggests that carbon sequestration under agroforestry can be much higher. Short rotation coppice gives a double benefit through carbon sequestration and energy substitution – if the wood is burned instead of a fossil fuel. Under such coppicing, soil carbon can increase by 6.6 t C/ha/yr over a 15-year rotation, and wood by 12-22 t C/ha/yr over the rotation. Silvopasture systems comprising mixed loblolly pine and grasslands can lead to increases in soil carbon of 5 t C/ha/year over 35 years, and plant carbon of 10.1 t C/ha/year.

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[1] Kätterer and Andrén (1999) conclude that when land use changes to annuals, soil C falls if the initial soil pool if high. But if it is low, then soil C can increase even with just cereal cultivation.

Smith et al.'s (2000) review of European experiments concluded that woodland regeneration can lead to accumulation of 3.43 t C/ha/yr, and short rotation coppicing to accumulation of 6.62 t C/ha/year. Grasslands within rotations, zero-tillage (or no-till) farming, and high amendments of straw, also lead to substantial carbon sequestration (Figure 1). New grasslands led to accumulation and incorporation of litter, with large amounts of net primary production allocated to root growth.

This confirms various studies indicating substantial increases in soil organic matter and carbon in systems using legumes and/or manures (Drinkwater et al., 1998; Tilman, 1998; Petersen et al., 2000). In one study, organic farms in the US midwest contained 0.14% more organic matter than neighbouring conventional farms, and in another in New Zealand, biodynamic farms contained 0.57% more soil carbon than conventional farms (Lockeretz et al., 1989; Reganold et al., 1993). At the Rodale Institute's experimental farm in Pennsylvania, organic systems with legumes and/or animal manures increased soil carbon from 1.8 to 2.4% over 14 years, compared with no significant change for conventional systems (Petersen et al., 2000).

Other studies in France (Viaux and Rieu, 1995; Bockstaller and Girardin, 1996; Robert et al., 2001), Belgium (van Bol and Peeters, 1997), Switzerland (Dubios et al., 1995; Dubois, 2000; Fliessbach and Mäder, 2000; FiBL, 2000), Germany (El Titi and Landes, 1990; El Titi, 1999), Netherlands (Wijnands et al., 1995) and the UK (Bailey et al., 1999; Jordan and Hutcheon, 1994; Ogilvy et al., 1995) have all shown accumulation of organic matter under integrated

Figure 1. Carbon sequestration rate according to farm system amendments in Europe (from Smith et al, 2000)

farming systems. In the Lautenbach experiment (1979-1994), soil organic matter increased at a rate of 1.73% per year, equivalent to 0.93 t C/ha/yr, under the integrated farming system (El Titi, 1999). And in the Versailles experiment, running from 1929 to the present day, soils under normal cultivation lost 60% of their carbon, whilst those receiving manures increased carbon content by 50% (Robert et al., 2001).

There is consensus that carbon sequestration potential is higher in humid temperate areas (0.1-0.5 t C/ha/yr) than in semi-arid and tropical areas (0.05-0.20 t C/ha/yr). Palm et al. (2000) measured carbon stocks, losses and rates of accumulation in Brazil, Cameroon and Indonesia. They concluded that carbon accumulation rates are much higher in above-ground biomass (at least 2 t C/ha/yr) than in soils (0.2-0.6 t C/ha/yr), and also indicate that tree-based agroecosystems, either plantation crops (eg oil palm, cacao and rubber agro-forests) or on smallholder farms, bring the greatest dividend, accumulating 3.0-9.3 t C/ha/yr (Sanchez et al., 1999; Sanchez and Jama, 2000).

There are also large benefits in the tropics from use of green manure/cover crop systems. The intercropping of *Mucuna pruriens* (velvetbean) with maize in Central America, for example, can lead to the addition of 35 tonnes of biomass per ha per year to soils (Bunch, 2000). There have been no empirical studies on carbon accumulation under these systems. However, assuming that half is carbon, then this could amount to the addition of some 17.5 t C per year – much greater than other estimates of net carbon sequestration, even accounting for the fact that some will decompose rapidly.

Arid and tropical lands remain of high concern for developing countries, and carbon sequestration solutions will centre on improvements to cultivated lands (750 million ha in the tropics), tropical forests (2 billion ha) and permanent pastures and rangelands (3 billion ha) (Robert et al., 2001). Land degradation by water and wind erosion, and by chemical and physical degradation, threatens the integrity of many of these soils, commonly leading to carbon losses.

There is, therefore, considerable evidence to show that more sustainable agricultural systems can lead to the annual accumulation of 0.3-0.6 t C/ha, rising to several tonnes per ha when trees are intercropped in cropping and grazing systems.

3. Energy Balance Studies of Agricultural Systems

Agriculture as an economic sector contributes to carbon emissions through the consumption of direct and indirect fossil fuel. With the increased use of nitrogen fertilizers, pumped irrigation and mechanical power, all of which are particularly energy-intensive, industrialised agriculture has become progressively less energy efficient. These three sources account for more than 90% of the total direct and indirect energy inputs to farming (Leach, 1976, 1985). Mechanisation reduces the labour required for agriculture and so can cut variable costs if energy is cheap relative to labour, as it is in most industrialised countries.

Since the 1970s, a wide range of approaches to energy accounting for agricultural systems have been developed (Leach, 1976, 1985; Stout, 1979; Stanhill, 1979; Pimentel, 1980; Smil et al., 1982; Dovring, 1985; Pimentel et al., 1989; OECD/IEA, 1992; OECD, 1993; Pretty, 1995; Cormack and Metcalfe, 2000; Robertson et al., 2000). These use many auditing methods. Some include only the direct fossil fuel energy consumed on farms; others seek comprehensive energy balances by including all the indirect energy consumed in manufacturing equipment and inputs, transporting produce to and from farms, and the energy required to feed human and animal labour on the farm. Direct energy represents what is immediately vulnerable to supply interruptions, and so is of more immediate interest to farmers. In general, apart from nitrogen fertilizers, the manufacture of which is extremely energy intensive, direct energy costs far exceed indirect costs (Leach, 1985).

According to the OECD (1993), the absolute energy consumption per hectare increased in OECD countries by 39% between 1970 and 1989. On average, some 1734 MJ are consumed per hectare of agricultural land, rising to 46,400 MJ for the highest consumer, Japan. Using standard conversion factors for carbon emitted per megajoule of energy consumed, this represents emissions of 37 t C/ha/year for all OECD countries; but rising to 1002 t C/ha/year in Japan.

With the greater use of machinery, fuel and nitrogen fertilizers in industrialised agriculture, energy consumption is substantially greater than equivalent sustainable, low-input or organic systems[2]. In the UK, organic systems use between 30-50% of the energy per hectare than

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[2] Sustainable agriculture seeks to make the best use of nature's goods and services as functional inputs. It does this by integrating regenerative processes (such as nutrient cycling, nitrogen fixation, soil regeneration and natural enemies of pests) into

conventional systems, and there are similar dividends in the USA, Philippines and India (Table 3).

Table 3. Energy use per hectare for sustainable and conventional agricultural systems

Country and system of production	Energy use – ratio of organic/sustainable to conventional	% increase in energy required for 1% increase in yield in conventional systems
UK		
winter wheat (organic vs conventional)	38%	+3.5%
potato (organic vs conventional)	49%	+4.9%
carrot (organic vs conventional)	28%	+1.6%
calabrese (organic vs conventional)	27%	+4.2%
USA		
maize (low input vs conventional)	45-82%	+22-120%
wheat (organic vs conventional)	68%	+1.7%
Philippines		
rice (organic and Azolla vs conventional)	33%	+7-20%
rice (rainfed vs conventional)	11%	5.3%
India		
wheat (traditional animal power vs modern with tractors)	27-52%	7.4-44%
rice(traditional animal power vs modern with tractors)	57-70%	2.3-7%

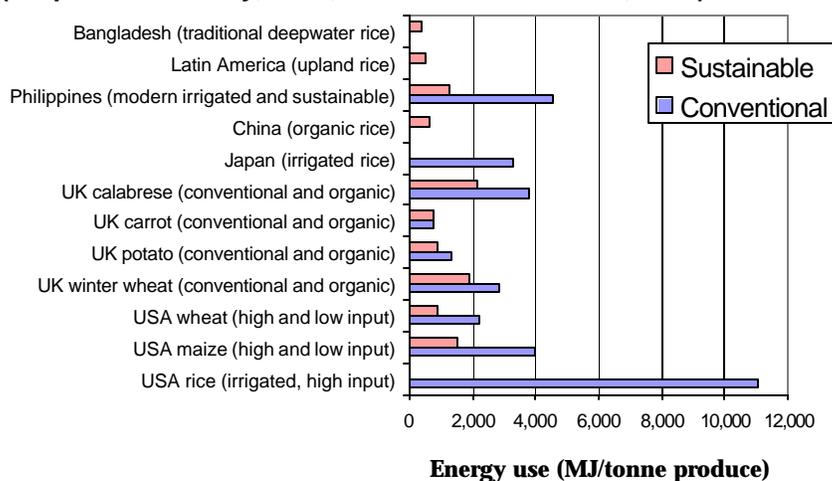*Sources: adapted from Pretty (1995); Cormack and Metcalfe (2000)*

This means that it is much more costly to achieve marginal increases in yield in conventional industrialised systems than it is in sustainable ones. In the Philippines, for example, a doubling of yields comes at the cost of an 8-30 fold increase in energy consumption. In India, a 10-20% increase in yields following mechanisation costs an extra 43-260% in energy consumption (Pretty, 1995). In the USA, high-input industrialised systems consume 22-120% more energy than sustainable and low-input systems, even though yields are comparable. Larger farms also tend to use relatively more energy than smaller ones. In the Punjab, large farms (14-25 ha) use three times as much energy per hectare as farms of 25-40% size (Singh and Miglani, 1976).

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food production processes. It minimises the use of inputs that damage the environment or harm human health. It builds on farmers' knowledge and skills, and seeks to make productive use of social capital, namely people's capacities for collective action for pest, watershed, irrigation, and forest management. Sustainable agriculture jointly produces food and other goods, but it also contributes to public goods, such as clean water, wildlife, carbon sequestration in soils, flood protection and landscape quality (Pretty, 1998; Pretty and Hine, 2000).

We summarise the evidence from both industrialised and developing countries by comparing sustainable and low-input systems of production with the high-input conventional systems (Figures 2a and 2b). Low-input or organic rice in Bangladesh, China, and Latin America is some 15-25 times more energy efficient than irrigated rice produced in the USA. For each tonne of cereal or vegetable from modernized high-input systems, 3000-10,000 MJ of energy are consumed in its production. But for each tonne of cereal or vegetable from sustainable farming, only 500-1000 MJ are consumed. One tonne of deepwater or upland rice in Asia or Latin America results in the emission of 8-11 tonnes of carbon; in comparison, each tonne of rice produced in California emits 240 tonnes of carbon.

Figure 2a. Energy use (direct + embodied energy for fertilizers and pesticides) in conventional and sustainable systems (adapted from Pretty, 1995; Cormack and Metcalfe, 2000)

Figure 2b. Emissions of carbon from conventional and sustainable systems (adapted from Pretty, 1995; Cormack and Metcalfe, 2000)
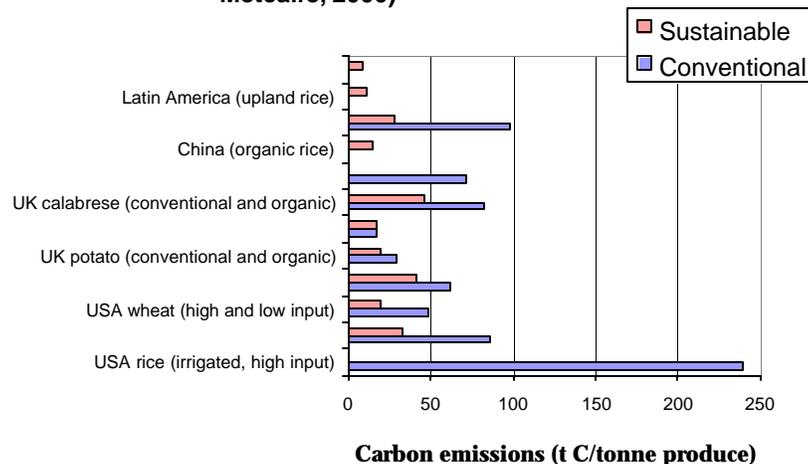
4. The Case for Conservation-Tillage and Zero-Tillage Systems

It is now known that intensive and continuous cultivation of cereals leads to reductions in soil organic matter and carbon. Rasmussen et al.'s (1998) analysis of long-term agro-ecological experiments indicates that soils under continuous wheat lose 0.21-0.36 t C/ha/yr in the USA (over 110-120 years) and 0.42 t C/ha/yr in Australia (over 70 years).

Reicosky et al. (1995) reviewed a wide range of long-term experiments in the USA (Ohio, Alabama, Georgia, Illinois, Nebraska, Kentucky, Oregon and Missouri) for losses of carbon under different cultivation regimes. Both erosion and biological oxidation remove carbon from soils. Conventional ploughing exposes soil to solar radiation, mixes residues into soil, and adds air to macropores, all leading to an increase in metabolic rate of microbial populations. The greatest losses of soil carbon and organic matter occurs under intensive and continuous maize (Table 5). As Don Reicosky put it: *"it is practically impossible to increase soil organic matter where mouldboard ploughing is taking place".* It is possible, however, to slow or stabilise carbon losses through large additions of manures and crop residues.

Table 5. Losses and gains of carbon under conventional and zero-tillage management systems in the USA

System	Rotations	Gains or losses of carbon (t C/ha/year)
Mouldboard plough	Continuous maize or wheat	- 0.105 to -0.460
	Mixed rotations and cover crops	- 0.033 to -0.065
Zero Till	Continuous maize or soyabeans	+ 0.330 to 0.585
	Mixed rotations and cover crops	+0.660 to 1.310

Sources: adapted from Reicosky et al. (1995), Langdale et al. (1992); Edwards et al. (1988, 1992)

Recent years have seen an extraordinary growth in adoption of `conservation tillage', `no till' and `zero-tillage' systems, particularly in the Americas. These systems of cultivation maintain a permanent or semi-permanent organic cover on the soil, comprising either a growing crop or dead organic matter in the form of a mulch or green manure. The function is to protect the soil physically from the action of sun, rain and wind, and to feed soil biota. The result is reduced soil erosion and improved soil organic matter and carbon content.

In Brazil, there were 1 million hectares under *plantio direto* (zero-tillage) in 1991; by 1999, this had grown to about 11 million hectares in three southern states of Santa Canterina, Rio Grande do Sol and Paraná. In Argentina, there were 9.2 million hectares under ZT in 1999 - up from less than 100,000 ha in 1990 (Peiretti, 2000), and in Paraguay, there were 785,000 hectares of ZT in 1998 (Rolf Derpsch, pers. comm.; Sorrenson et al., 1998).

In the USA, some 19 million ha are now said to be under forms of conservation tillage (WCCA, 2001) – though it still tends to be simplified modern agriculture systems – so saving on soil erosion, but with little use of agroecological principles for nutrient, weed and pest management. As Robert et al. (2001) put it: *"very often in the USA, conservation tillage is not a true no-tillage practice as is generally the case in Brazil and Argentina"*.

In Latin America, ZT has resulted in better input use, water retention, management by farmers, diverse rotations, break crops for weed control (eg ray and black oats between maize/soyabeans) and use of green manures and cover crops. ZT also cuts erosion and water run-off, so reducing water pollution. In many systems, farmers are using herbicides during fallow periods to suppress weeds, but when water is available, they prefer to use break crops during winter for weed control[3].

The result is greatly improved cereal productivity. In the Brazilian State of Santa Caterina, yields have grown steadily over ten years, rising from 3 to 5 tonnes maize/ha and from 2.8 to 4.7 tonnes soyabeans/ha. In Argentina, average cereal productivity was 2 t/ha in 1990; since then, it has increased on conventional farms to 2.2 t/ha, a rate surpassed by those farms with zero-tillage, where yields have grown to 3.5-4.0 t/ha (Peiretti, 2000).

Farmers are now adapting technologies – organic matter levels have improved so much that they are getting rid of terraces at some locations, indicating that there are no erosion problems. Other benefits of ZT include reduced erosion, and reduced silting of reservoirs; reduction in cost of water treatment; increased water retention in soils; increased winter feed

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[3] Zero tillage (ZT) had a much wider effect than just on soils. In the early days, there was a widespread belief that ZT was only for large farmers. That has now changed. A core element of ZT adoption in South America has been adaptive research – working with farmers at microcatchment level to ensure technologies are fitted well to local circumstances. *"ZT has been a major factor in changing the top-down nature of agricultural services to farmers towards a participatory, on-farm approach"*(Landers, 1999). In Brazil, some 200,000 farmers are members of the Friends of Land clubs, with some 8-10,000 groups formed. These comprise many types: from local (farmer micro-catchment and credit groups), to municipal (soil commissions, commercial farmers, farm workers), to multi-municipal (farmer foundations), to river basin (basin committees for all water users), and to state and national level (state ZT associations and national ZT federation).

for wild biodiversity. Landers (1999) suggests that ZT represents *"a total change in the values of how to plant crops and manage soils"*.

Conservation tillage systems (particularly zero-till) and those using legumes as green manures and/or cover crops can make a significant contribution to organic matter and carbon accumulation in the soil (Reicosky, 1997; Drinkwater et al., 1998; Lal et al., 1998; WCCA, 2001). Dobbs and Smolik's (1996) 8-year study of conventional and alternative farming systems in South Dakota demonstrated the additional value of mixed rotations. Both systems used no-till, but the mixed rotations resulted in an added accumulation of 0.023 t C/ha/yr.

Smith et al. (1988) reviewed long-term experiments comparing conventional tillage with zero till in UK (5-23 years) and Germany (4-6 years), and concluded that with zero tillage i) soil organic matter increases at 0.73% per year (95% confidence levels 0.34-1.12%); and ii) soil carbon increases at 0.39 t C/ha/year (0.18-0.60 t C/ha/yr). This compares with low estimates of net sequestration under ZT of 0.1-0.3 t C/ha/yr, and higher ones of 0.63-0.77 t C/ha/yr in Spain and Canada (Edwards et al., 1992; Lal et al., 1998). There are, however, occasional experiments in which soil carbon levels declined ZT (Kätterer and Andrén (1999).

Zero till systems also have an additional benefit of requiring less fossil fuel for machinery passes. Fuel use in conventional systems (Tebrügge, 2000; Smith et al., 1998) in the UK and Germany varies from 0.046-0.053 t C/ha/year; whereas for ZT systems, it is only 0.007-0.029 t C/ha/yr (0.007 is for direct energy use only; 0.029 includes the embodied energy in herbicides). Compared with the savings from reduced carbon loss and increased carbon sequestration in soils, these represent only a small proportion of total savings (approximately 7%).

In summary, it would appear that intensive arable with zero-tillage results in accumulation of 0.3-0.6 t C /ha/year, but ZT with mixed rotations and cover crops can accumulate 0.66-1.3 t C/ha/year. The rates are higher in humid-temperate areas (0.5-1.0 t C/ha/yr), lower in the humid tropics (0.2-0.5 t C/ha/yr), and lowest in the semi-arid tropics (0.1-0.2 t C/ha/yr) (Lal et al., 2000).

5. Carbon Trading Systems

Article 17 of the Kyoto Protocol permits countries to produce certified emissions reductions (CERs – also known as offsets) and emissions reductions units (ERUs) through joint implementation projects. As it is cheaper at the margin for many countries to abate greenhouse gas emissions, such joint implementation is in theory a cost-effective mechanism for achieving global targets. Ellerman et al. (1998) calculate that the global cost of achieving the Kyoto Protocol targets are $120 billion if each country satisfies its obligations entirely through domestic actions. But this drops to just $11-54 billion if trading and CER transfers are permitted.

But these gains are only achieved if the net effect (reduced emission plus increased sinks) is `real and additional' (Chomitz, 2000). Many commentators and policy makers fear that emissions' reductions and potential sinks will be exaggerated for domestic political and economic reasons, particularly as the 1990 baseline cannot be measured. Carbon accounting systems must, therefore, have six features: they must be transparent, consistent, comparable, complete, accurate, and verifiable (IPCC, 2000).

There are also many definitional problems. Carbon pools comprise above ground biomass, litter and woody debris, below ground biomass, soil carbon, harvested materials. Yet for such carbon to be traded, it is necessary to define clearly what is a forest, what type of agricultural and land management systems accumulate carbon, and how can any increases be verified and guaranteed in the long-term?

For real impacts on climate change to occur, sinks must become permanent. If land under conservation tillage are ploughed, then all the gains in soil carbon and organic matter are lost. This raises a core challenge for trading systems, as there is clearly no such thing as a permanent emissions reduction nor a permanent sequestered tonne of carbon. These can be reversed at any time. Trading and exchange systems must therefore address the issue of permanence risk – and almost certainly adopt lower bounds for both carbon sequestration potential and for allocated monetary values. The risk of reversal will be lower during the time period bound by a contract between a buyer and seller of carbon reduction credits, but permanence will only be guaranteed if there are long-term changes in behaviour and

attitudes. Over time, the scientific and measurement procedures may mature too, thus bringing greater clarity to the terms of trade.

Despite these uncertainties, carbon `boards of trade' or trading systems first emerged during the year 2000. There are three ways to calculate the value of carbon in such trading and exchange systems:

i) the first option is to allocate a value through calculation of the external costs of each tonne of carbon emitted to the atmosphere by assessing damage, mitigation and adaptation costs;

ii) the second option is to calculate the cost of implementing projects that would deliver a particular policy target, such as for the Kyoto Protocol;

iii) the third is to assess what businesses are currently willing to pay others as an offset for their own carbon emissions – companies are, in effect, hedging against the risk of future enforced payments to meet tougher carbon emission regulations.

The externalities of carbon have been calculated in Europe to be US$95 per tonne[4] according to ExternE and Open Fund models (Pearce et al., 1996; Eyre et al., 1997; Holland et al., 1999). This is higher than the $20-28 per tonne values estimated in the early 1990s (Fankhauser, 1994; Sala and Paruelo, 1997). ExternE studied external effects of greenhouse gases on climate change, health, parasitic and vector borne diseases, sea level rise, water availability, biodiversity, and storm, flood and drought incidence (Eyre et al., 1997). The data in the Open Framework and FUND models take account of differences in discount rate, are weighted according to wealth differences in affected countries, and take account of `social contingency' (the capacity of regions/countries to adapt to change). This means that uncertainty is still very large (cf Eyre et al., 1997). This value of $95/t C represents an upper bound of what could be paid in trading systems[5].

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[4] In this paper, we use the conversion factor of US$1.50 to £1, as rates have fluctuated between 1.40-1.60 during 1999-2000.

[5] We use conservative figures for damage costs based on a quarter of the difference between the lowest and highest estimates contained in the Open and FUND models, and according to two different discount rates (1% and 3%), suggest that the marginal costs of methane are $395/tonne (range $359—530/t); of nitrous oxide are $11,295/t (range $6400-26,000/t); and of carbon dioxide (as C) are $95/t (range $71-170/t) (see Pretty et al, 2000).

A number of carbon exchange or trading systems have recently been established, in which carbon credit values are being set at much lower levels than the real external costs[6]. Some of the first trading systems include:

i) The consortium GEMCo (a group of Canadian utility and energy companies) has agreed to pay via an insurance firm $1-3 per tonne CO_2e to Iowan farmers – equivalent to $3.67-11 per tonne C for CERCS (carbon emission reduction credits), or $14.8-24.7 per hectare. This includes cost of contracts, discounting, risk, verification costs (<$0.4-0.5 per t C) (Aldyen Donnely, pers. comm.)[7];

ii) An internal trading system set up by seven North American companies (BP Amoco, Royal Dutch Shell group, DuPont, Suncor Energy, Ontario Power Generation, Alcan Aluminium and Pechiney) is aiming to cut emissions by 20% below 1990 levels, and carbon credits have been agreed to be worth $5-16 per tonne C (£3.3-10.7 per tonne). BP Amoco's own internal trading system for its business units is seeking to reduce the company's own 77 million tonnes of CO_2 emissions by 10% by 2010; and uses a higher value of $22 per tonne (Mortished, 1999).

iii) The Tokyo Electric Power Company (TEPCO) has invested US$5 million in Tamar Tree Farms in Tasmania for 3000 hectares of eucalyptus plantation, which is expected to yield TEPCO 130,000 tonnes of carbon credits. The payment amounts to $38 per tonne C (Raghavan, 2000)[8].

iv) The Dallas-based utility company, Central and South West Corporation has spent US$5.4 million on acquiring 7000 ha of rangeland that was formerly forest in Paraná in Brazil (Ellison, 2000). The US Nature Conservancy estimates that it will sequester one million tonnes of carbon – putting the price at $5.4 per tonne[9].

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[6] Examples include the Chicago Climate Exchange (www.chicagoclimatex.com), the company Environmental Financial Products (www.envifi.com) , and the International Carbon Bank and Exchange (http://test.icbe.com). Successful trading systems already exist in the USA for SO_x and NO_x emissions, the annual financial volume of which is some $1.7 billion.

[7] The same company, GEMCo, paid a group of Iowa-based pig operators in February 2001 to reduce emissions of methane by converting waste management from anaerobic digester lagoons to closed manure containment in 172 facilities. The amount that has been paid has not been disclosed (the main recipient is Heartland Pork, which owns 20 of the operations).

[8] There are claims that this project is accelerating destruction of native forests, in order to plant fast-growing eucalyptus.

[9] The company, just to return to 1990 emissions levels, must cut annual emissions from 50 to 35 million tonnes of carbon – and so this project in Brazil represents only 1/15th of that target.

The range is wide – from US$1-38 per tonne of carbon, though the most common values are in the $2.50-5.00 range. These per tonne monetary values are considerably less than the optimistic wishes of some farmers[10]. These values are similar to estimates for market prices for sequestered carbon in tropical forests by Pearce et al. (1998) (US $5-23/t C) and by Ellermen et al. (1998) (US$13/t C). This would put the size of the global market for tropical forestry at some 200-300 million tonnes of carbon, with a value of US$2.5-7.0 billion. Though sizeable, this is well below some earlier more optimistic estimates (Jepma and Munasinghe, 1998; Smith J et al., 2000).

We use these market prices to plot the potential gains for zero-tillage farmers using three different types of ZT systems (Figure 3). Intensive ZT systems with no rotations yield less income than mixed systems. The best are ZT systems with mixed rotations and leguminous cover crops that accumulate more than 1 tC/ha/yr.

Figure 3. Potential annuals payments to zero-tillage farmers according to three ZT systems
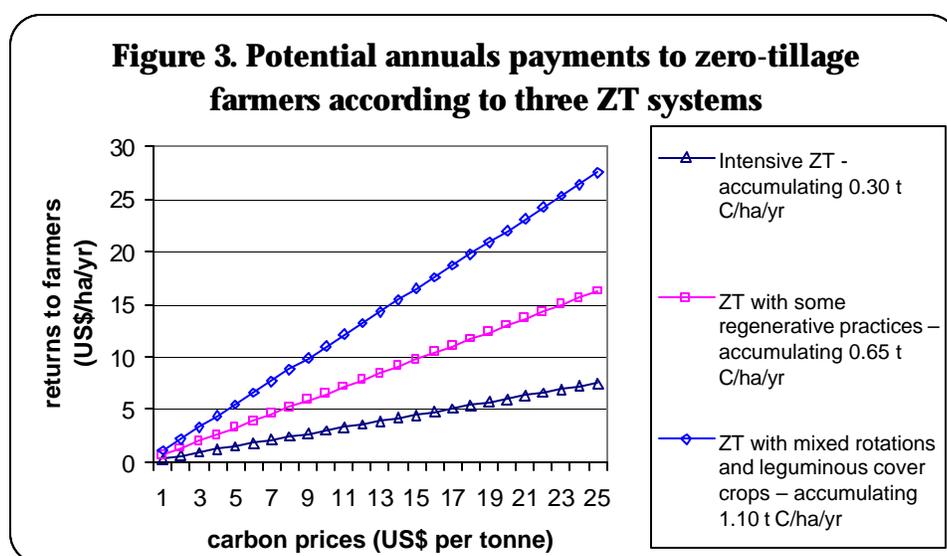
Using carbon accumulation rates of 0.5-1.0 t C/ha for US conservation tillage systems, Marlon Eve and colleagues of the USDA's Agricultural Research Service (in Comis et al., 2001) indicate that US farmlands and grasslands could be accumulating between 20 and 200 million tonnes of carbon annually (depending on the type of conservation tillage system

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[10] Jim Kinsella, Illinois farmer, was recently quoted as saying *"a minimum value that should be paid is $100 per tonne"* (in Perkins, 2000).

adopted). This would create an additional income to farmers worth $100 million (at low C accumulation and $5/ t C) to $4 billion (at high C accumulation and $20/t C).

Using similar ranges for the UK, we estimate that carbon could bring arable and grassland farmers (not counting rough grazing) between £18m ($27m) and £147m ($220m) per year. This would represent a significant additional source of additional income.

Nonetheless, at these carbon prices, it is clear that farmers are not set to become solely carbon farmers. However, systems accumulating carbon are also delivering many other public goods, such as improved biodiversity and clean water from watersheds, and policy makers may also seek to price these so as to increase the total payment package (Dobbs and Pretty, 2001).

6. Contested Issues on Sinks

The important policy questions centre on how to establish permanent or indefinite sinks; how to prevent leakage (eg reploughing of zero-tilled fields, deforestation); how to agree measurements; and whether the cost of implementation can be justified through their additional side effects or multifunctionality. For example, investments in a watershed development programme to improve forest cover and soil health would also improve the productivity of farms, the quantity of water yielded, and the local biodiversity (Hinchcliffe et al., 1999).

In the USA, a range of policy initiatives will have an important effect on carbon emissions and sequestration, and the likelihood of farmers adopting more sustainable practices. These are the Carbon Cycle and Best Practices Act that was approved in 2000, and which provides for $15 million for research on quantifying soil carbon sequestration; and the Domestic Carbon Sequestration Incentive Act (not yet passed, but likely to be agreed by Senate in early 2001) is proposing to pay farmers up to $50 per ha for employing conservation tillage practices.

The UK government has recently announced that it was take to steps `towards a low carbon future'. It has announced that it: i) will set up a `Carbon Trust'; ii) is looking for sustainable carbon technologies; and iii) will launch a joint DETR/DTI Waste and Resources Action

Programme. However, there are no plans at present to pay farmers for carbon sequestration under agri-environment policies under the new Rural Development Regulation of the Common Agricultural Policy.

Finding the balance between public policy support for carbon sequestration through stewardship or `green' payments and private trading systems will be difficult. Governments clearly have an important role to play – and many suspect the private trading systems will not deliver sufficient incentives alone to encourage farmers to make substantial changes towards sustainable practices. As indicated earlier, some analysts have suggested that carbon as a commodity could add up to US$4 billion to farm incomes in the USA (at high carbon accumulation rates and high carbon prices).

But it is also clear that we do not yet know how much carbon would be created in response to monetary incentives for carbon sequestration. The empirical evidence is relatively sparse, and practical experience even more limited. No agreed system of payment levels has yet been established. Trading and exchange systems are currently using values of between US$5-25 per tonne of carbon, which is substantially lower than the real external costs of each tonne of carbon. The levels agreed in early contracts are likely to change as the science becomes more precise. Moreover, establishing baselines against which to measure progress is inexact, as these have to be estimated in retrospect. Again, there is no established or agreed methodology.

Another unresolved issue relates to the location for the greatest carbon returns on investments. Investments in creating sustainable systems in the tropics are likely to be cheaper than in temperate regions, where industrialised agriculture prevails. Such transfers from industrialised to developing countries could produce substantial net global benefits as well as benefit poorer developing country farmers. But this would at the same time diminish markets for farmers in industrialised countries.

Trading and exchange systems offer significant new options, but it is also clear that emissions trading alone cannot solve climate change problems, as substantial cuts in emissions will also be needed. Perverse outcomes are also possible in the early stages of trading systems, such as the conversion of native forests to fast-growing tree monocultures

so as to obtain reward for emissions credits, or the ploughing of pastures so that they can be reconverted to qualifying zero-tillage systems.

A further difficulty centres on the responsibility for future emissions. For example, polluters may meet their emissions' quotas by buying carbon credits from farmers, who sequester carbon in their soil through zero-tillage. If for some reason, these farmers later have to plough, it is unclear who would be responsible for the re-emitted carbon. However, most current agreements and contracts have a stated `vintage', whereby an emission reduction credit is denominated as a CO_2e tonne reduced or absorbed in a particular year (Aldyen Donnely, pers. comm.).

7. Concluding Comments

There is strong evidence that sustainable agricultural and land management can make an important contribution to climate change mitigation through both emissions reduction and carbon sequestration. As the national and international markets for carbon grow, so the sequestered carbon could represent an important new source of income for farmers.

Agricultural systems that result in increased carbon sequestration are also more sustainable. They contribute both to farmers' incomes through natural capital accumulation on the farm, and they result in fewer negative externalities (Izac, 1997; Sanchez et al., 1999; Pretty et al., 2000). Soil biodiversity is also higher, including both micro-organisms and macrofauna. Moreover, sustainable systems are more energy efficient, particularly because of their lower reliance on purchased inputs that are energy-expensive to manufacture.

In reviewing evidence for experiments in both temperate and tropical environments, we conclude that adoption of zero-tillage systems will result in the annual accumulation of at least 0.3-0.6 tonnes of carbon per hectare. This increases with adoption of mixed rotations, particularly those with green manures and cover crops that add large amounts of biomass to the soil. If trees are incorporated into agricultural systems through agroforestry, and these are allowed to be long-term sinks or are used in the short-term to substitute for fossil fuel sources of energy, then the annual sinks grow considerably.

Carbon trading and exchange systems are beginning to emerge. These are currently putting a value at US$5-25 per tonne. This is considerably less that the marginal damage cost of each tonne of carbon emitted as carbon dioxide to the atmosphere, and less that the total positive benefits produced by sustainable farming systems accumulating carbon.

The policy challenges now centre on finding ways increasingly to divert public support to farmers in the form of stewardship or green payments so as to ensure the maximum supply of public environmental goods, as well as making progress on encouraging the success of private carbon trading systems. Carbon, therefore, represents an important new source of income for farmers, as well as helping to encourage farmers to adopt a wide range of sustainable practices.

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