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The potential role of compost in reducing greenhouse gases

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The contribution of the agricultural sector to emissions of climate change gases is becoming better understood. At the same time, the potential role of the sector as a means through which to tackle climate change, widely neglected in the past, is becoming more widely acknowledged. The absorption potential of agricultural soils could contribute significantly to constraining growth in greenhouse gas emissions, while also contributing to improvements in soil quality in some areas. In addition to the measures listed above, other benefits of compost application may have some relevance. Some of these measures include replacement of chemical fertilizers (implying avoidance of greenhouse gases related to their production) reduced use of pesticides (avoiding emissions associated with their production), improved tilth and workability (less consumption of fuels). Typically, life-cycle analyses (LCAs) exhibit limitations related to assessing the effects of 'time-limited' carbon sequestration in soils. This has tended to obscure the potentially important effect of composting, in which biogenic carbon is held in soils for a period of time before the carbon is released. The paper seeks to understand these effects and offers comments on the contribution of biological treatments to tackling climate change issues. Key issues include the replacement of fertilizers, reduction of N₂O emissions, and peat replacement.

Keywords: Composting, anaerobic digestion, biowaste, life-cycle assessment, climate change, carbon sequestration, wmr 1316-1

Introduction

The contribution of the agricultural sector to climate change through emissions of greenhouse gases (GHGs) is becoming better understood. At the same time, the potential of the agricultural sector to contribute to reducing emissions of the same GHGs, widely neglected in the past, is also becoming clearer, both from a scientific and from a strategic (i.e. in policy-making) standpoint.

A poorly known fact is that it has been estimated that more than twice as much carbon is held in soils as in vegetation or in the atmosphere (Batjes 1996). In 2001 the Working Group on Agriculture of the European Climate Change Programme reported that in 1990, methane (CH₄) emissions from agriculture were 41% of all CH₄ emissions, whilst nitrous oxide (N₂O) emissions from the sector accounted for 51% of total N₂O emissions. Further, taking into account emissions of

carbon dioxide as well, GHG emissions from the agricultural sector amounted to 11% of all EU GHG emissions in 1990.

On the other hand, the potential of agricultural soils to act as a sink for carbon suggests that this function could contribute significantly to fulfilling the objective of the EU to reduce GHG emissions by 8% between 2008 and 2012 from a 1990 base. On account of these facts, the Sixth Conference of the Parties (COP 6) held in Bonn in July 2001 considered agricultural soils to be suitable as sinks for the storage of carbon.

More generally, it is becoming more and more important to give proper consideration, in policy-making circles, for potential climate change mitigation measures within the agricultural sector. In this regard, the following measures were singled out by the Working Group on Agriculture.

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- Potential for reduction of nitrous oxide emissions from agricultural soils.
- Potential for sequestration of carbon in agricultural soils.
- Potential for reduction of carbon dioxide emissions of fossil origin by providing renewable raw materials for the energy and industrial sectors.
- Potential for mitigation of methane emissions from enteric fermentation.
- Potential for abatement of methane and nitrous oxide emissions through manure management.

Among the measures listed above, at least the first two might be properly tackled through a strategy aimed at proper reuse of composted organic waste. In addition to the measures listed above, many other possible side-effects of compost application may be considered and are of relevance in combating climate change. We consider it important to mention at least:

- displacement of chemical fertilizers (which implies avoidance of GHGs associated with their production);
- reduction in the use of pesticides (which would imply avoiding GHG emissions associated with their production, as well as wider environmental benefits); and
- improved tillage and workability (which might lead to less consumption of fuels).

Finally, to the extent that, in some EU countries, climate change may lead to changes in patterns of rainfall, the improved structure of soils associated with the application of organic matter can help:

- a. to reduce the requirement for irrigation water in periods of drought; and
- b. to increase the potential for soils to retain moisture in periods of rainfall, reducing the likelihood of flooding associated with moisture run-off.

This article seeks to advance some figures and develop some strategic perspectives that might further understanding of the potential contribution of composting to tackle climate change issues. These figures, although subject to various uncertainties, can no longer be neglected in the context of strategic environmental policy-making.

When organic matter or biowaste are considered solely from an energetic standpoint, there is a risk that some aspects of their role in soil will not be recognized as potential policy drivers. They are related to both the flux of GHGs associated with waste management (for example, through the build-up of soil organic carbon) and for the optimization of cropping techniques and yields. This is, arguably, a potential consequence of the Directive on Renewable Sources of Energy, which suggests the use of economic drivers for the energetic exploitation of organic waste, with little or no consideration of the role organic matter plays in carbon sequestration and in enhancement of soil and land fertility.

These points are stressed, for instance, in the Final Report of the Working Group on Organic Matter in the context of the European Commission Consultation on the Soil Strategy, which reads:

“Concerning the use of renewable energy sources, it should be recalled that any combustion of organic matter (biomass) necessarily impairs possibilities of incorporation of the residues into the stable pool of organic matter in soils. The EU Soil Thematic Strategy should therefore tend to mitigate the potential negative effects of such drawbacks, in particular when using biomass that was not harvested for energy purpose”.

And

“The implementation of the Kyoto Protocol for forestry and land use represents also a new incentive tool in order to fulfil the sustainable management of Soil Organic Matter (...) and the surface area involved will be millions of ha”.

In particular, from the standpoint of GHGs, assessments led in the past have neglected the important and positive effects of composting and compost application on:

1. soil organic carbon and related sinks;
2. its effects on improved uptake of nutrients;
3. avoided energy uptake for the production of equivalent chemical fertilizers; and
4. avoided release of nitrous oxide from chemical fertilizers when allowing for the nutrient release from organic amendments.

All the points listed above need to be addressed, properly considered and hopefully quantified, at least for a preliminary evaluation of the magnitude of their potential contribution.

In order to make an assessment of these contributions and to drive policy-making, for instance, in recent times the European Commission (EC) has contracted a study on different options to manage biodegradable waste, whereby many of the aforementioned topics have been investigated (Eunomia *et al.* 2002).

It should be noted that issues related to soil organic matter may be increasing in significance as a consequence of the progressive changes in climate which we appear to be experiencing. A possible feedback mechanism associated with climate change is that the release of soil organic carbon may increase as the climate changes, so deepening the significance of addressing the decline in soil organic matter status (Bellamy *et al.* 2005). Not all of the carbon lost from soils is necessarily mineralized as carbon dioxide. Some may be leached into deeper soil layers and drainage waters.

Soils as a potential sink for carbon

In general terms, organic matter is an issue of importance because of its influence on soil fertility, stability and structure, and the capacity of soils to retain moisture. Organic matter's decline in many European soils is threatening their capacity to remain fertile, and to continue performing their most essential environmental functions. The decline in soil organic matter is emerging as a key issue for EU policy. Looking at carbon stored in farm soils, it is very easy, indeed, to make a link with the organic fertility.

The Commission has indicated its intention, in the Sixth Environmental Action Programme (6EAP) to develop a thematic strategy on soil protection. The draft Council and Parliament decision on the 6EAP sets the objective of the promotion of a sustainable use of soil, with particular reference to preventing erosion, deterioration, contamination and desertification. EC communications have already noted that soil loss and declining fertility are eroding the viability of agricultural land. Accordingly, the Communication from the Commission on Soil Protection, issued most recently, places particular emphasis on organic matter and establishes a goal of promoting the use of high-quality composted products for such purposes as fighting desertification and erosion, avoiding floods, and promoting the build-up of carbon in the soil.

Sequestration potential of agricultural soils

The Intergovernmental Panel on Climate Change (IPCC) clearly identified carbon sequestration in soils as one of the possible GHG mitigation measures for agriculture at an early stage (IPCC 1996).

The loss of organic carbon in soils has been one of the major environmental consequences of industrial agriculture. Arable top soils in Europe commonly contain 1–3% of organic carbon. ECAF (not dated) suggest that following tillage over a period of around 20 years, most agricultural soils will have lost about 50% of their organic carbon. The annual net release of carbon from global agricultural activities has been estimated to be about 800 Mt year⁻¹, or about 14% of the carbon associated with fossil fuel burning (Schlesinger 1995).

The most important result of the Bonn Conference for the agricultural sector was the possible unlimited use of agricultural land as sinks for carbon. A calculation made by the European Commission assumed that 20% of the surface of agricultural land in the EU could be used as a sink for carbon. This would correspond to an absorption potential of around 7.8 Mt of carbon, which corresponds to around 8.6% of the total EU reduction objective. The EC Communication on a Soil Strategy also highlights the potential significance of sequestration. The Communication mentions, for instance, the fact that it has been calculated that an increase of just 0.15% in organic carbon in arable soils in a country like Italy would effectively imply the sequestration of the same amount of carbon within soil that is currently released into the atmosphere in a period of 1 year through the use of fossil fuels. [This calculation was referred to in a speech by Professor P. Sequi at the Compost Symposium, Vienna, 29–30 October 1998.]

This should be compared with the somewhat worrying decline in soil organic matter over past decades, the magnitude of which has been, in many areas, of the order of some percentage points, and which has led to soil organic matter content falling below 2% in many soils. Nearly 75% of the total area analysed in Southern Europe has a low (below 3.4%) or very low (below 1.7%) soil organic matter content. The problem is, however, not restricted to the Mediterranean. Figures for England and Wales show that the percentage of soils with less than 3.6% organic matter rose from 35 to 42% in the period 1980–1995. In the Beauce region south of Paris, soil organic matter has halved in 16 years. These figures suggest a net loss of organic carbon from soils, some of which can be expected to have occurred through mineralization of carbon, representing a net flux of GHGs from soils to the atmosphere. If one looks at these figures from the opposite standpoint, however, one sees an opportunity to deliver win-win scenarios through the management of organic wastes. A huge opportunity exists to lock-up considerable amounts of carbon while contributing to the restoration of soil fertility and health.

Many surveys have lately been focusing on measures regarding the application of composted organic fertilizers. Composting can contribute in a positive way to the twin objectives of restoring soil quality and sequestering carbon in soils. At the same time, in the EU, the waste management sector is being challenged, under the scope of the EC Directive 99/31 on the Landfilling of Waste, to achieve targets for the reduction of biodegradable municipal waste to be landfilled. This suggests there is considerable merit in the waste management sector seeking to ensure that opportunities for recovering organic materials in a manner suitable for application to soils are considered as a priority in seeking to meet targets for reducing the amount of waste sent to landfill.

Methodological remarks on 'sequestration'

Proper application of organic fertilizers in agriculture, besides the adoption of proper cropping and tilling techniques, can have a positive effect on soil carbon levels. Applications of organic matter can lead, depending upon the rate of application and other factors, either to a build-up of soil organic carbon over time, or a reduction in the rate at which organic matter is depleted from soils. In either case, relative to the situation where no organic matter is applied, a beneficial effect may be experienced in respect of the quantity of organic matter in soils.

Many assessments of waste management options adopt a life-cycle assessment approach to the comparative appraisal. The assumptions contained therein are crucial for the outcomes of the analysis insofar as GHG emissions from soils are concerned. Life-cycle assessment approaches have tended to suffer from several shortcomings. One of these is their failure to take into account the dynamics – or the dimension of time – in the assessment of environmental outcomes. In waste management systems, this is of particular significance when comparing biological processes with thermal ones. This

is because the degradation of biomass tends to occur over an extended period of time (over 100 years), whereas thermal processes effectively lead to emissions of carbon dioxide instantaneously.

In this context, it becomes important to understand the significance of two issues.

- Life-cycle approaches have to consider at what point in time one draws a cut-off to determine which emissions 'count' and which do not. Few take that point to be 'an infinite period ahead in the future'. This means that the cut-off point necessarily becomes an arbitrary one. Many analyses assume that the IPCC cut-off for modelling – 100 years in the future – is a relevant time horizon. Yet one can reasonably ask why this is considered the relevant period for the IPCC modelling, not to mention, why it should be considered relevant for a comparative analysis of waste treatment options (which is not what the IPCC is involved in). Why not 3 years, or 10, or 35, or 50? There is, in short, no logic behind the use of this arbitrary cut off. Why do emissions at any time before that date 'count', equally, but every emission after that point 'does not count'. The use of 'sequestration' values (un-emitted carbon dioxide at the cut-off point) does not adequately rectify the issue for reasons explained below.
- The fact that all emissions – in life-cycle assessment – count equally irrespective of the timing of their emission has to be questioned. There are logical and methodological reasons for questioning the adequacy of this approach. The pace of climate change is, it would seem, faster than was hitherto thought to be the case. What does this imply for the time profile of emissions? What does this imply for the choice between processes which emit carbon dioxide over an extended period of time, and those which emit all carbon dioxide on day one of the process? Life-cycle assessment, as conventionally applied, offers the analyst zero insight on this potentially critical point. Indeed, although several practitioners understand the potential relevance of discounting, as employed in cost-benefit analysis, some have sought to propose zero, or even negative, discount rates on grounds of sustainability without apparently understanding what their proposals might imply for the functioning of the economy.

Where compost is concerned, carbon dioxide is emitted first, in relatively large quantities, in the intensive phase of the process, and then, at a slower rate, in the maturation phase. Following application of material to soil, the initial rate of emission will depend upon the degree to which the compost has been matured prior to its application to the soil. Once applied to the soil, however, the rate of emission declines. Depending upon what assumptions one makes in the analysis, the application of compost to soil is either a 'time-limited sequestration process' (if one assumes that biogenic emissions of carbon dioxide are not to be counted in the analysis, in which case, the time perspective becomes critical) or a

management process where emissions of carbon dioxide simply occur over an extended period of time. However, as has been correctly stressed by many recent surveys (see for instance: Smith *et al.* 2001), estimating a precise lifetime for soil organic matter derived from compost addition is very difficult, because of the large number of inter-converting pools of carbon involved, each with its own turnover rate, which is in turn determined by local factors such as soil type, temperature and moisture (hence the potential feedback mechanisms associated with changing temperature and rainfall patterns in the wake of climate change). Although a great deal of valuable information now exists on the turnover of soil organic carbon, the question of assigning a typical average value for the persistence of carbon applied to soils in compost remains somewhat problematical.

Life times of various pools of soil organic carbon ranging from 20 to 2000 years have been proposed as means of setting boundaries by the US Environmental Protection Agency. Iso-tope studies (Carter 1999) have shown that turnover times differ widely for different fractions of soil organic matter, ranging from less than a year for microbial biomass to between 5 and 1000 years for organic matter associated with silt and clay particles. Applying first-order decay kinetics (which are widely used in this field), this global average suggests that only 2% of the carbon applied to soil today would remain in the soil organic matter in 100 years time.

Smith *et al.* (1997) have reported summary results from several long-term field experiments in which sewage sludge, animal manure and cereal straw had been incorporated annually into the top layer of soil. They derived linear correlations between the organic matter addition and the annual increase in soil organic carbon, which, if a steady state has been reached between carbon input and soil organic carbon, allows the amount of added carbon surviving in the soil for a given period to be calculated. Using the equations provided by Smith *et al.* and assuming a carbon content for manure and sewage sludge of 20% results in estimates of 9 and 6% as the proportion of added carbon persisting for over 100 years.

Despite all the findings listed above, which tend to make the potential contribution of compost (and in broader terms, of organic soil improvers) to sequestration particularly small, and almost negligible over a 100-year period, as suggested above, what matters is not 'what is left after 100 years' but how emissions of carbon, and the retention of carbon in soil, change over time.

Climate models are sufficiently sensitive to the dynamics of emissions so as not to be indifferent to a situation in which every unit of carbon dioxide likely to be emitted in the next 100 years is emitted today, and the situation where emissions occur continuously over the 100-year period. Indeed, if there was no such sensitivity within these models, the case for early, as opposed to later, action might be difficult to make as long as action occurred within a 100-year timeframe.

We think the focus ought to shift from whether something simply does or does not act as a 'net sequester of carbon', to how much carbon is emitted (and how much kept in the soil)

over time under different practices and scenarios, since the sequestration of carbon in soils is always 'time-limited'.

Organic fertilization does not result in the permanent and irreversible locking up of all carbon in compost. What organic fertilizers can do is reverse the decline in soil organic matter that has occurred in relatively recent decades by contributing to the build-up in the stable organic fraction in soils, and having the effect, in any given year, of ensuring that carbon which might otherwise be emitted as carbon dioxide is held within the soil. It is also important to realize that although the debate concerning 'sequestration' has emerged as a topical one in the wake of the debate on climate change, the role played by soil organic carbon is far more complex, and potentially far more important, than the single role played in terms of carbon sequestration.

The application of organic matter on a regular basis causes the accumulation of organic matter, but at some point, rates of application and rates of loss are likely to equalize, leading to a steady-state condition in the long run. The steady-state level – at which mineralization of organic matter offsets the annual accumulation of organic matter – depends upon factors such as climatic and cropping conditions, the annual rate of application of organic matter, and the nature of the organic matter applied. However, the overall potential for increasing the carbon content of soils can be considerable in the short and medium term, while the system is moving towards a steady-state condition. This means that the time-limited sequestration of carbon in soils can play a significant role in the achievement of targets for reducing GHG emissions over a period of years or decades.

The simplified modelling shown hereafter, based on dynamics among different pools of organic matter in the soil and the atmosphere, might for instance lead one to conclude that, depending upon starting conditions and climatic and cropping situations, the build-up of organic matter in soils over 50 years might enable a net accumulation of between 1 and 3% of soil organic matter, corresponding to an estimated increase of between 0.58 and 1.74% soil organic carbon. In comparison with the figures suggested above, this quantity could offset 4 to 12 years of annual emissions of carbon dioxide [i.e. around 0.15% more carbon in soil to offset the yearly CO₂ – eq. emission. This figure was referred to in a speech by Professor P. Sequi at the Compost Symposium, Vienna, 29–30 October 1998].

The assessment of this potential accumulation becomes even more impressive if one makes the comparison relative to a baseline scenario in which there is no application of organic fertilizers, nor any practice to increase or keep the quantity of organic matter in the soil, which might be considered to have been the case in many farmlands throughout recent decades, and might be a scenario driven by the consideration of biomass only as a substitute for fuel. Proper attention therefore ought to be paid to what seems to be a primary tool to tackle GHGs.

Simplified models for a preliminary assessment of lock-up of carbon

Usually dynamics related to the build-up of carbon in soil are neglected in policy-making in respect of climate change, notwithstanding the considerable body of scientific evidence that has been developed. Long-term trials demonstrate the capability of soil to store organic carbon over long periods, although the complexity of related dynamics makes it difficult to model the effects in a quantitative manner.

To provide a preliminary assessment of the potential contribution of sequestration of soil organic carbon (SOC) to management of global climate issues, we have modelled the dynamics of its application and build-up on the one side, and its mineralization, or loss, on the other.

In a simplified model, three pools of organic carbon are available for microbial utilization.

1. The 'active' soil fraction (representing short-term sequestration of carbon – provides source of energy for microbes, and the soil carbon and nitrogen supply necessary for amino acid synthesis).
2. The 'slow' or 'decomposable' soil fraction (of great importance to developing good soil structure. This is disturbed by cultivation and other disturbances and provides a source of carbon for biological digestion by microbes, so linking to the active pool. It can be viewed as mature compost).
3. The 'passive' soil organic fraction (this has a turnover time of the order 100 to 1000 years and is relatively resistant to oxidation processes. It acts as a 'cement' that binds particles).

Only the first two of these pools contains carbon in a readily available form for microbial utilization. The last pool contains carbon in a highly stable form. Some microbes can utilize this pool so depletion does occur. It can also be replenished from active and slowly decomposable fractions. It is the fact that this passive pool of carbon can be maintained or increased that leads to the idea that the passive pool can act to 'sequester', in a time-limited fashion, carbon in the soil. This long turnover appears to imply that this carbon is only released into the atmosphere very slowly. It will be kept within the soil for a long period of time, hence its potential value in mitigating the effects of climate change. The model omits to include the input of organic matter to the soil coming from photosynthetically produced plant biomass; this implies the model only focuses on the fate of 'exogenous' organic matter.

The application of compost is assumed to lead to the readily available carbon being mineralized at $y\%$ whereas $x\%$ of the readily available organic carbon is converted to stable organic matter. Of this stable organic matter, some carbon ($z\%$) is mineralized, but at a much lower rate than that at which the readily available matter is converted to stable organic matter. Consequently, application of organic matter to soil can act to increase soil organic carbon levels (although as we shall see, the degree to which this occurs varies accord-

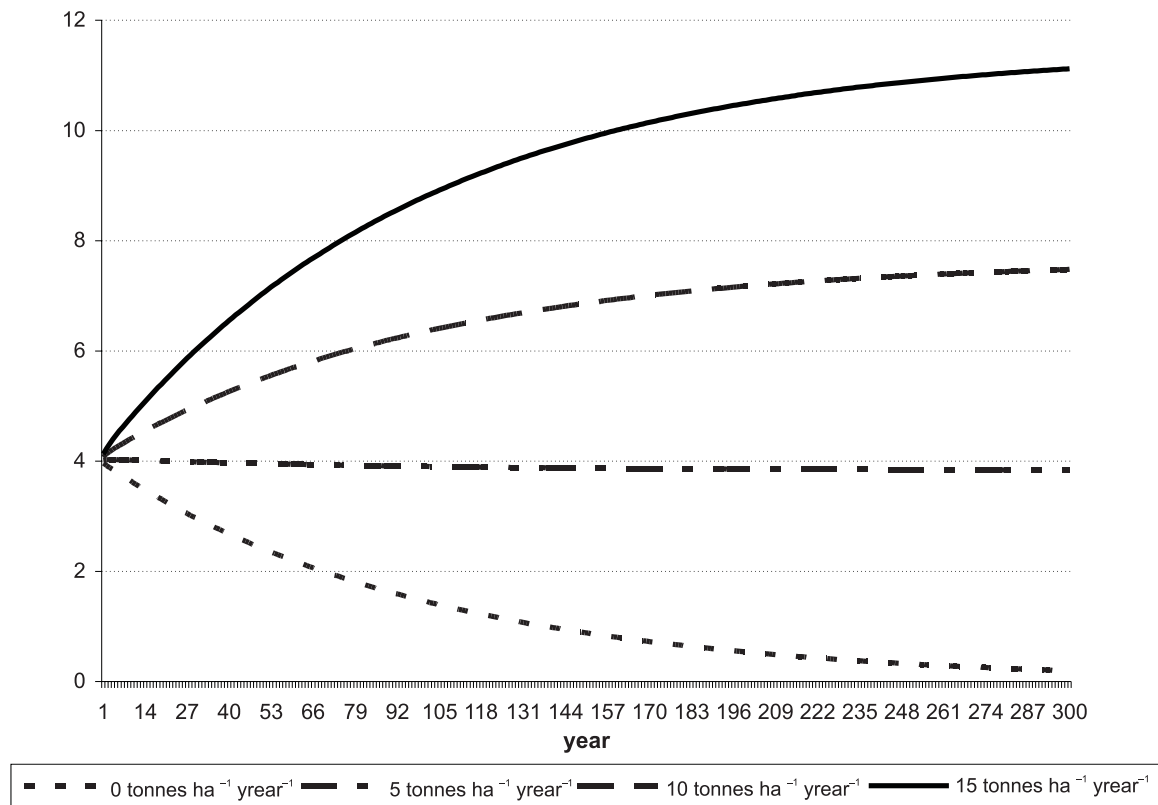


Fig. 1: Effect of different rates of compost application on soil organic matter levels (as a percentage of soil weight) in time.

ing to the choice of the different parameters chosen, the rate of application of compost and the baseline level of organic matter in the soil).

The model can then be run through the application of values for x , y , z as found in literature for mineralization of both stable and readily available organic matter (OM), and for humification of readily available organic matter. For instance, referring to z , one could consider the half-life ($t_{1/2}$) times of humic carbon reported in literature, ranging between some decades and more than 1000 years. Solving the equation:

$$0.5 = e^{-(z \times t_{1/2})} \quad (1)$$

where $t_{1/2}$ is the calculated half-life.

Different typical values of z are available. In Figure 1, the response curves are shown using the following conditions: $x = 30\%$, $y = 15\%$, $z = 1\%$ ($t_{1/2}$ time at some 68 years), and with an initial organic matter concentration of 4%, deemed to be typical of Northern European areas:

Such outcomes are generally consistent with long-term field trials that have already been run by the Rothamstead Agricultural Experimental Centre for more than a century, surveying long-term effects of different agronomic practices about the build-up or decrease of organic matter in the soil. Outcomes from Rothamstead (Table 1) clearly demonstrate that avoiding organic fertilization determines a big loss of organic matter in the soil, which causes a net transfer of carbon (as carbon dioxide) to the atmosphere. Although depletion is mitigated, *vis-à-vis* the model, by the effect of photosynthetically origi-

Table 1: Findings of long-term field trials in Rothamstead.

Type of vegetation or cropping	% C
Pasturelands	1.52
Under a forest	2.38
After cropping wheat continuously for 50 years, 1893	
No manure added since 1839	0.89
Only chemical fertilization since 1843	1.10
14 tonnes manure yearly since 1843	2.23

nated OM, the effect is still remarkable. The application – continued with time – of organic soil improvers (manure in the trial, but outcomes would hold similar with compost) makes it possible to keep concentrations of carbon at those levels that are typical of natural background concentration – or to increase the concentration in those soils already depleted. This makes the soil a powerful ‘sink’ for carbon. The numbers suggest that soils where manure was added showed soil organic carbon levels 1.34% higher than un-amended soils, and 1.13% higher than soils amended with chemical fertilizers over a 50-year period. This is clearly significant given the evaluations reported above regarding carbon being lost from soils, and the increasing amount of carbon dioxide in the atmosphere.

Reduced use of chemical fertilizers and related effects

Unlike mineral fertilizers, the use of organic fertilizers, although containing nitrogen (N), phosphorous (P) and potas-

sium (K) does not provide a specific amount of N, P or K that will be immediately available to the growing plant. In comparison with mineral fertilizers, they provide lower levels of N, P and K; however, their addition can provide essential trace minerals to the soil (calcium, sulfur, iron, boron, molybdenum and zinc) that are not supplied when mineral fertilizers are added.

Furthermore, the application of organic fertilizers can enhance nutrient uptake by reducing mineral leaching. Losses of nutrients by leaching can be reduced by increasing the soil organic matter content. Some nutrients in the water-soluble form required by plants are readily leached from mineral soil particles, whereas they are effectively held on the surface of humified organic matter.

Replacement of alternative nutrient sources

When organic fertilizers are applied to the soil, they may displace nutrients that are otherwise applied through synthetic fertilizers. We assume in the analysis that nutrients are displaced on a one-for-one basis from the perspective of plant uptake. Taking the view from the perspective of the plant is important, since the rate at which nutrients are leached from humus is lower than the rate at which they might be leached from synthetic fertilizer. As such, more of the nutrient in synthetic form would be required to be applied to have the equivalent mineral fertilization effect. The assumption of 'one-for-one' displacement is an unrealistic one to the extent that one is implying a perfect optimization of the replacement process. On the other hand, the situation is more likely to approach the ideal once farmers are well informed about the nutrient content of the matter being applied (which is happening more and more frequently, especially in those countries with a longer tradition in composting and compost application).

We have assumed that 10 tonnes of dry matter is applied through organic amendment per hectare. This is equivalent to approximately 16.7 tonnes of composted manure or other composted materials (CM, dry matter content 60%) or 25–33 tonnes of 'traditional' manure (TM, 30–40% dry matter). Specifically focusing on CM, we assume further that this material has the following composition in terms of nutrients:

Nitrogen:	1.5% dry matter
Phosphorous (as P ₂ O ₅):	1.0% dry matter
Potassium (as K ₂ O):	1.2% dry matter.

In order to run a test assessment, we assume a mineralization rate of the nutrients in CM to be 30% for all nutrients. Such a figure, which is fairly high, might be deemed appropriate for weather and cropping conditions typical of Southern Europe (warm weather, intensive cropping, high tendency to mineralize any added organic fertilizer). This determines the time profile of the displacement effect.

In order to allow for the part of chemical fertilizers which is leached, we also considered a 'loss rate', which actually increases the displacing potential of organic fertilizers. For

Table 2: Evolution in N displacement associated with 10 tonnes dry matter of compost applied to farmland.

Year	Displacement potential N (kg)	Cumulative displacement (kg)
1	58.4	58.4
2	40.9	99.4
3	28.6	128.0
4	20.0	148.0
5	14.0	162.1
6	9.8	171.9
7	6.9	178.8
8	4.8	183.6
9	3.4	186.9
10	2.4	189.3

synthetic fertilizers, we assume a loss rate of 23% for nitrogenous fertilizers (Hydro Agri Europe 1995). This means that more nutrient has to be applied in a given year in the synthetic form than would be available in mineralized form from the composted materials. For an application of 10 tonnes dry matter (d.m.) per annum in 1 year, the N displacement would follow the evolution set out in Table 2.

The use of compost as a replacement for fertilizer will thus displace the pollution and other externalities and energy associated with extraction of raw materials to manufacture and transport fertilizers. This may be an important consideration with respect to climate change. Mining phosphate rock, for example, is an energy-intensive activity, with approximately 3.3 tonnes of phosphate rock required to produce 1 tonne of P₂O₅ (Bocoum & Labys 1993). Energy use for producing phosphate rock has been estimated at 73.5 kWh tonne⁻¹ (UNEP & UNIDO 1998).

According to our preliminary calculations, a single compost application of 10 tonnes d.m. ha⁻¹, which has a potential displacing power of some 190 kg N, might save 160 to 1590 kWh of energy, and this would not account for the displacement of P and K, nor the CO₂-eq. related to other emissions (e.g. N₂O, see the following section).

Reduction of N₂O emissions from nitrogenous fertilizers

Fertilization of crops contributes to the emission of GHGs, especially through the emission of nitrous oxide (N₂O) from soils. This is a result of incomplete transformation of ammonia to nitrate (nitrification) and/or the incomplete turnover of nitrate to nitrogen gas (denitrification). Measures aimed at reducing nitrate content in waters may result in declining nitrous oxide emissions.

It is generally accepted that the application of nitrogenous fertilizers increases fluxes of N₂O. Therefore, the reduced application of N fertilizers, once the N-release by organic materials is accounted for, might influence the release of N₂O. Different fertilizers appear to be more or less susceptible to the loss of nitrogen as nitrous oxide. The emissions

depend upon temperature, soil moisture, fertilizer type, fertilizer amount, the timing and mode of application, and the type of soil and crop cultivated (see, for example, McTaggart *et al.* 1998). Ammonia products appear most susceptible, with anhydrous ammonia and aqua ammonia losing between 1 and 5% of nitrogen as nitrous oxide. Other products such as sodium nitrate appear to lose much less nitrogen in this way (Lashof & Tirpak 1990). A Dutch study cites figures for N₂O losses as between 1 and 3% of mineral N applied (Mosier 1993).

Reduction options for N₂O generally rely on:

1. the reduction of nitrogen inputs to soils through enhanced fertilizer use efficiency; and
2. a better accounting for N in manures and other humified products (including compost) applied to soil, so that the N of chemical fertilizers can be displaced by slow-release N, whose kinetics make it much less prone to producing N₂O.

In terms of assessment, it could be conservatively assumed that a unit loss as N₂O of 0.05 to 0.5% of nitrogen applied as chemical fertilizer relative to the situation where compost is applied. These assumptions can be matched with the N replacement figures for the compost as outlined in earlier sections and Table 2. The net effect is that over a 20-year period, an application of 10 tonnes of organic dry matter with 1.9% N content might offset nitrous oxide by 60–600 kg CO₂ equivalents. This is not a major effect, but it may become significant as our understanding of the key parameters become better developed.

Economic drivers and funding programmes

Some noteworthy attempts to internalize the positive externalities associated with the application of organic matter to soils are to be found in some regions of Italy, where under the scope of Rural Development Plans (2000–06) (Regulation of the EU 1257, on sustainable agriculture), farmers receive financial support in exchange for applying organic fertilizers, and in particular, composted products.

- Region Emilia Romagna has already been paying, for a period of a few years, some 130 € ha⁻¹ to make use of compost, and so promote the build-up of soil organic carbon in depleted soils.
- Region Piemonte pays 220 € ha⁻¹ for farmers to use up to 25 tonnes d.m. on depleted soils over a 5-year period (in order to take into account crop rotation).

Such grants might be considered precedent-setting, when it comes to environmental policy-making and economic instruments for driving agronomic practices – and the related waste management practices – towards a more sustainable approach to the apparently related issues of climate change and soil quality.

Other effects of compost application on GHGs

As discussed above, many other side effects of organic fertilization are likely to have implications for GHG emissions and the mitigation of climate change-related impacts.

1. Reduction in the use of pesticides (which would imply avoiding GHG emissions associated with their production, as well as wider environmental benefits).
2. Improved tilth and workability (which might lead to reduced consumption of fuels).
3. Reduced requirement for irrigation water in periods of drought.
4. Increased potential for soils to retain moisture in periods of rainfall, reducing the likelihood of flooding associated with moisture run-off.

Furthermore, another net benefit as to GHGs could stem from the use of compost as a peat substitute in horticulture. The use of peat results in the mineralization of the carbon kept in peat bogs (which might be treated as 'fossil carbon' due to its long-term storage), so making a net positive contribution to global warming.

The GHG emissions associated with peat bogs are extremely complex, and they change once the process of development (for extraction) occurs. In northern peatlands, the anaerobic conditions and cold temperature result in increased sequestration of carbon (relative to other wetlands). Wetlands store carbon in short- and long-term reservoirs. Storage occurs when primary production is high and exceeds the rate of decomposition, or when the rate of decomposition is slowed by a process known as anoxia, and cold temperatures (leading to accumulation of undecomposed organic matter). Although they may act as a sink for carbon, unperturbed peatbogs may also emit methane; however, as long as they are unperturbed, they most likely retain a balance between methane emissions and carbon sequestration.

Drainage and degradation of peatlands increases carbon dioxide emissions. It also increases nitrous oxide emissions significantly (Freeman *et al.* 1992, Roulet *et al.* 1993, Schlesinger 1995, Regina *et al.* 1998). It has been estimated that peatlands contain between 329 and 528 billion tonnes of carbon (equivalent to 1200–1900 billion tonnes of carbon dioxide). Unless the bogs are disturbed by extraction, drainage or other human intervention, much of the carbon will remain in-situ for near geological timescales.

Drainage of peatlands and other wetlands acting as carbon reservoirs will result in the oxidation of the organic matter, releasing it to the atmosphere as carbon dioxide, methane and other GHGs. Conversely, restoration or creation of new wetlands may provide additional carbon sinks (Environment Canada 1998).

Conclusions

From science-based evidence the following conclusions may be drawn.

- GHG-mitigation measures related to land use, land use change and forestry (LULUCF) suggest that comparatively inexpensive measures can offer remarkable GHG savings.
- Composting and the use of composted products ought to be considered among such measures as they imply a time-limited sequestration of carbon that could inform policy on climate change while indirectly reducing GHG emissions by reducing demand for, and application of materials such as mineral fertilizers, pesticides and peat.

The following points also deserve emphasis.

- Compost can only store carbon temporarily in soils. The carbon will be released, in the long run, into the atmosphere. As already argued, however, the time horizon over which the 'progressive build-up' of carbon in soils occurs may have a comparatively important duration. This may help reduce emissions of carbon dioxide in the short to medium term, essentially 'buying time' for further adaptation strategies

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