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Economic, biological and policy constraints on the adoption of carbon farming in temperate regions

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In this paper the issues surrounding the potential role for agriculture in temperate climates in the mitigation of greenhouse gases are examined, with a particular focus on the constraints and limitations on the adoption of practices contributing to carbon sequestration. Other land uses have come under close scrutiny for their potential to act as carbon sinks and it is likely that soil sequestration may become a legitimate part of the 'Land-use, land-use change and forestry' mechanism. However, for this to occur, further developments in our understanding of the biological processes involved in soil-carbon sequestration are required.

Keywords: carbon sequestration; soil microbiology; policy design

1. Introduction

We begin with an analysis of the estimates of the potential capacity for agriculture to sequester carbon. The necessary land-use and management practices are then considered, followed by a discussion of the limitations in our understanding of the biological processes leading to soil-carbon sequestration and the techniques currently being developed to address this. We then consider the economics of soil sequestration. First, the difficulties in measuring the costs and benefits associated with carbon sequestration are considered. Policy implications are then discussed with particular reference to how existing agricultural policies (such as the EU's set-aside policy) may be adapted to promote carbon sequestration. Available empirical evidence on the marginal cost of carbon sequestration in agriculture is presented and this is compared with the likely value of carbon permits. Estimates of the potential financial benefits to agriculture are considered and finally conclusions are drawn as to the future positive role of temperate agriculture in carbon sequestration.

One contribution of 20 to a special Theme Issue 'Carbon, biodiversity, conservation and income: an analysis of a free-market approach to land-use change and forestry in developing and developed countries'.

2. The role of agricultural land use in carbon sequestration in temperate regions

Pretty & Ball (2001) surveyed the results of long-term agricultural experiments in both Europe and North America and concluded 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. Antle & McCarl (2002) note that when undisturbed soil is brought into cultivation the result is a loss of between 20 and 50% of soil carbon over a period of around 50 years, with the amount varying by soil type, agricultural practices and other site-specific conditions. The Australian Greenhouse Office (AGO 2000) estimates that 80% of Australian mineral soils contain less than 80 $\mathrm{tC\,ha^{-1}}$, representing a loss of half the soil carbon originally present in the top 20 cm of the soil profile.

The key to agriculture's contribution to mitigating climate change is that soil organic matter and soil carbon can be increased to new higher equilibria with sustainable management practices. Therefore, in most cultivated soils there is the potential to rebuild the soil-carbon stock. However, the biological processes that are ultimately responsible for the additional soil-carbon sequestration, either as recalcitrant soil-organic-matter fractions with a half life measured in hundreds of years (Puget *et al*. 2000), or as a result of increased microbial biomass resulting in increased carbon which may become tied into a decomposing cycle (Ball 1997), have yet to be fully elucidated. However, rapid advances in the field of soil microbiology are being made since the advent of techniques based on the extraction, amplification using polymerase chain reaction and examination of DNA directly from the soil without culturing, and these will lead to a greater understanding of critical soil processes. An additional advantage of storing carbon in soils is that it is less at risk from loss through wildfire and pest outbreaks than aboveground biomass or forestry. This is perhaps more important in the US and Australia, where fire is more prevalent than in Europe.

The potential role of agriculture is substantial. For example, Kern (see Lal *et al*. 1998 and references therein) estimates that US agricultural soils hold 7 Gt of carbon. It is estimated that the US has the potential to sequester between 75 and 208 Mt of carbon equivalence per year (Lal *et al*. 1998). On average this represents 8% of US emissions of greenhouse gas (GHG) or 24% of the US reduction commitment under the Kyoto Protocol. In Australia conservative estimates of potential sequestration are of between 3.5 and 5 $\mathrm{MtC\,yr^{-1}}$ over a 20-year period for the 50 Mha of arable land and 13–15 $\mathrm{MtC\,yr^{-1}}$ for the 425 Mha of rangelands (AGO 2000). In Canada it is estimated that 736 MtC could be sequestered over the next 20 years (ASCCC 1999).

The Royal Society (2001) published figures, derived from the IPCC, which suggest that globally a total of between 1.53 and 2.47 $\mathrm{PgC\,yr^{-1}}$ could be sequestered between 2000 and 2050. Using the mid-point of these annual estimates they suggest that a total of 100 PgC could be sequestered during this period, of which just under 50% could come from temperate soils. Nonetheless, there is considerable uncertainty about the actual potential for soil sequestration, let alone whether the needed international cooperation could be attained to achieve this level of sequestration. In addition The Royal Society estimates that the required reduction in carbon in the atmosphere will be a total of 1000 PgC by 2100 and 400 by 2050. They therefore argue that the land sinks and forestry can only provide a part of the required reduction.

The potential role for agriculture in helping achieve targets such as those set under the Kyoto agreement does vary between locations. For example, The Royal Society notes that, for the UK, the possibilities of mitigation through land (0.006–0.008 PgC yr^{-1}, equivalent to 4–6% of 1990 CO_2 emissions) is proportionately less than for Europe as a whole, as land area is small in relation to emissions. This disparity in the potential for soils to act as sinks will mean those countries where options are limited (such as the UK and Japan) may be disadvantaged compared with those countries where there is greater potential (the US, Russia, Canada, Australia). If soil sinks are accepted, then the latter countries may use them to offset emissions in place of actual reductions in emissions (which may be more costly to industry). This could alter the international competitiveness of energy-intensive products.

A key point is that agricultural soils provide a short-term solution for reducing greenhouse gases. This is because they are finite in scale and require no technological change to make them operational. Therefore, it may be reasoned that their greatest use lies in an immediate focus on carbon sequestration while effective and efficient renewable energy sources that do not emit GHGs are developed.

Losses of soil carbon occur in agricultural soils primarily due to intensive crop-production systems following conversion of natural perennial vegetation. The factors that have most influence on soil-carbon levels are the amount and quality of the input of plant residues to the soil and the climate (temperature and rainfall). Soil properties (such as clay content) also affect soil-carbon levels. Table 1 highlights how the sink capacity of soils can be improved and the areas where there is still potential for agriculture to act as a source of CO_2. Soil sequestration can be achieved by changing land use, for example from cropping to set-aside, or management practices such as conservation tillage.

Evidence from Europe (reviewed in Smith *et al.* (2000)) suggests that woodland regeneration can lead to accumulation of 3.3 tC ha^{-1} yr^{-1} and short-rotation coppicing to 6.62 tC ha^{-1} yr^{-1}. It is also shown that other practices, such as zero till and the inclusion of grassland in rotations, can lead to substantial carbon sequestration. Pretty & Ball (2001) cite many studies that found accumulation of organic matter under integrated systems. In Australia (AGO 2000) it is argued that, because of the sheer scale of agricultural systems (45–50 Mha of land are either under pasture, cropped continuously or rotated through a crop–pasture sequence), even small changes in sequestration per hectare could lead to large increases in sequestered carbon.

The changes considered in table 1 range from simple management practices to complete land-use changes. One of the most discussed changes in management practices is the move to zero- or minimum-till techniques. 'Conservation tillage', 'no-till' or 'zero-till' systems maintain a permanent or semi-permanent organic cover on the soil, comprising either a growing crop or dead organic matter. The function is to protect the soil from the action of sun, rain and wind and to feed soil biota. Decomposition of the additional dead organic matter by the soil microflora will stimulate the activity and diversity of the microflora, resulting in increased stabilization of the dead organic matter in the forms of humic substances. However, increased microbial activity and microbial biomass also lead to increased respiration rates and therefore increased release of CO_2 by soils. Current research in the area of soil biology is

Table 1. *Sources and sinks in temperate agricultural systems*
(Taken from NRDC (2000) and Watson *et al.* (2000).)

	sources	sinks
transformations	croplands from wetlands	set-aside (to grassland or woodland)
	croplands from grasslands	
	croplands from natural ecosystems	
production	lower residue yield (inorganic fertilizer inputs)	higher residue yield
	change to crop types with lower biomass	change to crop types with higher biomass
	lower lignin content	higher lignin content
	longer fallow	shorter fallow
soil conservation	intensive till	no or minimum till
	residue straw sales	incorporation
	stubble burning	cover crops (inter-row with perennials)
		control of soil water
other	liming	animal manure or sewage sludge

aimed at understanding the effects on soil microbial biomass, diversity and activity of changes in both climate and land-management changes, leading to predictive models which will be essential if the potential of soils for carbon sequestration under systems such as zero till under future climate change are to be realized. Understanding the role of microbial diversity and activity in the sequestration of carbon may lead to the developments of land-management practices, developed on the basis of empirical data, which can increase the carbon sequestration potential of soils.

For example, figure 1 illustrates the interactive effects of atmospheric climate change and land-management practice on soil microbial biomass by showing the results of exposure of soil to elevated atmospheric carbon dioxide under both high- and low-fertilization regimes. This exposure resulted in a 20% increase in microbial C in soils exposed to elevated atmospheric CO_2 irrespective of the N concentration. Addition of high quantities of N increased the microbial biomass content of both soils. Whether this increase in microbial biomass is a permanent feature of the soils is unknown. However, evaluation of the microbial diversity of the control and fumigated soils, assessed using microbial-diversity measurements such as denaturing gradient gel electrophoresis (DGGE) and microbial-activity measurements such as BIOLOG plates, indicates that the increased microbial biomass observed is not accompanied by an increase in soil microbial diversity, but rather by either no change in the diversity indices or a decrease in microbial diversity when the DGGE results were interpreted (table 2).

The potential result of such land-management changes is reduced soil erosion and improved soil organic matter and carbon content. The gains from such systems com-

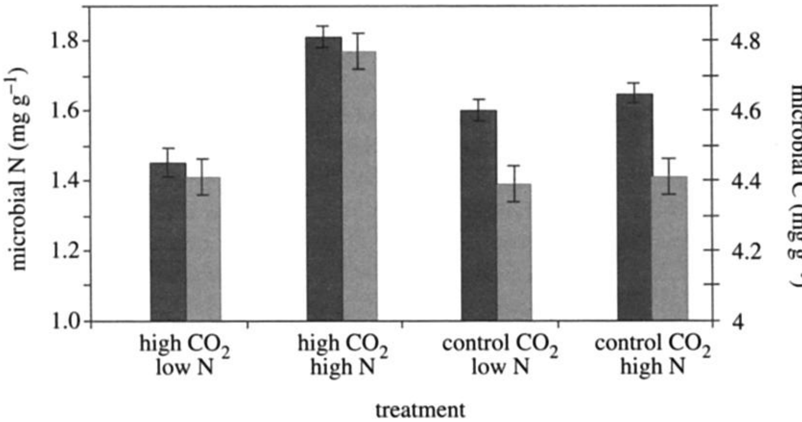

Figure 1. Microbial C (light grey bar) and N (dark grey bar) of control soil (360 ppm) and soil collected exposed to elevated atmospheric CO_2 (ambient plus 200 ppm CO_2) exposed to high and low N fertilization rates (350 kg ha^{-1} yr^{-1}, respectively) at Arizona free air–carbon dioxide enrichment site in September 1998. Standard errors are shown. (From Porteous *et al.* (2002).)

Table 2. *Species richness and Shannon–Weiner diversity index (H') value for soil collected in Arizona, calculated from BIOLOG and DGGE profiles. (From Porteous (2002).)*

		BIOLOG		DGGE	
CO_2 treatment	N application	species richness	diversity (H')	species richness	diversity (H')
ambient	low	31	1.490	30	1.32
ambient	high	31	1.496	30	1.31
elevated	low	31	1.499	28	1.30
elevated	high	31	1.502	23	1.17

Table 3. *Losses and gains of carbon under conventional and zero-tillage management systems in the USA*

(Data taken from Pretty & Ball (2001) (adapted from Reicosky *et al.* (1995); Langdale *et al.* (1992); and Edwards *et al.* (1988, 1992)).)

system	rotations	gains or losses of carbon (tC ha yr^{-1})
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

pared with conventional methods can be seen for the USA in table 3. It would appear that intensive arable with zero tillage results in accumulation of 0.3–0.6 tC ha^{-1} yr^{-1} but zero tillage with mixed rotations and cover crops can accumulate carbon at a faster rate (0.66–1.33 tC ha^{-1} yr^{-1}).

It has been shown that through changes in land-use and management practices it is technically possible for agriculture to play a significant role in sequestering carbon. However, many technical studies fail to take into account the economic feasibility of such practices, as they ignore the cost and resource allocation implications of changes in land-use or management practice. The next section considers the economics of soil sequestration and also considers how a policy to encourage sequestration may be implemented.

3. Economic considerations

The issues raised when considering the economics of carbon sequestration and appropriate policy design are complex. This is mainly due to the existence of market failures. However, these failures are not unique to carbon and many of the issues are similar to the provision of other environmental benefits, and so parallels can therefore be drawn.

The public-good nature of the atmosphere means that there is little incentive for individuals or even nations to take actions to prevent GHG accumulation. Given this situation, it is clear that action has to come from coordinated government policy and this is the underlying rationale for the Kyoto Protocol. A price for carbon may be seen to arise from either direct government payments or governments setting limits and allowing trade, although Antle & McCarl (2002) do note that incentives may arise as a result of action by interested groups or by firms wishing to show environmental responsibility. Firms already engaging in carbon projects may be doing so in anticipation of future legislation.†

(a) *Opportunity costs*

Antle & McCarl (2002) highlight the fact that the economic feasibility and competitiveness of soil C sequestration depend on the opportunity cost per tC, that is, the opportunity cost per hectare of changing land-use or management practices divided by the rate of soil accumulation. The key issue is whether this cost is competitive with alternative methods of reducing GHG such as forestry or emission reduction.

When considering the opportunity costs, a key factor is the spatial variability in the productivity of land. This variability means that the opportunity cost associated with changing land-use and management practices will also vary. For example, Asby & Renwick (2000) highlight the fact that the profitability of wheat production in the UK varies by £330 per hectare between the most and least profitable quartile group of cereal producers. This variability can also be seen by analysis of farmers' offer curves for placing land into set-aside voluntarily (CRER 2001). These are plotted in figure 2.

The figure reflects producers' perceptions as to the opportunity costs of changing land use. For example, to achieve a level of set-aside of 10%, a payment of between £200 and £300 (with cereal prices of £70 per tonne) would have to be made, whereas the payment would have to be over £500 per hectare to retire 50% of eligible land.

However, as noted above, these figures reflect only the opportunity costs in terms of lost income for a change in land use. For an efficient policy the fact that land

† For example, the Tokyo Electric Power Company (TEPCO) has invested US$5 million in Tamar tree farms in Tasmania for 3000 ha of eucalyptus plantation, which is expected to yield TEPCO 130 kt of carbon credits. The payment amounts to $38 US per tC (Pretty & Ball 2001).

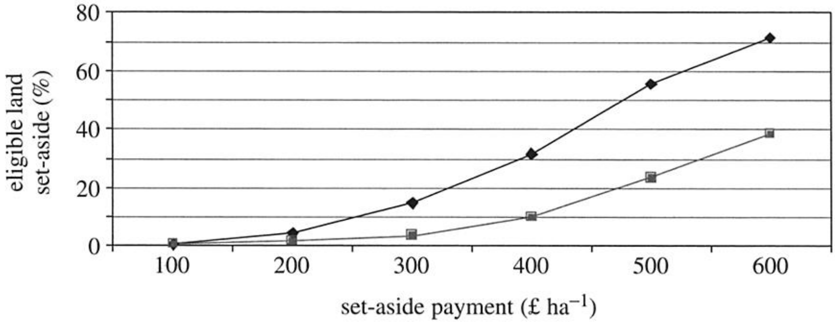

Figure 2. Area of arable land set-aside under different payments. Cereal price: diamonds, £70 per tonne; squares, £100 per tonne. From CRER (2001).

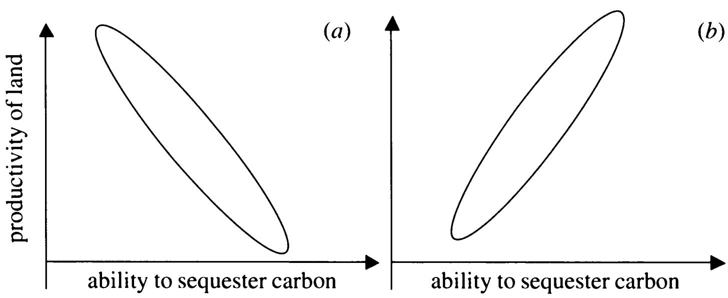

Figure 3. Possible relationships between land productivity and carbon sequestration.

also varies in its ability to sequester carbon needs to be taken into account. The possible impact of this on the policy is highlighted in figure 3. Here two hypothetical relationships between land productivity (and hence opportunity cost of land-use change) and sequestration potential are plotted. In figure 3 the ellipses represent confidence intervals for the relationship between land productivity and ability to sequester carbon, such that 95% of observations can be found within them.

In figure 3*a* an inverse relationship between the ability to sequester carbon and the productivity of land is depicted. This may be a reasonable argument based on the impact of soil organic matter on the yield potential of land.† Under this scenario, the most appropriate land to target for change would be the least productive land (this land would also have the lowest opportunity cost for change). This would make the opportunity cost per tonne of carbon sequestered relatively low. Figure 3*b*, on the other hand, highlights the situation where there is a positive relationship between carbon and productivity. In this case the most productive land is also that which has the most ability to sequester carbon. If this is the case, then the opportunity cost per tonne of carbon sequestered would be much higher.

Therefore, knowledge of both the productive capacity of land and its ability to sequester carbon are necessary to calculate the true opportunity cost of sequestering a tonne of carbon. However, the situation is complicated further by the fact that changes in land-use or management practices may produce other costs and benefits

† The AGO argues that practices that enhance carbon are likely to have more impact on highly depleted soils.

not directly related to carbon sequestration. These are considered in the following section.

(b) *Externalities*

The benefits arising from soil sequestration are multi-dimensional in that the individual business, the wider national community and the international community all benefit. There are gains to the individual farmer because increased soil organic matter is linked to increased productivity. Wider gains to the community may be achieved, as improved soil structure can reduce pollution from agriculture (for example, from sedimentation or run-off). Finally, the mitigation of global warming provides international benefits.

It is clear that the gains to the farmer are internal and hence, as long as they have sufficient information, it is possible that they will optimize the stock of carbon for their business. However, as soil carbon is not observable, it is argued that farmers are not sufficiently aware of the quantity they have in their soil and are therefore unable to optimize soil carbon for their own benefit (Antle & McCarl 2002). In addition, as individual farmers are unlikely to take into account the national and international benefits of increased carbon in soils when operating their business, this will lead to an under-provision of soil carbon. Therefore, a policy that provides the necessary incentives to increase the level of soil carbon should move society towards a more efficient resource allocation.

An understanding of the externalities associated with increasing carbon in soils is important when considering how policy should be designed to achieve a socially optimal level of sequestration from agriculture (Pretty 1995; Pretty *et al*. 2000). McCarl & Schneider (1999*a*) list the possible positive and negative externalities from sequestration, shown below.

Positive externalities are as follows.

(i) Reduced soil erosion may result as the soil structure improves. This will lead to less sedimentation and improved water quality.

(ii) Reduced tillage could alter soil organic matter, increasing soil water-holding capacity and leading to less irrigation water.

(iii) Expanded conversion of agricultural lands to grasslands or forests could stimulate wildlife populations.

(iv) Diminished use of fertilizer could alter chemical content of run-off from agricultural land with effects on quality and ecology. This would improve the situation for non-agricultural users.

(v) Diversion of agricultural land into energy crops may lead to technological improvements which may permit expanded electricity generation at lower cost.

Negative externalities are as follows.

(i) Movement of new land into forestry may have detrimental impact on the economics of forestry and lead to deforestation.

(ii) Changes in land use may not necessarily improve the environment†.

(iii) Reduction in tillage in some areas may lead to an increased use of pesticides.

(iv) If expanded carbon is equal to reduced food and fibre this may lead to higher prices and reduced exports.

The above list highlights a crucial point that introducing new land-management systems will not only provide significant greenhouse benefits but support broader objectives of ecologically sustainable development (AGO 2000). It is this link that the Australians see as an important driver for implementing activities that enhance soil carbon. It is clear though that as far as the wider environment is concerned the land use is very important. For example, the move to zero till with increased use of herbicide chemicals may improve the soil structure but may have relatively small environmental benefits in terms of improving wildlife habitats.

For an accurate measure of the opportunity cost per tonne it is clear that the externalities like those cited above need to be taken into account when calculating the costs of changing land-use or management practices. However, this does raise important questions about the valuation of environmental benefits. This is an issue that arises with many environmental payments. Unless the full benefits of environmental programmes are known, it will not be possible to design a policy that optimizes them. The impact of incorporating externalities is considered in the next subsection, where the economics of a possible method of increasing soil carbon, zero till, is examined.

(c) *The economics of zero till*

In this section the economics of conservation-tillage techniques are considered. It is clear that even without payments for carbon these techniques have become increasingly popular. For example, it is estimated that around 19 Mha in the US is under various forms of conservation-tillage (not strictly zero till) and in Canada and Australia (where moisture retention is a major benefit) areas are also increasing. Zero till is yet to be widely adopted in the EU. It may be assumed that those adopting conservation-tillage techniques do so because they are more profitable. If this is the case, then increased use should be possible through wider dissemination of information about the benefits through education and extension. However, other factors are important in the decision to change to low-till methods. First, as it involves a complete change in management, producers may not have the ability or confidence to adopt the methods. Second, there may be large initial capital outlays, such as for new drills and other equipment.† Therefore, businesses that are capital constrained may not be able to invest in this new technology. Third, it has been argued that though on average zero-till techniques may be more profitable they do result in greater year-on-year variability in returns and hence risk (ASCCC 1999).‡ The first constraint may be overcome to a certain extent by education and extension efforts.

† For example, there are claims that the TEPCO project discussed above is accelerating the destruction of native forests, in order to plant fast-growing eucalyptus.

† For example, in Australia drills can cost around $AU150 000. In addition one farmer made the point that due to the differences between the summer and winter planting conditions they might actually require two different types of drill (Batterham 2001, personal communication).

‡ Whether zero till leads to greater variability is contested. However, it may be argued that if producers perceive it as more risky, then they may not adopt the technique.

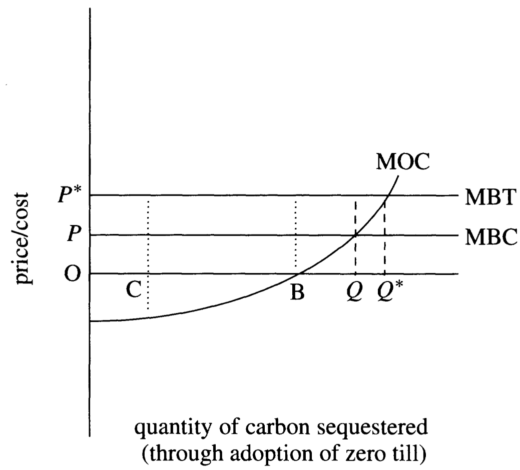

Figure 4. The economics of using zero till to sequester carbon.

It is possible that the capital constraints may be overcome by one-off grants, or some form of conversion payments could be made for a specified period. The question of risk is one that is preoccupying policy makers in Europe and the US, and the answer may lie in some form of crop or revenue insurance.

Figure 4 highlights some of the issues surrounding the adoption of conservation techniques such as zero till (but can be generalized to represent all land use changes). In the figure, MOC represents the marginal opportunity cost for the farm of adopting these techniques. It is drawn as a rising function because clearly not all land is equally suitable for zero-till techniques. For example, in the UK it is estimated that around 80% of cereal land (38% of arable land) is suitable (Smith *et al.* 2000). It has been argued that some farmers will profit from conversion and hence the MOC is negative for at least part of its length.

The current situation may be reflected by a point such as C (figure 4). Here a number of farms have converted to zero till with the subsequent increase in the amount of carbon sequestered in the soil. However, further gains for the sector could be made by increased adoption of the technique. These gains would continue up to point B, where internal gains from adoption of carbon sequestration would be maximized (this is the point where MOC is equal to zero). However, given the external benefits this is not an optimum amount for society. First if we consider the benefits of reduced global warming (represented by MBC)†, then the quantity Q should be sequestered. However, if we include the other external benefits such as improved water quality (and with the assumption that the net benefits are positive), then the total marginal benefits can be represented by MBT. Under this situation, the optimal level of carbon sequestered by zero till is at the higher quantity of Q^*. Therefore, for society it would be beneficial to encourage the adoption of zero till for those farms where the internal economics do not justify it. This analysis suggests that significant progress (a movement towards point B) could be made through improved extension to farms.

† For simplicity, MBC and MBT are drawn as non-decreasing functions of quantity of carbon sequestered. This may be the case if agriculture is a small player in reducing emissions and hence the quantity sequestered through agriculture has little impact. The analysis is equally valid if we draw the marginal benefit curves as sloping downwards.

The figure also gives an insight to the public versus private debate. If a market for carbon is established and carbon has a value, this value may be represented by MBC. However, this would not lead to the optimum level for society as a whole and some form of government payment for the additional benefits may be required ($P^* - P$). These issues are discussed in more detail in § 4. The following subsection considers further issues surrounding sequestration through agricultural practices.

(*d*) *Measurement costs*

A major complication is that, in order to calculate the cost per tonne of carbon sequestered, accurate measurement of soil carbon is required. There are two issues: first whether the technology is really available to accurately calculate soil-carbon accumulation, and second the level of costs associated with obtaining these measurements.

A possible drawback with carbon sequestration is that the costs of obtaining accurate measures required for international acceptance may be so high as to make the whole scheme uneconomical. While general estimates have been made of the sequestration ability of soil, a large amount of uncertainty exists as to measurement. For an optimal policy to be designed it is clear that a fundamental prerequisite is that the amount of soil-carbon flux in soils can be monitored. According to the NRDC (2000) there are several options for measuring soil-carbon flux in a given country.

(1) Employing a system of towers that can sample changes in ambient carbon dioxide levels at a given site.

(2) Using soil investigations and census and topographical data for setting priorities for sampling soil-carbon flux throughout the country and modelling the results for a national estimate (subsequently ground-truth models assumptions can be assessed through site sampling).

(3) Implementing a large-scale expansion of soil-carbon flux sampling that would apply to most individual farms, such that individual farmers could receive rewards based on the actual level of carbon sequestered.

According to the NRDC, all these methods have their drawbacks. The first can be dismissed as too expensive, based on the scale necessary to create a national inventory. The second is flawed because existing investigations are not considered sufficiently comprehensive in spatial area, crop type and typography to provide sufficient data for reasonably accurate model-based national estimate. A convincing predictive ability to estimate carbon flux that considers the many variables of soil type, climate, management and crop type is not yet available, although under investigation. For the third approach, consideration of the logistical problems involved suggests it would not be feasible to institute comprehensive sampling of agricultural soil flux at the farm level at reasonable cost. For example, in the US the number of farms exceeds two million and, as a range of samples would have to be taken from larger farms with heterogeneous crops, practices and conditions the sampling requirements would be too great. In addition, none of the methods attempts to study the microbial activity and diversity present in the soils, but rather merely study the result of their activity.

The NRDC notes that, in the US, considerable resources have gone into developing a model-based approach supplemented by remote sensing. However, these aggregated approaches pose a problem for incentive programmes. Summary parameters based on estimates of the frequency of different practices may be difficult to disprove or prove at the level of a single farm or single hectare. Monitoring and incentives provided at a larger scale, for example by bundling farms, may offer practical difficulties if the bundled units are heterogeneous in terms of practices and conditions. If rewards are offered to individual farmers, then there is a need for verification and reporting at the level of the individual farmer, but the costs of such monitoring and verification may be prohibitive. Factoring in the effect of climate in terms of its spatial variability and also changes over time is an added complication for soil-carbon models.

In contrast to the NRDC, Sandor & Skees (1999) argue that it is not necessary to be concerned with measuring how much additional carbon is sequestered on an individual field, as there are more effective ways of monitoring and verification. They argue that wholesalers in carbon sequestering could develop, and while estimates at an individual level may be flawed, they argue that the error has typical statistical properties and that estimating many individual parcels and aggregating them into one parcel will improve the estimate considerably. However, such an approach still leaves unanswered the problem of incentives at the individual farm level.

Another issue related to measurement is raised by the AGO. Here they argue that information is not currently available about soil conservation management practices taking place. They argue that this is needed to establish a baseline from which future changes can be measured. This is particularly important if international agreement is to be reached on the use of soil as a carbon sink. In the EU such a database may be quite easily obtained, for arable land at least, through the Integrated Arable Cropping System. It could be extended to consider tillage methods as well as the current information on land use.

The analysis to date has shown that the calculation of the real opportunity costs associated with using agriculture to sequester carbon is complicated by the existence of externalities and the difficulties of measuring changes in soil carbon. However, even if these difficulties are overcome there is still a large number of issues surrounding the design of a policy to encourage carbon sequestration.

4. Policy considerations

(a) *Finiteness and permanence*

The AGO notes that building soil-carbon levels is a slow process and that they could take decades to increase as a minimum sustained management of inputs will be needed over many years. A major issue with soil sequestration is that the quantity of carbon that can be sequestered is finite, as gains cannot be counted as a recurring annual sink. Initially they can offset emissions, but later the net gain falls towards zero as the new equilibrium is approached. However, once the sink has become saturated there is still the need to maintain to carbon in the soil. McCarl & Schneider (1999*a*) argue that the accumulation and storage of carbon needs to be considered when designing policy.

A major problem with sequestration through changes in management practice is that the process is easily reversible. If at some time the landowner reverts to less-friendly practices such as ploughing or tree felling, then the stored carbon will be lost.

Therefore, land-based sinks cannot be considered to be permanent, unlike reductions in emissions. There is a need to ensure that the alterations are maintained.

A second issue raised by McCarl & Schneider (1999) is the need to prevent countervailing actions. Countervailing actions are important, as the adoption of emission-reduction strategies in one segment of the economy may lead to a substantial offset by actions in other parts of the economy. A prime example may be if agricultural land is converted to forestry (and if demand for forestry products does not change) there will be an increase in supply, which reduces price and therefore the returns from forestry. There may be an incentive to move existing land from forestry into agriculture. This is in addition to the fact that the potential exists for the new forestry land to revert after one rotation. McCarl & Schneider argue that there may be a case for a policy with a semi-permanent ban on deforestation and non-reversion clauses.

(*b*) *Property rights*

The above points touch on the fundamental issue of property rights. This relates to the responsibilities of farmers with respect to carbon emissions and storage. If it is reasonable to argue that farmers had no need to consider the release of carbon from their land in the past, then the current position may be used to define the reference level for property rights. Having established a reference level, it may be valid to apply the 'polluter pays' principle to those who diminish carbon levels further and the 'provider gets' principle for those increasing the amount of carbon stored in their soil. However, the instigation of policies that apply the 'polluter pays' principle for those who continue to deplete soil-carbon levels may face stiff opposition from the farming community.

An example of the likely difficulties associated with payments for environmental improvement can be seen with the Countryside Stewardship Scheme as operated in the UK. Eligibility for this scheme is assessed on a number of criteria but one is to provide environmental gains. Now those who have already undertaken improvements at their own cost may not be able to show that joining the scheme will bring further gains and hence may not be accepted. In contrast those who have neglected their environment, or worse actively degraded it, can show the greatest benefit from joining the scheme. A parallel may be drawn with carbon sequestration. Those who have already undertaken conservation techniques may not be eligible for payments, while those who have degraded their soils will be able to show the most carbon-sequestering potential. If the scheme is not carefully designed, there may be an incentive for those producers who already practice conservation measures to plough up their land to take advantage of possible government payments (this is the perverse incentive problem considered by Wu & Babcock (1996)). It is argued that this problem may be overcome by setting a baseline year (such as 1990) and crediting those that can show they have changed practices since this period. It is argued that even if this not acceptable to the international community, an individual government could still buy and hold the credits from those who have already changed their land-use techniques.

(*c*) *Transaction costs*

Antle *et al.* (2001) note that there are two costs associated with sequestering carbon. Firstly there is the opportunity cost of the farm and secondly there is the cost associated with implementing contracts and that involves brokerage fees, monitoring and other transaction costs. An example of the potential importance of contract costs has already been shown with the possible costs of measuring changes in carbon. Enforcement costs are likely to vary, depending on the way that sequestration is undertaken. For example, changes in land use are relatively easy to monitor, and the EU already has a system in place for arable land, which could be easily adapted for the needs of carbon sequestration. However, changes in practices (such as tillage techniques) would be harder to monitor and therefore ensuring compliance may be more expensive. These issues reflect the fact that there are likely to be problems with asymmetric information, as the producer is likely to know more than the regulator.

Antle *et al.* (2001) proceed to formally assess the relative merits of a per-hectare payment compared with a payment per tonne sequestered. (The 'per-tonne sequestered' in Antle *et al.*'s work is not assessed on a per-field basis but is estimated on the best available information about the impact of changes in land use or practices within specified regions (agroecozones).)

Detailed analysis is undertaken and, allowing for spatial heterogeneity, it is argued that a per-tonne payment is likely to be more efficient than a per-hectare payment. That is, the marginal opportunity cost of the per-hectare payment mechanism is likely to be greater than the per-tonne mechanism. This is particularly the case with high variability in land quality, because those farmers with land with a low ability to sequester carbon will enter a per-hectare payment scheme and hence the cost per tonne of carbon will be increased.

Consideration has to be given to the question of additionality. If farmers have changed or were going to change their practices anyway, then it may be considered inefficient to compensate them for doing so. This is particularly the case if changes have been undertaken that improve the profitability of the business (this can be seen with the adoption of zero till in many countries). However, it may be reasoned that payments are valid, as they reflect the true value of the practice to society. For example, if the economics of agriculture changes (due to, say, some technological advance) and zero till becomes for some reason less profitable than conventional tillage practices, the payment may keep farmers using zero till, thereby preserving the environmental gains in the longer term.

The analysis so far has concentrated on a discussion of the factors that impact on the economics of carbon sequestration and how these will influence policy design. The following section considers how policy may be enacted.

5. Policy implementation

Much work has concentrated on how a policy to encourage carbon sequestration should be designed (Antle & Mooney 1999; Feng *et al.* 2001; McCarl & Schneider 1999). An immediate question and one directly related to the overall theme of this issue is whether the establishment of a market for carbon is the appropriate instrument or whether direct government payments are required. As mentioned above, a market could be developed if GHG emissions are controlled and trading allowed. However, as in the discussion of zero till highlighted, the existence of externalities means that a free-market approach is unlikely to lead to an optimal level of sequestration. For example, on the assumption that the externalities associated with carbon storage are positive, the market value for carbon itself (based purely on the costs or value of reducing carbon in the atmosphere) will be too low for agriculture to optimize sequestration.

If some form of direct government involvement is required, then the question clearly arises as to how this can best be undertaken. When considering the possible policy options to encourage soil sequestration it should be remembered that the government already heavily intervenes in the agricultural sector in all industrialized countries. This means that there may be some scope for altering existing policies to achieve the goals of carbon sequestration.

A key factor is that, for many countries in temperate climates, the price of agricultural products is maintained at an artificially high level. This means that alternative land-use options, such as the production of non-food crops or environmental goods, are disadvantaged. Therefore, it may be argued that the first step to encouraging practices such as carbon sequestration would be to remove these distortionary price supports. In relation to our earlier analysis this would reduce the opportunity cost to farms of adopting practices that sequester carbon. The EU has taken steps in this direction through the reduction of the level of price support offered for cereals. Though farmers are still influenced in their land-use decision by the fact that these price cuts have been compensated for by direct area-based and headage payments.

The 'greening' of agricultural policy offers a potential source of revenue to encourage sequestration. For example, in the US and EU, environmental payments are offered under a range of programmes (the Environmental Quality Incentives Program (EQIP) and the Conservation Reserve Program (CRP) in the US and the Rural Development Programme in the EU). Often these payments are made on a per-hectare basis (CRP, Environmentally Sensitive Areas, etc.) (Dobbs & Pretty 2001). These payments have been considered to be inefficient, as they do not take account of the relative opportunity cost of obtaining the specified benefits. For example, it has been argued in the US that much of the land 'retired' may not have been in production anyway (McCarl & Schneider 1999*a*). However, they are relatively easy to administer and police.

A European example highlights the potential for altering existing policies. At present in the EU a form of compulsory set-aside is in operation. This policy was initially implemented as a form of supply control; however, it became clear that it could also provide environmental benefits. It has been shown that specific land use on set-aside can lead to an accumulation of carbon. However, the current system in the EU was not designed with this in mind and hence is not an efficient approach for a number of reasons. First, in order to be eligible for area aid payments, farmers (with the exception of small farmers, who are exempt) are required to set-aside land. This is beneficial in that the coverage of set-aside is large; however, no account of the opportunity cost of producers is made. Economic efficiency could be improved by targeting set-aside at the high-cost producers. Alternatively, set-aside could be targeted at those who can provide the greatest level of environmental benefits (including carbon sequestration) through allowing trade and linking payment to value of output provided. A further problem with set-aside in its current form is that, in the UK at least, the vast majority of producers rotate the set-aside land around their holding (74% according to CRER 2001). Given that zero tillage is not widely practiced in the UK, this suggests that a gain can only arise if the losses from reploughing are less than the gains from setting aside the next piece of land. A final problem is that the set-aside rate has varied from year to year depending on the market situation

Table 4. *Possible policy actions to attain changes in management practices*

(Reproduced from Bruce *et al.* (1998). H denotes high; M, medium; L, low; CS denotes cost share (paying all or part of the costs of implementing the practice; cost could be defined to include lost income); CC, conservation compliance (requires landowner to participate in a market transaction, commodity support or other governmental programme with economic benefits); ETA, education and technical support (requires that practice be profitable); LR, land retirement (providing payments, usually annually, for land to be put into specific uses).)

management practice	relative carbon gain	possible policy actions
cultivated lands		
adoption of no-till or reduced-till	M	CS ETA CC
use of winter cover crops	L	CS ETA
elimination of summer fallow	M	CS ETA
use of forages in rotations	M	CS ETA
use of manures and other organic fertilizers	M	CS ETA
set-aside lands		
establish perennial grasses	H	CS LR
soil/water conservation measures	H	CS ETA CC
establish forests	H	CS LR
restore wetlands	H	CS
pasturelands		
improved grazing methods	M	CS ETA
fertilizer applications	M	CS ETA
irrigation	M	CS

for cereals. Again, this means that gains are lost as land is moved back and forth between intensive cropping and set-aside.

CRER (2001) proposes a more environmentally targeted scheme with farmers tendering to provide a specific set of benefits. These benefits are then weighted according to their importance. These weights could vary spatially. It is clear that such a scheme could include carbon sequestration as one potential benefit. Following Antle *et al.*'s arguments this should in theory be in the form of tC accumulated rather than just a change in land use, although in practice changes in land use may be the only viable indicator. A problem with this approach is that it does require the policymaker to have some idea of the relative value of the various environmental benefits on offer in order to determine the weights.

Bruce *et al.* (1998) consider the possible policy actions required to encourage a wide range of management practices for the US (table 4). Here they argue that the options available to the government are some form of cost-share arrangement, education and training and conservation compliance.

Feng *et al.* (2001), consider how policy can be designed given that soil-carbon sequestration is potentially reversible. Their analysis is equally applicable whether payments come through government policy or through a fully functioning market for carbon credits, though their discussion is couched in terms of a functioning market that determines the price of carbon abatement. That is, the price of one unit of carbon credit is the price associated with one unit of permanent carbon reduction. They consider three policy designs, which they term 'pay as you go' (PAYG), 'variable-length contract' (VLC) and the 'carbon annuity account' (CAA).

The PAYG system applies the price of one full credit for each unit of carbon released or sequestered, with no consideration given to the permanence issue. However, while a sink owner gets rewarded a full credit when they remove one unit of carbon from the atmosphere, they will also have to pay a full credit when they release the sequestered carbon. In the VLC, the temporary carbon sequestering will be paid at a discounted rate. The rate of discount will depend on how long the carbon is kept out of the atmosphere. Under the CAA approach the generator/maintainer of the sink is paid the full carbon price and payment is made directly into an annuity account. As long as the sink remains in place, the sink operator can access the earnings of the annuity account but not the principal sum. The principal is recovered by the ongoing permit price if and when the carbon is released. If the sink remains permanently, the sink owner eventually earns all of the interest payments, the discounted present value of which equals the principal itself (the permanent permit price). All three methods have potential drawbacks but they do suggest that policy can be designed to overcome the problem of permanence.

The next section considers some of the, admittedly sketchy, empirical evidence on the costs of sequestering carbon in agriculture and how this relates to estimates of the value of carbon.

6. Estimates of the cost and returns from carbon sequestration

There have been a number of studies that have attempted to quantify the marginal opportunity cost of sequestering carbon in agriculture. A study of the work by McCarl & Schneider (1999*b*) suggested that agriculture could operate for as low as \$10–\$25 per tonne. A later paper by Antle & McCarl (2002) analysed a number of mainly US studies and concluded that the least-cost agriculture providers could be competitive with alternative methods such as forestry and emission reductions but that payments in excess of \$50 per tonne may be required for agriculture to be a major player. Pautsch *et al.* (2001) estimate that the cost of soil sequestration through low tillage ranges from zero to \$400 per tonne, depending on the quantity of carbon sequestered.

These estimates can be related to the current estimated market value of carbon to give some indication of whether agriculture would be competitive in a market situation of permits and trade. The estimates of the sequestration costs of agriculture seem high in relation to the current estimated market value of carbon. Pretty & Ball (2001) highlight that the range of prices in some pilot schemes is between \$1 and \$38 per tonne of carbon, though common values are in the low \$2.50–\$5.00 range. These values are similar to those found for tropical forestry by Pearce *et al.* (1998).

Earlier work seems to have been more optimistic about the likely value of carbon; for example, Sandor & Skees (1999) reported estimates of the value of carbon-emissions allowances ranging from \$15 to \$348 per tonne, though they concluded at the time that early market signals suggested a market value of carbon of between \$20 and \$30 per tonne. The current estimated value of carbon also seems low in relation to the potential damage that global warming will cause. It has been estimated that when worldwide losses are taken into account each tonne reduction in carbon could be worth as much as \$95 (Eyre *et al.* 1997).

Pretty & Ball (2001) cite estimates produced in Comis (2001) that the potential addition to gross income in the US from carbon sequestration ranges from \$100m (with low C accumulation and a price of \$5 per tonne) to \$4 billion (high C and \$20 per tonne). Sandor & Skees (1999) suggest that carbon could increase the net farm income of the US farming community by 10% (though this is based on the high-end estimates as cited in Comis (2001)). Pretty & Ball (2001) use similar ranges for carbon accumulation and price as those considered in Comis (2001) and estimate that carbon could bring arable and grassland farmers between £18m and £147m per year in the UK. However, these are gross income figures and account needs to be taken of the cost to farmers of adopting the techniques required to sequester the carbon.

Although the estimates placed on the value of a tonne of carbon vary considerably, the evidence does increasingly point to a fairly low market value. This would suggest that, while the additional income to farmers in temperate climates would be welcome (especially in the current economic climate), it is clear that farmers are unlikely to become just 'carbon farmers'. In addition it is also clear that carbon does not offer a panacea for the problems associated with small 'family' farms that have preoccupied much of agricultural policy. The ability to sequester carbon is clearly related to farm area and hence, in absolute terms, it is likely to be the larger farms that gain the most from any payments either through the market or from government environmental policy. A larger farm may also be more likely to have areas suitable for carbon-intensive products such as coppicing. It is not clear that carbon sequestration on its own will help the smaller producers, although, once again, if it was linked to other environmental policies that encourage guardianship it might be beneficial.

There are other indirect impacts associated with carbon sequestration. For example, widespread conversion of land to non-food energy crops may reduce the supply of food and raise prices. As food is a staple commodity this will impact more on low-income households. However, as food is now a small proportion of overall expenditure, these effects may not be as significant as they would have been 20 years ago.

7. Conclusions

Agriculture provides significant possibilities for sequestering carbon. These arise because conventional agricultural techniques have led to a large loss of carbon from soils, and changes in tillage and management practices can replenish this carbon. But there remains uncertainty surrounding the role of soil sinks. This relates to factors such as the amount of carbon that can be sequestered, how the gain is measured and also how permanent the sequestration will be. In addition, while there appears to be considerable potential, the actual contribution that agriculture can make depends on the economics of soil sequestration, and this is complicated by the problems with market failure due to the existence of external costs and benefits from land-use and management changes.

The key factor in determining the competitiveness of temperate agriculture in mitigating climate change is the opportunity cost per tC stored. Empirical evidence suggests that this can be as low as \$10–\$25 per tonne but that for the majority of agriculture it exceeds \$50 per tonne. Whether this is competitive with alternative approaches and emission reductions depends on the final monetary value that is placed on a per-tonne reduction of carbon emission. This will emerge either from the establishment of a fully functioning market or from government payments. Estimates of the value have ranged from an optimistic $100 per tonne to a low of between $1 and $5 per tonne. The current evidence does appear to suggest a price in the lower regions of this range.

There has been considerable speculation as to the annual value of carbon to temperate agriculture. For example, it has been shown that, for the US, estimates range between £100 million and $4 billion. If we accept the low estimates of carbon it is clear that although it has the potential to contribute to farm income it is unlikely that the returns themselves will engender a widespread dash to carbon farming. However, a point that has been made repeatedly is that increases in soil organic matter and the methods adopted to achieve this are likely to lead other environmental benefits which might justify government payments. This is particularly relevant as the stated aim in many industrialized countries is a move to more sustainable forms of agriculture.

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