



Environment,
Climate Change
& Water



Short report:
The benefits of using compost
for mitigating climate change



The Organic Force

Acknowledgement:

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This short report is not referenced, except for graphs and tables. Please refer to the full report for acknowledgements of the data used, a full list of proper references and a comprehensive list of abbreviations. Most data related to the use of organic soil amendments such as manure, biosolids and compost is sourced from Europe and North America, and therefore does not necessarily reflect soil and environmental conditions that might be encountered in Australia. In most cases the terminology used by authors of reviewed papers and reports has been adopted, thus terms such as 'sewage sludge' and 'biosolids', or 'soil carbon' and 'soil organic matter' are used in parallel.

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Executive summary

This report summarises an extensive and detailed literature review entitled *The benefits of using compost for mitigating climate change*, which was commissioned by Department of Environment, Climate Change and Water NSW. The report findings support the NSW and Federal government priorities to reduce waste and tackle climate change.

In NSW, the State Plan, Waste Avoidance and Resource Recovery Strategy (WARR) and the NSW Climate Action Plan set waste and greenhouse gas (GHG) reduction targets and identify priority actions and strategies that guide the work in the key areas of waste reduction and climate change adaptation. Returning recycled organics to the land in the form of compost can deliver many benefits and assist in achieving these targets.

A key objective of this report is to summarise the scientific literature reporting on research on the use of compost and related products in mitigating climate change. Compost and related products are processed from recycled organic materials such as garden organics, food organics, crop residues, biosolids and manures. Diverting these materials from landfill reduces methane emissions. Applying the products leads to climate change benefits through carbon sequestration in soil, substitution of nitrogenous and other synthetic fertilisers and the flow-on effects of improved soil health and water holding capacity following their application.

Across Australia an estimated 3.7 million tonnes (Mt) of garden and food organics and a percentage of wood residue were diverted and recycled from landfill in 2007–08, preventing methane generation equivalent to ~ 4.28 Mt CO₂-e. Methane is a potent greenhouse gas (21 to 25 times as potent as carbon dioxide) that is normally produced when organic materials break down in landfill. The drop in greenhouse gas emissions from the waste sector has largely been attributed to the rise in landfill gas capture measures (~4.5 Mt CO₂-e in 2007–8); however, what goes unreported is the fact that emissions figures would be almost twice as large if the organics which are currently recycled were to be landfilled instead.

If only 50% of the 9.68 Mt (2007–8 figures) of organic residues sent to landfill was recycled, methane generation of more than 5 Mt CO₂-e per annum could have been prevented. This would have brought methane generation savings through organics recycling activities to around 10 Mt CO₂-e in Australia.

There are also significant opportunities for mitigating greenhouse gas (GHG) emissions through improved agricultural management, particularly of croplands. Greenhouse gas emissions from agriculture (excluding emissions caused by 'Landuse, Landuse Change and Forestry' – land clearing, soil carbon in grazing and cropland and forest management) and waste management contributed 15.2% and 2.5%, respectively, to Australia's total GHG emissions in 2008. Of the estimated global technical agricultural mitigation potential by 2030, about 89% is from soil carbon sequestration and about 2% from mitigation of soil nitrous oxide (N₂O) emissions (Smith *et al.* 2007a^{*}). The soil carbon content can be raised by increasing the carbon input, decreasing the output or a combination of both.

^{*} quoted in IPCC: Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes and O. Sirotenko (2007). Agriculture, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. [Climate Change 2007: Mitigation](#). O. R. D. B. Metz, P.R. Bosch, R. Dave, L.A. Meyer (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, IPCC: 497-540.

Increases in soil carbon storage can be achieved by changes in the following areas of agricultural production, expressed as average annual global carbon sequestration rates over a 20-year period:

- agronomy 0.29 to 0.88 t CO₂-e ha⁻¹ yr⁻¹
- nutrient management 0.26 to 0.55 t CO₂-e ha⁻¹ yr⁻¹
- tillage/residue management 0.15 to 0.70 t CO₂-e ha⁻¹ yr⁻¹
- water management 1.14 t CO₂-e ha⁻¹ yr⁻¹
- manure/biosolids use 1.54 to 2.79 t CO₂-e ha⁻¹ yr⁻¹
- compost 1.10 to 1.80 t CO₂-e ha⁻¹ yr⁻¹

The addition of external carbon sources (such as **compost**) has the **highest soil carbon sequestration potential**. There are factors which limit soil carbon sequestration including nutrient supply (e.g. lack of nitrogen, phosphorus), sink saturation (optimum carbon levels reached) and reversibility (carbon sequestration is not necessarily permanent).

Although relatively small in absolute terms, nitrous oxide emissions cannot be ignored due to their high global warming potential (nitrous oxide is 310 times more potent as a GHG than CO₂), the permanency of any reductions and the potential of nitrous oxide emissions annulling carbon sequestration gains. In agriculture, nitrous oxide gas is primarily produced when there are high levels of moisture in the soils leading to anaerobic pockets and when nitrogen in excess of crop needs is applied. The primary consideration for mitigating nitrous oxide emissions from the agricultural sector is to match the supply of mineral nitrogen commensurate with the needs of crops. Nitrous oxide emissions in Australian agricultural systems were below the IPCC default (1.25% of added nitrogen) in cotton and wheat, but well above that level in high rainfall south east Queensland, and extreme in sugar cane on acid sulfate soil.

The increased input of carbon from organic soil amendments (animal manure, compost, crop residues, sewage sludge) is one of the most efficient measures for soil carbon sequestration. **Organic farming systems** prove this through reliance on high organic matter inputs, and on carbon and nutrient cycling to maintain soil quality and productivity. Virtually all comparative trials showed superior carbon sequestration for organic farming systems compared to conventional systems, although maintaining carbon levels on sandy soil can be difficult even for organic farms. Organic farming usually manages to reduce GHG emissions per unit land area, but not necessarily per unit of product.

It is estimated that approximately 3.2 Mt of **animal manures** are generated annually in Australia. Studies over a wide variety of soil textures and climates in diverse agricultural cropping systems have reported increases in soil organic matter following the addition of manure. The rate of increase in soil organic matter depends on temperature, moisture and tillage conditions, as well as the amount of manure added. For all climatic regions except for cold climates, it can be expected that between 5% and 20% of carbon applied with manure is retained and incorporated into the soil carbon pool. **Composted manure** retains considerably higher proportions of applied carbon in soil than does raw manure.

During the digestion of **sewage sludge**, much of the easily decomposable carbon is lost. The organic carbon added to soil in digested sludge is therefore more resistant to decomposition than the carbon in raw sludge. There are dramatic differences between sludges in their ability to release nitrous oxide, but there is no clear explanation of mechanisms controlling these differences.

In broad terms, there are two basic **compost products**:

- (i) composted mulch (70% of mass >15mm, applied to soil surface)
- (ii) composted soil conditioners, suitable for incorporation into the soil.

Due to a lack of data regarding the use of organic mulches, most compost information in this study relates to compost used as a soil conditioner.

During **composting**, about 50% of carbon contained in the raw materials is lost as CO₂, and 50% is retained, mostly in recalcitrant organic compounds. The rate and extent of **mineralisation of compost products after application to soil** depends on the quantity, type, maturity and particle size distribution of the applied product, as well as on soil properties, environmental conditions, and agricultural management practices. The labile organic compounds contained in compost are degraded relatively quickly, and the recalcitrant fractions remain in the soil. The consecutive use of mature garden/food organics compost for 12 years in a study has shown carbon retention rates of 45% to 50%, while the use of pasturised garden organics compost indicated about 30% carbon retention. However, the latter compost showed the highest carbon retention per dry tonne of compost applied.

No model is currently available that fully describes soil carbon dynamics following the use of compost. In the interim, a **simplified compost carbon sequestration model**, 'CENTURY', is available. The model predicts that new equilibria for soil organic carbon will not be reached before 200 and 300 years for annual compost application rates of 10 and 15 t ha⁻¹, respectively for northern European conditions, and that soil carbon sequestration will be possible for much longer than 20 years.

Using the CENTURY model, it was predicted that 117 kg C (428 kg CO₂-e) is sequestered per dry tonne of applied compost over a 100-year time frame for Australian conditions, and 88 to 93 kg C (321–342 kg CO₂-e) per dry tonne of applied mulch.

The IPCC framework for estimating greenhouse gas fluxes is based on a 100-year time horizon and will only consider compost carbon as 'sequestered' if it remains locked in the soil for at least 100 years. It has been suggested that 2% to 10% of carbon introduced with compost will still be in the soil after 100 years. More recent data suggests a range between 9% and 14%, depending on soil type and crop rotation.

The proportion of compost-derived carbon that becomes part of the stable soil carbon can be considered as 'sequestered' in the realm of the IPCC framework and for the purpose of international carbon trading. Accordingly, if C_{input} (kg) is the carbon content in compost and C_{bind} is the fraction that is or will become 'stable', then the carbon sequestration, expressed as CO₂ (CO_{2,bind}, kg) can be calculated as: $CO_{2,bind} = C_{input} \times C_{bind} \times 44/12$.

If carbon levels range between 10.0% and 28.5% (dry matter (DM)) and between 19.1 and 47.0% (DM) for garden and food organics compost respectively, and if between 2% and 14% of compost carbon are sequestered, carbon sequestration can be calculated to be in the order of two to 79 kg CO₂-e t⁻¹ for food organics and three to 73 kg CO₂-e t⁻¹ for garden organics, assuming mass losses during the composting process of 60% and 30% respectively. When compost is used regularly for four or more years, between 5% and 15% or more of **nitrogen** applied with compost will be utilised by crops annually, which means that between about 20% and 35% of compost-applied nitrogen will support plant growth over a three-year crop cycle. Because only a small proportion of the total nitrogen applied with compost is mineralised and used by plants, continuous compost use increases soil nitrogen levels substantially, providing significantly higher soil nitrogen supply potential.

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The use of compost can supply at least some of the crop's nitrogen, as well as most, if not all, of the phosphorous, potassium and trace elements required. Substituting the use of mineral fertiliser through compost use offers the opportunity of reducing GHG emissions generated in the manufacturing and transportation of fertilisers. If 10 t ha⁻¹ DM of 'typical' garden organics compost is used continuously, resulting in 40% uptake of nitrogen and 100% of phosphorous and potassium, GHG emissions of approximately 180 kg CO₂-e can be avoided.

When considering the **sequestration of compost-derived carbon** over both the long-term (100 years) and the medium term (20 to 50 years) we can say carbon sequestration resulting from compost use is an important interim climate change mitigation measure, because it provides opportunities for implementing low-cost measures that are immediately available and deliver a wide range of other environmental, agronomic and societal benefits.

Studies indicate that we can assume 45% of carbon applied with compost is retained over a 20-year period, 35% over a 50-year period, and 10% over a 100-year period. Therefore the use of mature garden organics compost as agricultural soil conditioner at a rate of **10 t DM ha⁻¹** will sequester carbon that is equivalent to reducing GHG emissions by:

- **5,046 kg CO₂-e over 20 years**
- **3,532 kg CO₂-e over 50 years**
- **1,009 kg CO₂-e over 100 years.**

If GHG emission savings from fertiliser replacement are added, using **10 t DM ha⁻¹** mature garden organics compost as agricultural soil conditioner can result in GHG emissions savings of:

- **5,224 kg CO₂-e within a 20-year time frame**
- **3,710 kg CO₂-e within a 50-year time frame**
- **1,187 kg CO₂-e within a 100-year time frame.**

In summary, the literature found that using compost as an agricultural and horticultural soil amendment:

- can contribute to mitigating climate change directly and indirectly
- provides opportunities for implementing low-cost measures that are immediately available
- is one of the fastest means of improving soil carbon levels
- is ideally suited as a mitigation measure in productive agricultural soils
- fits easily into the Australian National Carbon Accounting System
- can attract carbon credits
- delivers many agronomic benefits and enhances long-term agricultural productivity and production
- offers environmental and societal benefits.

1 Introduction

This report is a summary of a more extensive and detailed report with the same title: *The benefits of using compost for mitigating climate change*. The full report can be obtained from the Department of Environment, Climate Change and Water NSW.

Facilitating the diversion of organics from landfill has been a primary concern of all government jurisdictions. On the one hand, organic material is responsible for methane generation from landfills but the application of products processed from recycled organics to soil results in a range of important environmental benefits. These environmental benefits include improved soil health, water savings, improved crop productivity, reduced need for synthetic fertiliser and biocidal products, reduced water and wind erosion, improved tillage and, as this literature review demonstrates, enhanced capacity to mitigate climate change by 'locking up' or sequestering carbon in soils, reducing nitrous oxide emissions and reducing agricultural energy use.

Despite the growing body of studies demonstrating the capacity of the diversion of organic material and the application of compost products to mitigating climate change, the Australian National Carbon Accounting System does not currently include compost in its calculations. This report has been commissioned to assist in facilitating the recognition of compost's contribution by climate change governmental bodies, research institutes and agricultural enterprises.

In order to understand the current research that has been conducted in this arena, the Department of Environment Climate Change and Water NSW (DECCW) commissioned Johannes Biala of The Organic Force to review relevant scientific studies.

An extensive literature review entitled 'The benefits of using compost for mitigating climate change' has been prepared for policy makers and researchers. The full literature review can be obtained from DECCW. From this comprehensive survey, this short report draws together a summary of the full review.

The short report targets government officials from all jurisdictions, agricultural research and advisory bodies, agricultural enterprises, bodies involved in carbon quantification, verification and trading, compost processors and compost customers.

This Short Report provides condensed background information on key aspects of agricultural climate change mitigation in croplands (section 2) and the effects on climate change of using organic soil amendments (section 3) as well as conclusions of the literature review and recommendations for further work (section 4).

Note:

In Australia, the application to land of waste derived materials including biosolids and paper mill sludge, is subject to consent of the relevant state or federal authority.

For example, in New South Wales, waste is regulated under the Protection of the Environment Operations (Waste) Regulation 2005. The Government encourages the recovery of resources from waste where this is beneficial and does not harm the environment or human health. A provision for resource recovery exemptions within the legislation enables the reuse of waste or waste derived materials as fill or fertiliser (land applications) that may otherwise go to landfill.

2 Key aspects of agricultural climate change mitigation in croplands

2.1 Greenhouse gas emissions from the waste and agricultural sectors

Greenhouse gas (GHG) emissions from agriculture (excluding emissions caused by 'land use, landuse change and forestry' (LULUCF)) and waste management contributed 15.2% and 2.5% respectively, to Australia's total GHG emissions in 2008. Across Australia an estimated 3.7 million tonnes (Mt) of garden and food organics and a percentage of wood residue were diverted and recycled from landfill in 2007–08, preventing methane generation equivalent to ~ 4.28 Mt CO₂-e. Methane is a potent greenhouse gas (21 to 25 times as potent as carbon dioxide) that is normally produced when organic materials break down in landfill. The drop in greenhouse gas emissions from the waste sector has largely been attributed to the rise in landfill gas capture measures (~4.5 Mt CO₂-e in 2007–8); however, what goes unreported is the fact that emissions figures would be almost twice as large if the organics which are currently recycled were to be landfilled instead.

If only 50% of the 9.68 Mt (2007–8 figures) of organic residues sent to landfill was recycled, methane generation of more than 5 Mt CO₂-e per annum could have been prevented. This would have brought methane generation savings through organics recycling activities to around 10 Mt CO₂-e in Australia.

There are also significant opportunities for mitigating greenhouse gas (GHG) emissions through improved agricultural management, particularly of croplands. Greenhouse gas emissions from agriculture (excluding emissions caused by 'Landuse, Landuse Change and Forestry') and waste management contributed 15.2% and 2.5%, respectively, to Australia's total GHG emissions in 2008. Of the estimated global technical agricultural mitigation potential by 2030, about 89% is from soil carbon sequestration and about 2% from mitigation of soil nitrous oxide (N₂O) emissions.

According to the federal government's *National Inventory Report*, agricultural soils accounted for 17% and manure management for 3.9% of total agricultural emissions in 2007 (88.1 Mt CO₂-e). Agricultural nitrous oxide (N₂O) emissions accounted for 85.9% of the national nitrous oxide emissions. A closer look at the *National Inventory Report* reveals that composting is not considered as one of the manure management options, although it is likely to reduce methane and nitrous oxide emissions associated with alternative manure management systems. A review should be undertaken to determine whether and to what extent composting of manure can reduce methane and nitrous oxide emissions. Composting should then be included and featured as a separate manure management system in future national greenhouse inventory reports.

It is important to understand that agricultural sector GHG emissions from soils take into account only nitrous oxide and methane emissions, while changes in plant and soil carbon pools are dealt with in the 'Landuse, Landuse Change and Forestry' sector. Consequently, due to zero methane emissions from soil, all GHG emissions directly allocated to agricultural soil in the Commonwealth's *National Inventory Report* are solely attributed to nitrous oxide emissions.

Nitrous oxide is generated during biochemical nitrogen transformations in soil (mainly nitrification/denitrification). These transformations involve inorganic nitrogen compounds, which can become available from various sources, the major source being the application of inorganic fertilisers. While the Intergovernmental Panel on Climate Change proposes a default nitrous oxide emission factor for nitrogenous mineral fertilisers of 1.25% of applied nitrogen, Australia has developed differentiated factors for different farming systems. These factors are:

- 0.3% for non-irrigated crops
- 0.4% for irrigated and non-irrigated pasture
- 0.5% for cotton
- 1.25% for sugar cane, and
- 2.1% for irrigated and horticultural crops.

An emission factor of 1% of applied nitrogen was adopted in Australia for manure spread on pastures and crops. This was based on the average of the generic class 'organic', sewage sludge and wastes from animal waste management systems.

As mentioned previously, within the Australian National Greenhouse Inventory, soil carbon emissions and stocks are taken into consideration within the Landuse, Landuse Change and Forestry sector. Within this sector, croplands comprise emissions and sinks from *Croplands remaining Cropland* (20 million ha) and *Forestland converted to Cropland*, amounting to total net emissions of 23.6 Mt CO₂-e in 2007. Emissions from grasslands, which were estimated to have been more than ten times higher than from croplands, were not considered, as grasslands are relatively unimportant for compost use. Reporting of cropland emissions and sinks within the National Carbon Accounting System is based on estimates using the Full Carbon Accounting Model (*FullCAM*).

2.2 National Carbon Accounting System

The National Carbon Accounting System (NCAS) was developed to provide a comprehensive system to report on Australia's land-based greenhouse gas emissions and sinks. The analysis and reporting of the NCAS includes all carbon pools (biomass, dead organic matter and soil carbon) and all principal greenhouse gases (CO₂, CH₄ and N₂O), and can be applied at a variety of scales to both forestry and agricultural land uses. The national scale, fine spatial and temporal resolution, and breadth of data (climate, soil type, productivity, land cover and management information) that are combined in FullCAM, provide comprehensive data and a unique modelling capability. By incorporating five sub-models, including the carbon accounting model for cropping and grazing systems (CAMAg), the microbial decomposition model (*GENDEC*), and the Rothamsted Soil Carbon Model (Roth-C), the terrestrial ecosystem model FullCAM manages to cover biological and management effects on carbon pools, as well as transfers between different pools, including the atmosphere.

The report details how the NCAS estimates changes in soil carbon, and provides information on the data upon which these estimates are based, including soil mapping and inventory, calibration and validation of the Roth-C soil carbon model, and environmental, management and biomass data (e.g. climate, soil type, landuse and management data, crop growth and plant parameter, partitioning of crop residues, carbon content of crops and grass species, crop litter and decomposition rates, crop carbon turnover rates). At present, the NCAS accounts only for crop residues as input into soil carbon pools, but does not account for external inputs that replenish soil carbon pools, such as compost, manure, biosolids or sugarcane residue (mill mud). However, because of the very detailed nature of the NCAS, it should be relatively easy to expand the existing system to account for increase in soil carbon through external organic inputs into farming systems.

2.3 Soil carbon and climate change

The soil organic carbon pool under undisturbed natural vegetation can range widely between about 40 and 400 tonne carbon per hectare ($t\ C\ ha^{-1}$), depending on soil properties, profile characteristics, landscape position, temperature, and rainfall. This carbon pool is rapidly depleted when natural ecosystems are converted to agricultural production systems. The magnitude of depletion in soils of temperate climates is estimated to range between 25% and 50% after 20 to 50 years of agricultural use following deforestation. In the tropics it may be up to 50% or 75% during 5 to 20 years of agriculture after deforestation. Soil organic carbon losses in agricultural systems are caused by accelerated mineralisation, erosion and leaching, and are enhanced by regular ploughing, planting, and harvesting.

This situation is no different in Australia, with estimates that soil carbon stocks have decreased by 30% to 60% in Queensland since native soil was cleared for cropping about 100 years ago, and data from Victoria indicates that soil carbon levels had fallen by 50% after 20 years of continuous annual cropping. Carbon levels often decline for long periods of time after deforestation and landuse change until a new steady state is reached, where the rate of formation of new soil organic carbon from organic residues equals the rate of soil organic carbon decomposition. However, carbon emissions due to landuse change are not confined to historic times and forest-clearing; this is an ongoing process, which can be brought about by intensification of agricultural production systems.

The world-wide decline in soil organic carbon levels has resulted in carbon dioxide emissions, which are thought to have contributed significantly to increased atmospheric carbon dioxide levels.

2.4 Nitrogen and climate change

A number of agricultural activities increase mineral nitrogen availability in soils directly or indirectly, thereby increasing the amount available for nitrification and denitrification, and ultimately the amount of nitrous oxide (N_2O) emitted. Denitrification, which occurs primarily where soil oxygen is depleted, is probably the main source of N_2O , although it can also be generated by nitrification. Both nitrification and denitrification are an integral part of naturally occurring nitrogen transformations. Emissions of nitrous oxide depend primarily on the conditions detailed below.

2.4.1 Moisture and aeration

Maximum N_2O emissions usually occur when soil water content provides for an abundance of aerobic and anaerobic sites. For example, irrigation or rainfall events result in high N_2O emissions, especially when nitrogen fertiliser is applied with irrigation or soon before the irrigation event. Thus soil water content within the range of 55–85% water-filled pore space gives maximum N_2O emissions from denitrification and/or nitrification, while higher water content favours denitrification towards N_2 formation.

2.4.2 Temperature

Nitrification and denitrification, with which N_2O emissions are associated, primarily occurs when temperatures are between (approximately) 25°C and 35°C. N_2O emissions also increase with rising soil temperature, at least up to 35°C.

2.4.3 Soluble and readily decomposable carbon

Generally speaking, the addition of degradable organic materials increases N_2O production in soils that contain nitrate (NO_3^-), or that receive either fertiliser NO_3^- or materials containing degradable organic nitrogen (e.g. animal and green manures). As easily degradable organic compounds are the source of energy for denitrifying organisms, and because oxygen consumption in soils with high levels of decomposable carbon is normally high, the addition may result in anaerobic microsites.

2.4.4 Nitrogen from soil and fertiliser

The rate of N₂O emission after fertiliser application is influenced by the amount and type of fertiliser nitrogen, soil properties, environmental conditions and how all of these factors interact. Generally, the rate of denitrification increases with increasing NO₃⁻ content in soil under conditions suitable for denitrification (e.g. high moisture). Although, N₂O production often declines within a few hours or days after NO₃⁻ addition, and N₂ production increases, even when relatively high concentrations of NO₃⁻ are still present. Under aerobic soil conditions, fertilisation with ammonium (NH₄⁺) can result in marked N₂O emissions.

2.4.5 Soil pH

The optimal pH for both nitrification and denitrification is approximately 7–8. Hence, at pH levels above 8.0 and below 5.5 to 6.0, N₂O emissions can be several times higher than in neutral soil.

In the USA, it was estimated that direct emissions account for 82.5% and indirect emissions account for 17.5% of agricultural N₂O emissions, with most emissions (direct and indirect), being generated from cropland (69%), and less from grassland (31%). Emissions from synthetic fertiliser accounted for around 40% of direct N₂O emissions from agricultural cropland (mineral soils). Mineralisation and asymbiotic nitrogen fixation accounted for approximately 46%, and organic amendments for around 8% of emissions. Surface leaching and run-off in cropland accounted for 45% of all indirect N₂O emissions across all landuse types.

2.5 Potential for mitigating climate change in agriculture

The opportunities for mitigating GHG emissions in agriculture comprise:

- reduction of emissions by more efficient management of carbon and nitrogen flows in agricultural ecosystems
- removal of atmospheric carbon by increased biomass production and soil carbon sequestration
- avoidance of emissions by utilising crops and residues from bio-energy production.

Croplands offer many generic opportunities to impose practices that reduce net GHG emissions, including:

- improved agronomic practices that increase yields and generate higher inputs of carbon residue and can lead to increased soil carbon storage
- more carbon intense crops (e.g. perennials and orchards)
- more efficient nitrogen use from all sources that can reduce direct and indirect N₂O emissions and limit the use of nitrogen fertiliser, indirectly reducing GHG emissions associated with the manufacturing of nitrogen fertiliser
- reduced tillage that decreases soil carbon losses due to lower decomposition and erosion, and hence often (but not always) results in soil carbon gains
- improved and expanded irrigation (where water reserves allow) that can enhance carbon storage in soils through enhanced yields and residue returns
- restoration of degraded agricultural land that offers opportunities for carbon sequestration.

However, due to the complex nature of natural processes within agricultural ecosystems, certain management changes often affect more than one gas, through more than one mechanism, sometimes in opposite ways and on different temporal patterns, fully or partly negating other GHG benefits. Hence, the net benefit depends on the combined effects on all gases.

2.5.1 Technical and economic mitigation potential

Of the estimated global technical agricultural mitigation potential by 2030 ($-4,500-6,000$ Mt CO₂-e yr⁻¹), about 89% is from soil carbon sequestration, about 9% from mitigation of methane and about 2% from mitigation of soil N₂O emissions. As far as management options go, cropland management, grazing land management and restoration of organic soils and degraded land provide the highest potential.

It is recognised that soil carbon levels cannot be returned to their original value while used for agricultural production, with suggestions that no more than 60% to 75% of carbon lost in land use change can be returned. Based on the premise that 75% of carbon lost after converting native land to cropping can be restored, it was estimated that up to 31.6 Mt C can be sequestered in cropped agricultural soil in Queensland, based on average sequestration potentials of 11 t C ha⁻¹ for lower (500–800 mm yr⁻¹) and 14.8 t C ha⁻¹ for higher rainfall (800–2,000 mm yr⁻¹) areas. However, merely optimising inputs and reducing losses will deliver considerably lower carbon sequestration gains than when external carbon sources are added.

The marginal abatement curve for agricultural mitigation practices (the amount of mitigation achieved for a given carbon price) showed that cropland management activities are the most cost effective agricultural GHG mitigation measure. These activities achieved around 50% of the technical mitigation potential at modelled carbon prices of up to US\$20 t CO₂-e⁻¹. It is clear that land managers are reluctant to adopt GHG mitigation techniques unless they improve profitability and they will favour options that both reduce GHG emissions and increase productivity, over those that reduce emissions alone.

2.5.2 Mitigation by means of sequestering soil carbon

The soil carbon content can be raised by increasing the carbon input, decreasing the output or a combination of both. Soil carbon sequestration is the managed removal of atmospheric CO₂ by higher plants and micro-organisms, and its transfer into the stable soil carbon pool.

While organic matter was previously differentiated mainly into humic substances, soil organic matter is today largely characterised on the basis of physical fractionations. This differentiation is based on size and/or density. These factors better relate to the role organic matter components play in soil structure and soil function, and help to partition organic matter into components that differ in their lifespan chemistry, and origin. The domestic and international terminology for these organic matter fractions has not yet been settled, although the following have been proposed and used in Australia:

- surface plant residue
- buried plant residue
- particulate organic carbon
- humus
- dissolved organic carbon
- resistant organic carbon.

For convenience, the organic soil carbon pools are often grouped into three pools according to the speed of breakdown and replacement:

- **fast** - this pool has a short turnover time, with fast decomposition (e.g. daily to annual); also referred to as the *labile* or *active* pool
- **slow** - this pool has a longer turnover time, with slower decomposition (e.g. annual to decadal); also referred to as the *stable* or *humus* pool
- **passive** - this pool has a much longer turnover time (e.g. decadal to centennial/millennial); also referred to as the *recalcitrant* or *refractory* pool.

In addition to the above three soil carbon pools, the FullCAM model refers also to recalcitrant carbon, but in that case it represents charred carbon.

The proportion of total soil carbon in each pool can vary widely, but is assumed to be in the range of 10% for the fast pool, 40% to 80% for the slow pool, and 10% to 50% for the passive pool. These pools contribute approximately 10%, 40% and one% respectively to soil CO₂ emissions (respiration), with the remaining 50% contributed by live roots. From a carbon sequestration point of view, it is most desirable to increase the amount of organic soil carbon in the slow and passive pools due to their relative stability, although one has to be aware that active carbon responds to management changes more rapidly than total soil carbon. For example, recovery of total organic carbon after landuse change relies primarily on increases in particulate organic carbon with slow recovery of humus, while recalcitrant organic carbon is often unaffected by short to medium term management changes.

2.5.2.1 Effects of agricultural management practices

Land management practices affect carbon sequestration and loss rates, and the degree to which this happens depends on a wide range of variables, including site conditions, climate, and vegetation. Due to the variability in effects, it proved difficult to provide average carbon sequestration yields for certain measures. Work is continuing in this area.

In order to get a better handle on potential soil carbon sequestration levels attributable to different management practices, climatic zones are differentiated into *cool to dry*, *cool to moist*, *warm to dry* and *warm to moist*. Accordingly, it is estimated that the following average global carbon sequestration rates can be achieved over a 20-year period:

- agronomy 0.29 (dry) to 0.88 (moist) t CO₂-e ha⁻¹ yr⁻¹
- nutrient management 0.26 (dry) to 0.55 (moist) t CO₂-e ha⁻¹ yr⁻¹
- tillage/residue management 0.15–0.33 (dry) to 0.51–0.70 (moist) t CO₂-e ha⁻¹ yr⁻¹
- water management 1.14 (all climates) t CO₂-e ha⁻¹ yr⁻¹
- manure/biosolids use 1.54 (dry) to 2.79 (moist) t CO₂-e ha⁻¹ yr⁻¹
- compost 1.1–1.8 t CO₂-e ha⁻¹ yr⁻¹.

Although these and other data vary widely and have a high uncertainty level, the addition of external organic soil amendments usually has one of the highest carbon sequestration rates. Use of compost is not considered separately in most cases, except for European Union reports. The rate of sequestration is said to range from negative or zero under arid and hot climates, to approximately 3.67 t CO₂-e ha⁻¹ yr⁻¹ under humid and temperate climates, with normal rates of soil organic carbon sequestration in agricultural soils set at 1.1 – 1.8 t CO₂-e ha⁻¹ yr⁻¹.

In the USA, in particular, it is believed that high sequestration rates are obtained with no-till farming, retaining crop residue as mulch, growing cover crops in the rotation cycle and adopting complex farming systems, as well as integrated nutrient management, including manuring. As minimum and no-till agriculture has never been

demonstrated to achieve the same level of carbon sequestration in Europe and Australia as reported from the USA, the promotion of no and minimum-till agriculture as one of the optimal management practices for increasing soil organic carbon in the USA and Canada has recently been questioned.

2.5.2.2 Limits to carbon sequestration

Apart from soil, environmental and management constraints, there are other factors that can limit soil carbon sequestration, including:

- **nutrient supply** - the humification process can be severely constrained by the lack of nitrogen, phosphorous, sulphur and other building blocks of soil humus
- **sink saturation** - changes in carbon input and/or decomposition rates change soil carbon stocks, moving them towards new 'equilibrium' carbon levels. This is why soil carbon sequestration rates are non-linear and diminish over time, often reaching their maximum soon after a change in land use or land management. While the new equilibrium may not be reached for a long time after such change, carbon sequestration potential may be minimal after 20 to 50 years. Soil carbon sequestration does not, therefore, have limitless potential to offset CO₂ emissions. The potential for carbon sequestration depends on the carbon equilibrium of the current practice relative to the saturation level (optimal carbon level) that can be reached with the new practice at the given soil and environmental conditions
- **reversibility** - sequestration of carbon in soils is not necessarily permanent, as changes in agricultural management or land use, can result in declining soil carbon levels. Once equilibrium, or a certain content of carbon, is reached, it is still necessary to add significant amounts of carbon to maintain the attained soil carbon level. For example, cropped soil with 50% clay requires >2.2 t C ha⁻¹ annually (or 5.5 t ha⁻¹ of biomass of 40% carbon) to maintain a given carbon level, while cropped soil containing 30% clay requires >6.5 t C ha⁻¹ (or 16 t ha⁻¹ of biomass, including root biomass). In addition, the rate of carbon input has to be higher at higher existing soil carbon levels, in order to maintain soil carbon stock at that level.

2.5.3 Reduction of nitrous oxide emissions

Nitrous oxide emissions cannot be ignored due to their high global warming potential, the permanency of any reductions, and the potential of nitrous oxide emissions to annul carbon sequestration gains. The primary consideration for mitigating nitrous oxide emissions from the agricultural sector is to match the supply of mineral nitrogen and keep it to a minimum, commensurate with the needs of crops. Management practices to minimise nitrous oxide emissions from nitrogen fertilisers and legumes, as well as ways of improving nitrogen use by crops and/or reducing application rates, include the following:

- applying fertiliser nitrogen at optimum rates by taking into account all nitrogen sources available to the crop from soil, legumes, manure or compost
- applying fertiliser nitrogen at the rate and time to meet crop needs
- avoiding fertiliser nitrogen application outside the crop-growing season, and during fallow periods providing guided fertiliser nitrogen application through crop monitoring, yield maps and soil tests
- applying other nutrients if required to balance crop nutrient supply and optimise nitrogen utilisation
- avoiding surface application, incorporate or band so that fertiliser nitrogen losses are minimised and plant utilisation maximised
- incorporating manure immediately after application, and accounting for nitrogen release from organic soil amendments in nutrient budget.

2.5.3.1 Zero/reduced tillage

The effects of conservation tillage practices on nitrous oxide emissions are variable, with some reports demonstrating that emissions increased, while others showed exactly the opposite. It is suggested that the impact of no-till on nitrous oxide emissions is small in well-aerated soils but most often positive in soils where aeration is reduced by restricted drainage.

2.5.3.2 Fertiliser use

There is a marked relationship between nitrous oxide emissions and increased nitrogen application rates, that may be linear or non-linear. Agricultural nitrous oxide fluxes can be reduced, with no or little yield penalty, by reducing nitrogen fertiliser inputs to levels that just satisfy crop needs. Other options for reducing nitrous oxide emissions include avoiding wet soil conditions, applying nitrogen fertiliser as NO_3^- or as controlled-release and stabilised nitrogen, and subsurface fertiliser placement.

For some, increasing crop nitrogen-use efficiency by altering nitrogen management practices is the most promising strategy for mitigating agricultural nitrous oxide emissions across a range of cropland systems.

2.5.3.3 Crops

Rotational cropping is already practiced in many areas but optimising crop selection, considering in particular the addition of nitrogen fixing crops, can increase soil carbon storage and reduce mineral fertiliser requirements. While biological nitrogen fixation does not seem to be a measurable source of nitrous oxide *per se*, inclusion of legumes in corn and cotton rotations has increased the level of emissions during the subsequent year of rotation.

2.5.3.4 Australian data

Nitrous oxide emissions in Australian agricultural systems were determined mainly in dryland cropping, cotton, and sugarcane. Nitrous oxide losses in cotton (NSW) and dryland wheat cropping in subtropical south east Queensland accounted for 0.16 and 0.36% of added nitrogen in cotton, and between 0.54–0.91% in wheat cropping, with emissions from conventional tillage being higher than from no-till agriculture. Emissions from pineapple and macadamia in the high rainfall south east Queensland region indicate losses of 2.1–4.7% (0.8–1.4 kg N ha⁻¹) of applied fertiliser nitrogen, and of up to five kg N ha⁻¹ from non-fertilised pasture with high soil carbon (> 4% in 0–10 cm layer).

The assessment of emissions from sugarcane in northern NSW and central Queensland vary significantly. A site in northern NSW with acid sulfate soil recorded soil moisture conditions that were near optimal for nitrous oxide production for around five months, resulting in the emission of 45.9 kg N ha⁻¹, or 22% of fertiliser applied nitrogen. Even unfertilised plots emitted 11.3 kg N ha⁻¹. In contrast to most other (sugarcane) soils, acid sulfate soil appeared to be a source of methane, not a sink. The net sequestration of CO₂ by the crop from the atmosphere of 51.4 t ha⁻¹ during the growing season was offset by nitrous oxide and methane emissions amounting to 23 t ha⁻¹ CO₂-e. On the other hand, nitrous oxide emissions in central Queensland on sandy loam amounted to 3% of the applied nitrogen and no methane emissions were recorded, despite high rainfall and green sugarcane trash blanketing (mulch). The main drivers of nitrous oxide emissions appeared to be the availability of surplus nitrogen and the water content of the near-surface soil.

2.5.4 Outlook

There are significant opportunities for GHG mitigation in agriculture, but for the potential to be realised, numerous barriers must be overcome - including climate and non-climate policy, as well as institutional, social, educational and economic constraints. The mix of agricultural mitigation options that are adopted in the future will also depend upon the price of carbon dioxide equivalents. With appropriate policies, education and incentives, it may be possible for agriculture to make a significant contribution to climate mitigation by 2030, creating offsets of between 5% and 14% of total annual CO₂ emissions, depending on the price for carbon.

3 Effects of using organic soil amendments on climate change

The promotion of increased carbon input from organic amendments (animal manure, compost, crop residues, sewage sludge) is one of the most efficient measures for soil carbon sequestration, according to the European Union Working Group on Sinks Related to Agricultural Soils. Despite this recognition, so far only limited work has been undertaken to investigate the effects of organic soil amendments on climate change, particularly when it comes to the use of compost. Work carried out in Europe related to compost use seems to have focused primarily on carbon sequestration without paying much attention to N₂O emissions. Nevertheless, information regarding the use of animal and green manure is available from Europe and North America, and also from warmer environments such as India, China, and Africa.

There does not seem to be a comprehensive, Australia-wide inventory of potentially available resources, despite increased interest in utilising organic residues and by-products, both for improving soil properties and generating fuel or energy. Nevertheless, it is clear that apart from municipal organics (about 10.6 Mt, of which 3.7 Mt is already converted into recycled organic products), there are large quantities of agricultural and food/fibre processing residues that can be utilised beneficially.

3.1 Organic farming

Organic farming systems rely on high internal or external organic matter inputs, and on carbon and nutrient cycling for maintaining soil quality and productivity. Although it can be assumed that composted organic residues are often used in organic farming systems, reported carbon sequestration, changes in nitrous oxide emissions, and the overall potential for organic farming to reduce GHG emissions are by no means due to compost use alone, but a wide range of farm management practices.

3.1.1 Carbon sequestration

For decades, organic agriculture was at the forefront of systematically developing and optimising the quantity and application of organic manures, based on the principles of integrating crop production and animal husbandry, and the recycling of organic residues. Likewise, organic residue processing techniques were improved to obtain high quality manure, and composting was employed to minimise losses and increase humus production.

Modelling for Northern European conditions suggested that conversion from conventional to organic farming practices increases SOC levels by 100–400 kg ha⁻¹ annually for the first 50 years, but actual long-term trials and farm-level comparisons conducted in the USA and Europe that are presented in this report provided diverse results. Virtually all such trials showed superior carbon sequestration for organic farming systems compared to conventional practices, with carbon sequestration rates of 180 kg C ha⁻¹ yr⁻¹ for an organic farming system with high animal density in Southern Germany (14 years) for example, or 981 kg C ha⁻¹ yr⁻¹ for a manure-based organic farming system in Pennsylvania, USA (22 years). Despite the fact that not all organic farming system trials showed increasing SOC levels, for example on sandy soil in Germany (18 years), most organic farming systems with that experience still managed to reduce the decline of soil organic carbon in comparison to conventional farming systems.

3.1.2 Nitrous oxide emissions

The highest nitrous oxide efflux in organically managed soil usually occurs after manure application and incorporation of legume (cover) crops. Nevertheless, most studies that compared nitrous oxide emissions from organic and conventional farming systems concluded that organic farming results in lower emissions than conventional production. Comparison of an organic and a conventional farm in southern Germany, for example, showed that nitrous oxide emissions (mainly from soils) contributed about 60% of total GHG emissions in both farming systems, representing, on average, 2.53% of total nitrogen input by synthetic fertilisers, organic fertilisers and crop residues. Mean emissions from organic and conventional crop production (emissions from cropping, fertiliser production, and the consumption of fossil fuels for field management and drying of crops) amounted to 3.2 and 4.4 t CO₂-e per hectare field area respectively, and for winter wheat alone, emissions amounted to 1.48 and 2.5 t CO₂-e ha⁻¹.

Comparison of nitrous oxide emission rates in crop rotations of organic and conventional dairy farms across five locations in Europe showed a significant relationship between total nitrogen inputs and nitrous oxide emissions, with annual average nitrous oxide losses amounting to $1.6 \pm 0.2\%$ of total nitrogen inputs. Modelling of GHG emissions from organic and conventional dairy farms in Europe showed that the emissions at farm level could be related to either the farm nitrogen surplus or the farm nitrogen efficiency. The farm nitrogen surplus appeared to be a good proxy for GHG emissions per unit of land area, as GHG emissions increased from 3.0 t CO₂-e ha⁻¹ yr⁻¹ at a surplus of 56 kg N ha⁻¹ yr⁻¹ to 15.9 t CO₂-e ha⁻¹ yr⁻¹ at a surplus of 319 kg N ha⁻¹ yr⁻¹. Organic farms showed considerably lower nitrogen surpluses than conventional farms. The GHG emissions per product unit were quite closely related to the farm nitrogen efficiency, and doubling of the nitrogen efficiency from 12.5% to 25% reduced the emissions per product unit by approximately 50%. Farm nitrogen efficiency may therefore be used as a proxy for comparing the efficiencies of farms with respect to supplying products with low GHG emissions. It was shown that organic farming usually manages to reduce emissions per unit land area, but not necessarily per unit of product.

Most research found that, in comparison to conventional agriculture, organic farming resulted in significantly reduced nitrate leaching rates, which reduces the risk of indirect nitrous oxide emissions.

3.1.3 Multilevel assessment of using soil amendments

An evaluation of using mineral fertiliser and different organic soil amendments application on yield, soil quality, soil health, environment and climate change after completion of the first eight-year crop rotation in an organic farming systems trial showed that no product scored high in all of the five chosen agricultural and societal criteria. On the light sandy clay soil, use of farmyard manure resulted in the highest crop yields (in 2006) and, together with compost products, showed a slight increase in SOC levels over the eight-year trial period.

Table 1 Qualitative evaluation of using different soil amendments (Source: Koopmans *et al.* 2008^{*})

Criteria	Yield	Soil Quality	Soil Health	Environment	Climate Change
Indicator	Fresh matter yield 2006	Nitrogen supply	Parasitic nematodes	P surplus and NO ₃ leaching	SOC sequestration
Mineral fertiliser	-	-	-	+	0
Poultry manure	0	0	+	-	0
Farm yard manure	+	+	0	0	+
Cattle slurry	-	+	0	0	-
Household compost + slurry	0	+	+	-	0
Plant compost 1	0	+	-	+	+
Household compost	0	-	0	+	+
Plant compost 2	-	0	0	+	+

- = negative effect, + = positive effect and 0 = no effect

3.2 Using manures

It was estimated that approximately 3.22 Mt of animal manures are generated annually in Australia, comprising approximately 1.33 Mt of feedlot manure, 1.56 Mt of poultry manure, and 0.32 Mt of pig manure. These quantities are similar to the amount of municipal organics that was recycled in 2006–07, but are relatively small compared to about 62 Mt of collectable manure produced in the USA in the mid 1990s and some 90 Mt of animal manure being land-applied annually in the UK.

At present, the vast majority of animal manures are used as soil amendment for supply of plant nutrients and improvement of soil properties. Using animal manures for land management purposes can deliver agronomic and environmental benefits but also have certain drawbacks and risks.

3.2.1 Decomposition

Decomposition of animal manures in soil depends upon factors such as type of manure, feeding ration, animal age, living conditions of animals, and how manure is handled, as well as moisture and temperature conditions in the soil. Comparison of 47 animal manures of different origins, physical properties and processing levels, showed that carbon mineralisation varied from 5% to 62% of the organic carbon added during the 224-day incubation. Seventy per cent of the manures induced net nitrogen mineralisation at the end of incubation, ranging from 3% to 51% of organic nitrogen. Some manures induced net soil inorganic nitrogen immobilisation, ranging from -1% to -31% of the organic nitrogen added. Carbon present in the water-soluble fraction at 20°C gave the best indication of carbon mineralisation and the organic nitrogen content or carbon to nitrogen ratio were the best indicators for nitrogen mineralisation.

^{*} Koopmans, C. J., M. Zanen and J. G. Bokhorst (2008). Organic Fertilisers of the MAC Trial and their Impact on Soil Quality, Environment and Climate Change. The 5th International Scientific Conference on Sustainable Farming Systems - ECOMIT, Slovakia.

3.2.2 Soil carbon

3.2.2.1 Increase in soil organic matter

Research has shown that manure application has a significant effect on chemical, physical and biological soil properties and that most of these effects are due to an increase in soil organic matter. The increase in soil organic matter with manure addition was reported in many studies over a wide variety of soil textures and climates for diverse agricultural cropping systems. The rate of increase in soil organic matter depends on temperature, moisture and tillage conditions, as well as the amount of manure added. Manure needs to be applied for at least two years to see increases in soil organic matter. Higher/longer applications are needed to produce measurable changes in soil properties, particularly physical properties. Where that was not achieved, manure application reduced soil organic matter losses in production systems under tillage.

It appears that long-term use of manure can increase carbon levels in all soil particle size fractions (clay, silt, sand).

Results of long-term field trials are particularly important in evaluating the effects of using manure on soil organic matter levels. The marked and sustained increase in soil organic matter due to long-term use of manure compared to mineral fertiliser in continuous wheat cropping was shown in the Broadbalk Long-Term Experiment (Rothamsted Research Station, UK) where, after 160 years, carbon levels were around 2.5-fold higher in soil that had received manure ($35 \text{ t ha}^{-1} \text{ yr}^{-1}$), compared to soil that received mineral fertiliser or no amendments. As can be expected, the development of soil nitrogen levels in the three treatments followed a very similar pattern to that observed for soil carbon. However, this meant that nitrogen lost in drainage water (1990–98) was also relatively high -approximately 40 and 80 $\text{kg N ha}^{-1} \text{ yr}^{-1}$ where manure and manure + fertiliser ($96 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) were used.

A similar long-term trial at Woburn (also at the Rothamsted Research Station) demonstrated that it is much more difficult to maintain or increase soil organic matter in a sandy loam (8–14% clay) than it is on the silty clay loam (20–40% clay) at Broadbalk. The Rothamsted results were confirmed by a similar trial in Bad Lauchstädt (Germany), where 75 years of unchanged agricultural practices resulted in new soil organic carbon equilibria, which varied between 1.61% carbon for the unfertilised soil and 2.27% carbon for the soil that was amended with manure ($15 \text{ t ha}^{-1} \text{ yr}^{-1}$) plus mineral fertiliser (Figure 1). The reversal of the trial's high input ($15 \text{ t ha}^{-1} \text{ yr}^{-1}$ manure + N and no input treatments) after 75 years also clearly demonstrated the reversibility of carbon sequestration.

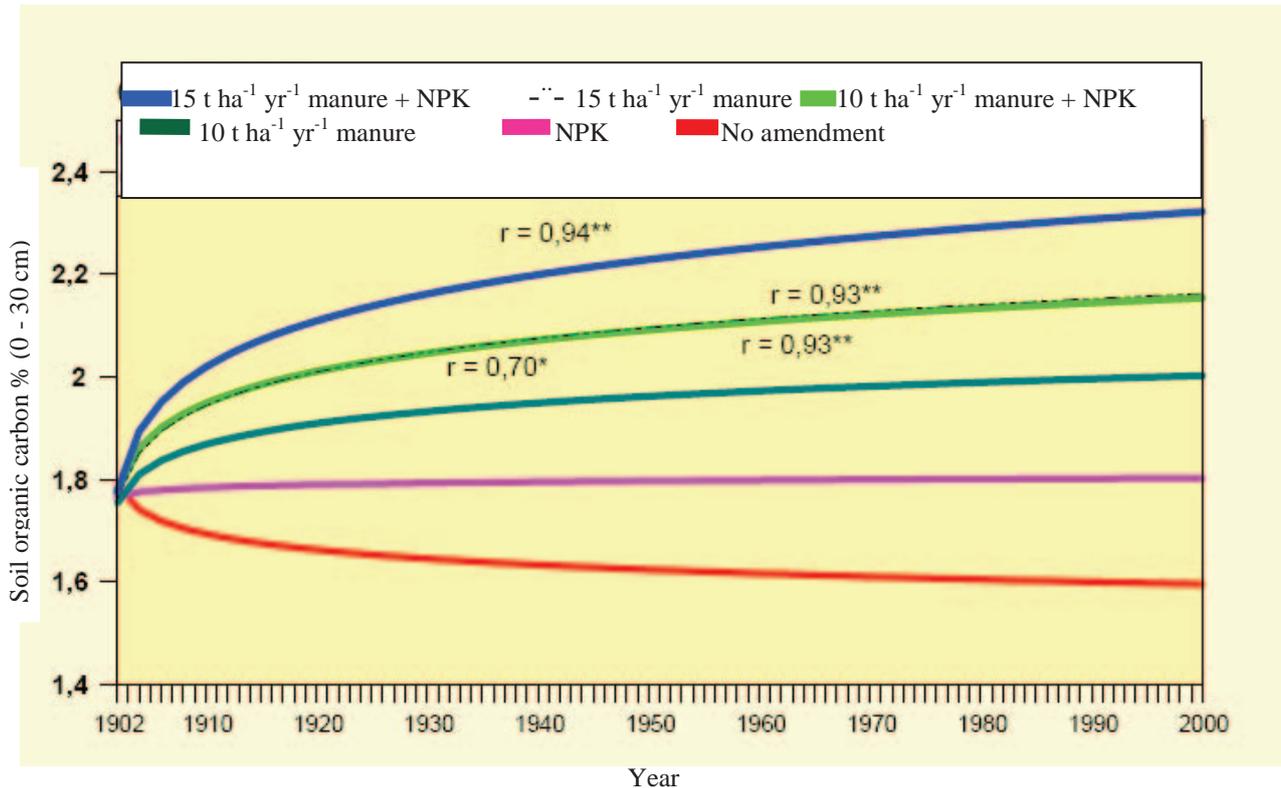


Figure 1 Development of soil organic carbon levels in the main treatments of the static fertilisation experiment Bad Lauchstädt (Source: Körschens 2009*)

A great many short, medium and long-term field trials were conducted in diverse environments, soils and agricultural production systems, in which the effects of manure application on soil carbon pools was determined. The results of many such trials are described in the report, but because of their divergent nature are summarised here for different climatic zones. The average percentage (and range) of carbon applied as manure that was retained in the soil was found to be:

- 23% (\pm 15%) in temperate or frigid regions
- 7% (\pm 5%) in thermic regions
- 8% (\pm 4%) in moist regions
- 11% (\pm 14%) in dry regions.

Hence, for all regions except for cold climates, it can be expected that between 5% and 20% of carbon applied with manure is retained and incorporated into the soil carbon pool. Over all, the data gathered in the UK indicated that 23% of the carbon applied was retained in the topsoil, which means that soil organic carbon increased by an average of 60 (\pm : 20) kg ha⁻¹ yr⁻¹ per tonne of manure DM applied. Comparison of ten long-term agricultural experiments in Germany showed that optimum fertilisation (organic + mineral) resulted in soil organic carbon levels that were between 16% and 76% higher than in soil that had no fertilisation, with increases at most sites ranging between approximately 30% and 50%. Most, but not all trials where organic and mineral fertilisation were combined, reported superior carbon storage, and in most cases increased yield responses were also recorded.

* Körschens, M. (2009). Humus – Voraussetzung für Bodenbildung und Bodenfruchtbarkeit [Humus - a pre-condition for the development and fertility of soils] (PPT). Naturland - Ackerbaulagung 2009. Bernburg - Sirenzfeld, Germany, Landesanstalt für Landwirtschaft, Forsten und Gartenbau Sachsen-Anhalt.

The analysis and evaluation of many long-term agricultural field experiments, combined with in-depth knowledge about carbon and nitrogen dynamics led senior soil scientist* to draw the following conclusions:

- improved soil organic matter levels, and hence improved soil properties, contribute up to 10% of crop yield on sandy soils, and up to 5% on loamy soils
- the highest yields are only attainable in an environmentally acceptable way if organic and mineral fertilisation are combined
- changes to the soil organic carbon equilibrium due to management changes occur very slowly and affect almost exclusively the decomposable carbon fraction. Whether management changes (including fertilisation) result in increasing or decreasing SOC levels depends on the initial soil carbon level
- hot water extractable carbon has proved to be an appropriate criterion for the characterisation of the decomposable carbon
- considering texture, environmental conditions and agricultural practices, it is possible to determine optimum soil organic carbon levels in agricultural soils
- the ranges of optimum soil organic carbon and nitrogen levels are relatively narrow. Under conditions in Central Europe (mean annual temperatures 6-10°C, annual precipitation 450-800 mm), the optimum content of mineralisable carbon ranges between 0.2% and 0.6% of total carbon, and optimum nitrogen levels range between 0.02% and 0.06%
- soils with lower carbon and nitrogen levels are prone to encounter soil fertility problems, experience yield depression, and plant biomass will absorb less CO₂, while soils with higher levels might pose environmental risks (nutrient leaching)
- use of optimum soil organic carbon levels (standard values) together with methodology for developing 'humus balances' allows management of soil organic matter content in arable soils that ensure high yields and prevent detrimental environmental effects
- increase in soil organic carbon by 0.1% results in improved soil physical properties that approximately amount to:
 - an increase in hygroscopicity of 0.06% to 0.08% (w/w)
 - an increase in water holding capacity of 0.4% to 0.6% (w/w)
 - a decrease of dry matter density of 0.004 to 0.005 g/cm³
 - a decrease of bulk density of 0.006 to 0.008 g/cm³
- due to increased stability of its carbon compounds, compost is suitable to increase the SOC level of sand and clay soils and hence to improve their physical characteristics.

3.2.3 Composting of manure to enhance carbon sequestration

Composting of animal manures reduces volume, limits odours, stabilises nutrients, kills weed seeds and pathogens, and reduces volatile organic compounds. Composting of manure also induces chemical changes that affect carbon cycling processes in the soil. Composting of cattle manure for 100 days, for example, doubled the proportion of humic substances from 35% before composting to 70% at the end of composting. Overall, it can be said that carbon in manures is lost during composting and transformed into more stable carbon forms, and because of this, the remaining carbon is less decomposable when applied to land. Unfortunately, considerable proportions of nitrogen are also frequently lost during the composting of manures. For example, composting of feedlot cattle manure resulted in 51±9% loss of carbon, and 31±12% loss of nitrogen, while composting of poultry litter for 65 days resulted in 16% loss of carbon, and 49% loss of nitrogen.

*M. Körschens

Various incubation tests and field trials have shown that the use of composted manure results in retention of considerably higher proportions of applied carbon in soil than when raw manure is used, although there are also reports where no difference was observed. Several results showed that soil containing composted manure retained about three times as much carbon as soil with added raw manure.

In addition to aiding soil carbon sequestration, composting of manure yielded a more predictable and reliable source of mineralisable nitrogen than fresh manure, and composting of liquid pig manure (plus straw) was found to reduce N₂O emissions compared to using liquid pig manure.

3.2.4 Nitrous oxide and methane emissions

Laboratory incubation of soil to which different dairy manures (n=107) were added showed that denitrification accounted for approximately 5% of the added manure nitrogen. Potential denitrification is strongly influenced by mineralisable nitrogen and the water-soluble organic carbon content of manures. Slurries often contain greater concentrations of these important components than stacked or composted manures. Another incubation trial showed that sand with low cation exchange capacity emitted more GHGs (N₂O, CO₂ and CH₄) than clay with high cation exchange capacity.

Field trials with manure confirmed that the nitrous oxide flux significantly correlates with the mineral nitrogen and water-filled pore spaces in soil, and is also affected by the soil's redox potential. Most of the nitrous oxide emissions occur within a few weeks of manure application, but might also peak when rain or irrigation results in high water-filled pore space. It is suggested that the depletion of readily decomposable carbon within a few weeks of manure application is responsible for decreasing nitrous oxide emissions.

Depending on circumstances, trials showed higher, equal or lower nitrous oxide emissions when manure or slurry was used, compared with mineral fertiliser. For example, nitrous oxide losses from fertiliser use amounted to 3.3% and 0.2% respectively in sandy and heavy clay soil, while it accounted for 2.7% and 1.8% respectively of applied slurry nitrogen for sand and clay. In another trial, the cumulative nitrous oxide loss was 0.6% of total nitrogen applied as mineral fertiliser, 1.2% of total nitrogen applied with 60 t ha⁻¹ yr⁻¹ of swine slurry, and 1.7% of total nitrogen applied with 120 t ha⁻¹ yr⁻¹ of swine slurry.

3.3 Using biosolids and paper mill sludge

3.3.1 Biosolids

Long and short-term biosolids application trials in the UK showed average soil organic carbon increases of 130 (90–170) kg ha⁻¹ yr⁻¹ per tonne of raw solids DM applied, and of 180 (130–230*) kg ha⁻¹ yr⁻¹ per tonne of digested solids DM applied. A higher proportion of carbon added with digested sludge (ca. 56%) was retained in the topsoil than with raw sludge (ca. 36%), and this supports the notion that, similar to composting, much of the easily decomposable carbon is lost during the digestion process, so that the organic carbon added with digested sludge is more resistant to decomposition than raw sludge carbon. Partitioning of carbon in composted sewage sludge and cattle manure into two components differing in ease of decomposition, showed that the labile component accounted for 16% to 20% of total carbon in both products, with a decomposition rate constant of 2.4 x 10⁻² d⁻¹ for labile carbon, and 1.2 to 1.4 x 10⁻⁴ d⁻¹ for the resistant pool.

Strip mined land was reclaimed over 34 years with rotational biosolids application, at cumulative loading rates between 455–1,654 t ha⁻¹ DM (over 8–23 years). The mean net soil carbon sequestration was 1.73 (0.54–3.05) t C ha⁻¹ yr⁻¹ in biosolids-amended fields, compared with -0.07–0.17 t C ha⁻¹ yr⁻¹ in fertiliser controls. Soil carbon

* at 95% confidence interval (CI)

sequestration was significantly correlated with biosolids application rate. The equation for this correlation can be expressed as: $y = 0.064x - 0.11$, in which y is the annual net soil carbon sequestration ($t\ C\ ha^{-1}\ yr^{-1}$) and x is the annual biosolids dry matter application ($t\ DM\ ha^{-1}\ yr^{-1}$).

Characterisation and incubation of over 40 sludges of diverse properties, representing different treatment and stabilization processes, showed dramatic differences between sludges in their ability to release greenhouse gases (N_2O and CO_2), but failed to deliver a clear explanation of mechanisms controlling these differences. Some biosolids of similar properties represented entirely different emission behaviour. Other work showed that increasing application rates resulted in both increased nitrous oxide emission rates and higher cumulative emissions, but had mixed results in comparing nitrous oxide emissions from biosolids (processed and unprocessed) and mineral fertiliser.

3.3.2 Paper mill sludge

Around 700,000 tonnes of paper mill sludge was applied to agricultural land in England and Wales, but; there is no equivalent quantitative data available for Australia. With a 'typical' carbon content of around 30% DM, and a proportion of recalcitrant (lignin) and readily decomposable carbon comparable to farm manures, paper mill sludge clearly has the potential to increase soil organic carbon levels in the range of manures; i.e. by ca. $60\ kg\ ha^{-1}\ yr^{-1}$ per tonne paper mill sludge DM applied. Nevertheless, paper mill sludges seem to vary somewhat, at least as far as nitrogen immobilisation is concerned, and, by extension, their various effects on nitrous oxide emissions.

3.4 Using compost

Composting is a partially controlled and accelerated bio-oxidative process through which highly diverse and heterogeneous organic material is decomposed and transformed into humified material. Composition of the raw materials to be composted determines CO_2 evolution during composting, and residual carbon levels in finished compost. Readily degradable components (e.g. sugar, starch, protein) are the most important source of carbon during the intensive composting phase, and are primarily broken down during this period. Lignin is the compound most resistant to biodegradation and strongly influences degradability of organic materials. Most labile organic compounds are broken down during the composting process, and are recorded as 'carbon loss', i.e. transformation of solid into gaseous (CO_2) carbon. The literature provides the following examples of carbon losses during composting:

- ~46% loss open windrow composting of mixed food and garden organics (biowaste), average over 10 years
- ~50% loss 40–60 day open windrow composting of animal manure
- ~83% loss 9 months covered windrow composting of corn silage
- ~41–45% loss 9 months covered windrow composting of two-phase olive waste.

This means that around 50% of carbon contained in the raw materials is retained and found in compost, mostly in recalcitrant organic compounds such as humic substances. The formation and increasing presence of humic substances during the composting process has been documented on various occasions. It has also been shown that humic acids found in compost consist of a stable fraction and a labile fraction, the relative contents of which depend on the duration of the composting process.

In very broad terms, there are two basic compost products defined by their end use:

- composted mulch (70% of mass $>15mm$, applied to soil surface)
- composted soil conditioners, suitable for incorporation into the soil.

Due to a lack of data regarding the use of organic mulches, most compost related information in the following sections concerns use of compost as a soil conditioner.

The variability of the organic matter undergoing composting, the diversity of composting conditions, the levels of stability and maturity reached during composting, and the degree of product refining makes compost research a great challenge. To limit the variability in input materials, this section will deal primarily with composted soil conditioning products made from municipal and commercial residues other than manures, paper sludge and biosolids.

3.4.1 Fate of compost carbon after soil application

Compost is a complex mixture of inorganic and organic components, ranging from labile to resistant in terms of degradability, as well as dissolved organic carbon, which may be degraded or leached. As with other organic soil amendments, the rate and extent of mineralisation of compost products after application to soil depends on the quantity, type, maturity and particle size distribution of the applied product, as well as on soil properties, environmental conditions, and agricultural management practices.

3.4.1.1 Degradation

Distinct differences in the level of carbon degradation in soil were observed between different organic residues, and between composted and uncomposted materials. The longer organic materials were composted, the smaller the proportion of organic matter degraded after soil application. Again, the labile organic compounds contained in compost are degraded relatively quickly, and the recalcitrant fractions remain in the soil.

Research by means of incubation trials reported the following carbon losses after incorporating compost into soil:

- 5.4% in 70 days at 25/20°C tree prunings + yeast composted for 25 wks
- 21% in 32 wks at 25°C two sources of two-phase olive mill residue composted for 34 wks
- 14% in 24 wks 20 samples of manure and plant based composts
- 5% in 60 days MSW + biosolids compost in two soils
- 8% and 14% in 60 days biosolids compost in two soils
- 5% in 54 days biowaste compost (food and organics)
- 17% in 52 wks at 14°C biowaste compost in mine site rehabilitation
- <20% in 78 wks at 5 and 14°C biowaste compost in mine site rehabilitation and agricultural soil.

Incubation of fresh (C:N ratio = 15.4) and mature (C:N ratio = 9.2) biowaste compost in sand for 112 days at five, ten, 15, 20, and 25°C showed cumulative carbon losses for fresh compost that ranged from 36% of the initial carbon content at 5°C to 54% at 25°C, while carbon losses were small for mature compost, ranging from 1% to 6% within the assessed temperature range of 5 to 25 °C (Figure 2).

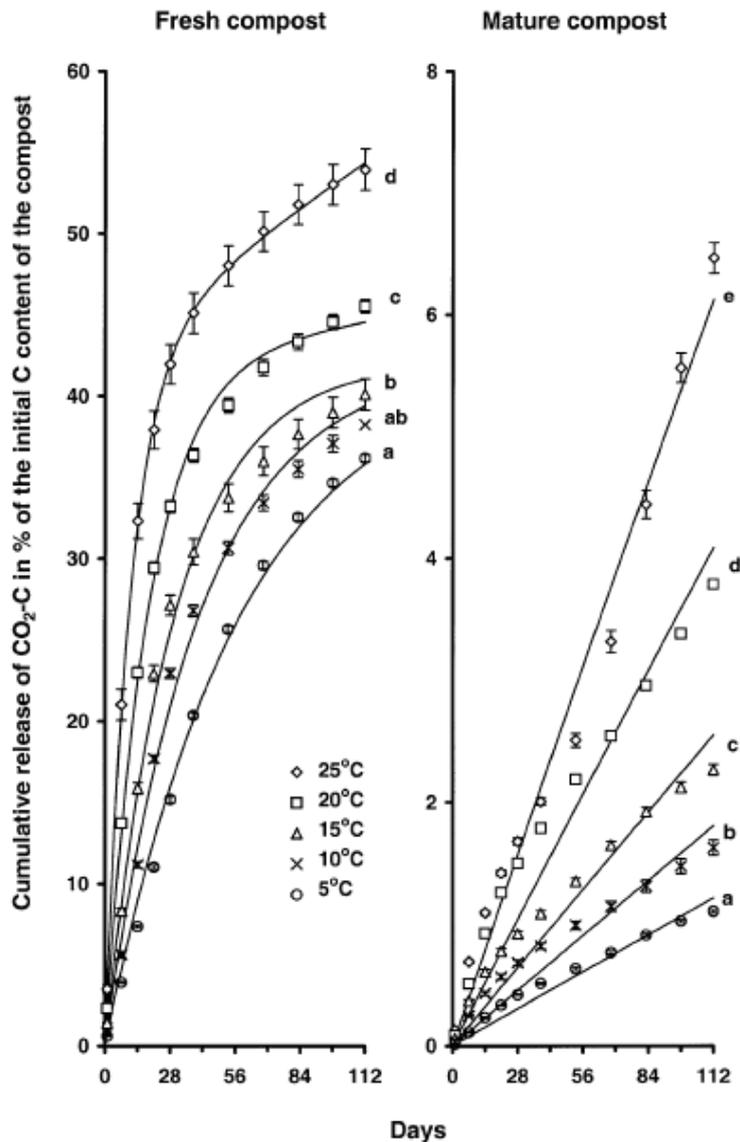


Figure 2 Cumulative CO₂ emissions from fresh and mature biowaste compost in sand during 112 days at various temperatures. Treatments with the same letter assigned are not significantly different ($p < 0.05$) (Source: Chodak et al. 2001)*.

3.4.1.2 Sequestration

Scientific trials have established the application of compost to arable soils can increase SOC levels. This has been demonstrated in Europe (UK and Germany), North America and Australia as shown below.

For the **United Kingdom** it was estimated that, over a 20-year time frame, carbon retention is greatest from the addition of digested biosolids cake (56%) and composted garden organics (43%), and least from manure (23%) and straw (7%). These materials deliver between 370 and 1,500 kg ha⁻¹ additional carbon annually, if the organic materials are applied at rates of 250 kg ha⁻¹ total nitrogen. Estimates for garden organics compost are based on four medium-term (5-8 yrs) compost experiments at four locations, at which 50 t ha⁻¹ of compost was applied annually or 100 t ha⁻¹ bi-annually, with or without addition of inorganic nitrogen fertiliser.

On average, soil organic carbon increased by 60 (36–84) kg ha⁻¹ yr⁻¹ per tonne of compost DM applied. While this figure is similar to estimates for farm manure when expressed as a proportion of the organic carbon applied, soil

carbon retention following compost use (43%) was almost double that from farm manures (about 23%), since composts have a lower carbon content (per tonne of DM) than farm manures. The proportion of applied carbon that remained in the soil varied between 28% and 60% for the three locations where compost was used for five years, with the eight-year trial showing 54% carbon retention. However, it is stressed that these increases in soil carbon can be regarded only as the initial rate of increase (up to about 20 years), as soil organic carbon accumulation rates decline with time.

Another large-scale, unreplicated trial (ten fields on four farms), in which garden organics compost was applied at rates of 0, 25, 50 and 75 t ha⁻¹ to a range of different crops, showed that the two highest application rates arrested the decline in SOM between 2001–05. This was surprisingly high (30%) in unamended soil (average across all sites). Extension of the trial by two years (five fields on two farms) demonstrated that the longer compost is used, the more obvious its carbon sequestration benefits become. The lowest application rate (25 t ha⁻¹) did not increase SOM at the selected trial sites. This is a reflection of the significant decline in SOM at the trial sites and evidence that the lowest compost application rate halted the decline of SOM. Nevertheless, higher application rates increased SOM levels by about 20% (50 t ha⁻¹) and 30% (75 t ha⁻¹) over a seven year period.

Compost application trials that were conducted over a period of 9 and 12 years at five locations in **Germany** provide the most comprehensive data set to date regarding the medium-term effects of compost use in agriculture. Continuous compost application for 9 and 12 years resulted in organic matter level increases across all five sites by approximately 0.3 percentage points for every 5 t DM ha⁻¹ of compost applied annually, and even by approximately 0.42 percentage points at the three cooler sites. Assessment of sites with a 12-year compost application history revealed a linear correlation between compost application rate and soil organic matter content. Averaged over all five trial sites, the addition of 8–9 t DM ha⁻¹ of organic matter from compost over 9 and 12 years increased soil organic matter levels by approximately 0.1 percentage points. Annual compost application rates of 5 t DM ha⁻¹ delivered between 20 and 35 t DM ha⁻¹ of compost organic matter over the trial period, and this demonstrates that even low compost application rates can affect soil organic matter levels positively.

Annual compost application rates of 6.7 t DM ha⁻¹ added 2.4–2.8 t DM ha⁻¹ of organic matter, or around 1.5–2.2 t ha⁻¹ of carbon to soil. Where mature compost was applied, it was estimated that around 50% of the added carbon, i.e. 0.75–1.1 t ha⁻¹, contributed to humus production, at least in the short term. These were quite sizable additions to the humus carbon pool, considering that in order to maintain soil humus levels, around 0.3 t ha⁻¹ of carbon has to be added annually to the humus carbon pool of average soils in the region where the trials were conducted.

The capacity of compost products to increase soil humus levels has been studied over a 12-year period. The main findings are presented below:

- proportion of organic matter added with compost retained in the topsoil (0–30 cm):
 - mature garden organics compost (used on silty loam) 50.6%
 - mature biowaste compost (used on loamy sand) 45.7%
 - pasteurised biowaste compost (used on silty clay loam) 29.7%.
- the annual increases in soil organic carbon recorded at compost application rates of 10 t DM ha⁻¹ yr⁻¹:
 - mature garden organics compost (used on silty loam) 0.82 t C ha⁻¹ yr⁻¹
 - mature biowaste compost (used on loamy sand) 0.97 t C ha⁻¹ yr⁻¹
 - pasteurised biowaste compost (used on silty clay loam) 1.13 t C ha⁻¹ yr⁻¹.
- the application of compost at rates of 5, 10 and 20 t DM ha⁻¹ yr⁻¹ over 12 years did not result in the establishment of new organic matter equilibria in the soil. On the contrary, the increase of soil organic matter due to compost use observed in the 12th year was still linear
- long-term fertilisation field trials suggest that, as an average for Germany, around 0.4 t ha⁻¹ of carbon has to be added annually to the humus carbon pool of soils to maintain current levels, if no crop residues are added. Hence, in order to maintain current soil organic matter levels, the following compost quantities need to be applied annually:
 - mature garden organics compost (used on silty loam) 4.8 t DM ha⁻¹ yr⁻¹
 - mature biowaste compost (used on loamy sand) 3.8 t DM ha⁻¹ yr⁻¹
 - pasteurised biowaste compost (used on silty clay loam) 2.6 t DM ha⁻¹ yr⁻¹.

This medium-term compost application trial showed that the regular and agronomically appropriate use of compost (20–30 t DM ha⁻¹ yr⁻¹ over three years) is a suitable means for increasing and optimising soil organic matter levels.

Carbon storage on loam soil in **The Netherlands** over **almost 30 years** amounted to 6% for green manure, 18% for composted farmyard manure and 'Municipal solid waste (MSW) compost after preselection of the organic fraction'; 22% for composted sewage sludge and 40% for peat moss. In neighbouring **Belgium**, 20.1% of applied organic matter was recovered after applying 22.5 t ha⁻¹ of biowaste compost annually for four years to silage corn monoculture grown in sandy loam.

Two long-term compost field trials were conducted in **Austria**. During a 13-year trial on silty loam (3.4% organic matter) the use of biowaste compost (8, 15 and 22 t ha⁻¹ yr⁻¹ on average) on its own or in combination with mineral fertiliser stored between 1,900 and 6,500 kg ha⁻¹ organic carbon, which represents 10–19% of the organic carbon applied with compost. Results of a 12-year trial in which four types of compost (biowaste, garden organics, cattle manure, sewage sludge) were applied at annual rates of 175 kg N ha⁻¹ yr⁻¹ with and without additional nitrogen fertiliser (80 kg N ha⁻¹ yr⁻¹) on a loamy silt (1.9% organic matter) showed that using compost made from garden organics and sewage sludge was most effective in raising soil organic carbon levels, effecting an increase of about 20%. The application of garden organics compost at 175 kg N ha⁻¹ for 12 years, (ca. 11 t DM ha⁻¹ yr⁻¹), sequestered around 780 kg C ha⁻¹ annually, or 70 kg C ha⁻¹ per tonne of compost DM applied per year.

Around 76% of carbon added with a single application of 50 and 85 t ha⁻¹ of biowaste compost in **Italy** was recovered after four months. In a similar trial, in which composted food and ligno-cellulosic residues were applied at 50 and 85 t ha⁻¹ to corn in silty-clay, it was found that, after five months, around 62% of compost applied carbon was retained in the soil for both application rates. The amount of carbon sequestered was similar to the content of recalcitrant carbon in compost, which amounted to 58.6% of total organic carbon in the compost.

The amount of compost needed to maintain soil organic matter levels in north-western **Spain** over a 25 year period at current mean soil temperatures (13.5°C) was estimated at 4.0 to 7.2 t DM ha⁻¹ of compost. If mean soil temperatures increased by 2°C due to climate change, the amount of compost needed to maintain soil organic carbon levels would increase by ca. 10%.

In **Canada**, the application of compost (50 kg N ha⁻¹) over a three year period in snap beans resulted in the retention of 43% of added carbon. Tripling the application rate to 13 t C ha⁻¹ yr⁻¹, reduced carbon retention to 27.7%. Elsewhere, composted corn silage (composted for nine months), dairy manure and sewage sludge were applied to a temperate grassland soil. In the first year after application, 95% (composted corn silage), 75% (dairy manure) and 88% (sewage sludge) of applied carbon remained in the soil. In the second year after application 89%, 63% and 42% of applied carbon remained in the soil for the respective treatments.

A nine-year trial in the **USA**, in which two composts, raw manure and mineral fertiliser, in combination with legume cover crops in all treatments, were used in a corn-vegetable-wheat rotation in a 2 ha field with silt loam, demonstrated that continuous compost use increased soil carbon levels by between 16% and 27%. Annual soil carbon sequestration over the nine-year trial period amounted to 1,261 kg C ha⁻¹ for chicken litter and leaf compost and to 2,363 kg C ha⁻¹ for dairy manure and leaf compost, while the use of fresh manure accrued only 312 kg C ha⁻¹. Mineral fertiliser reduced soil carbon levels by 317 kg C ha⁻¹ yr⁻¹, although green manure crops were used also in this treatment.

The application of mature compost made from garden organics and chicken litter (~10% v/v) in vegetable cropping on sandy soil (0.6% C) in **Western Australia** showed that after the fifth compost application, i.e. around 18 months after compost was first applied, residual compost carbon levels amounted to 42.7%. The addition of clay (200 t ha⁻¹) to the sandy soil demonstrated the important role of clay minerals in preserving compost carbon, as 78.7% of compost carbon was still present in the clay amended sand 18 months after applications began.

The diversity of compost products, as well as the environmental and soil conditions in which they are used, combined with the complexity of related dynamics (turnover), has so far prevented development and adoption of a model that describes soil carbon dynamics following compost use. However, in the interim, a **simplified compost carbon sequestration model** can be used. The model assumes that the application of compost results in readily available organic matter being mineralised at $y\%$. $X\%$ of the readily available organic carbon is converted to stable organic matter and $z\%$ of this stable organic matter is mineralised. The example in Figure 3 predicts the expected development of SOM levels associated with compost use at different application rates (0, 5, 10 and 15 t ha⁻¹ yr⁻¹) in northern European conditions (over a 300-year period). This example uses the following mineralisation and transformation rates: $x=30\%$, $y=15\%$ and $z=1\%$ ($t_{1/2}$ of some 68 years). This model predicts that a new equilibrium for SOC will only be reached within a time frame of probably 200 and 300 years for annual compost application rates of 10 and 15 t ha⁻¹ respectively. Annual application rates between 2.5–5.0 t ha⁻¹ are expected to prevent further decline in soil carbon levels.

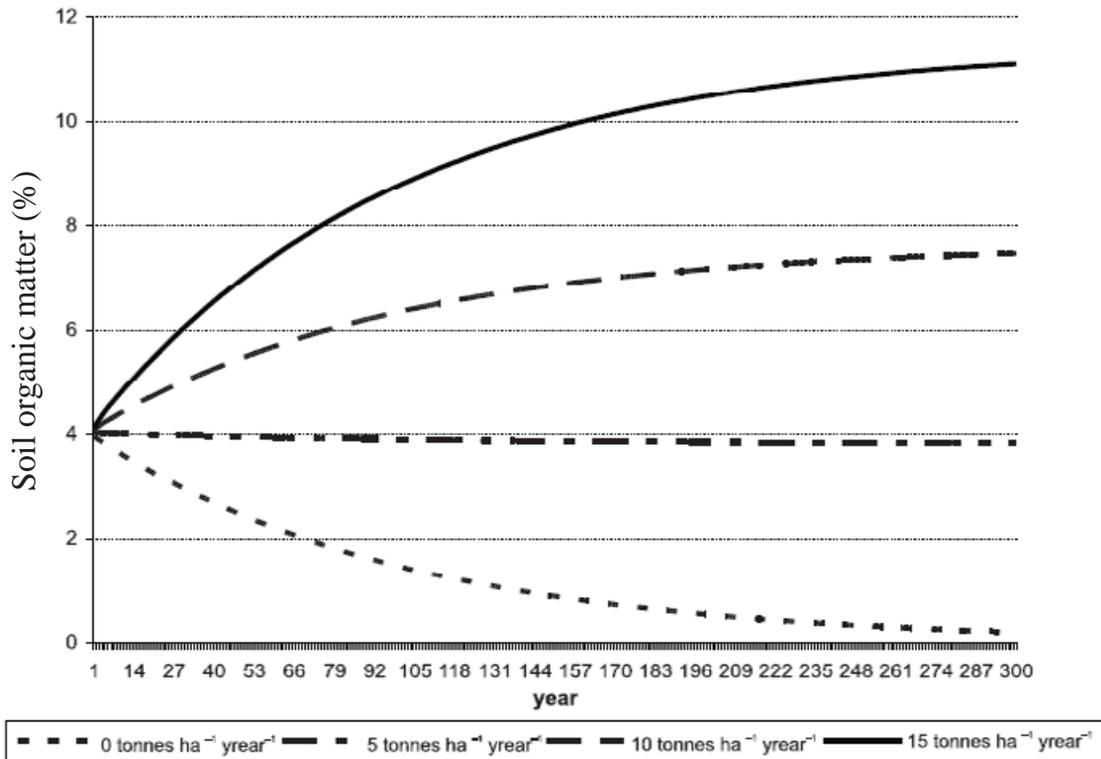


Figure 3 A simplified carbon sequestration model for compost use (Source: Favoino and Hogg 2008*).

In another simplified model using European data ('3-pool carbon sequestration model'), compost carbon sequestration was modelled and calculated over a 50-year time frame. It was calculated that, at $t_{1/2} = 20$ years for the active soil organic matter pool, annual application of 22.8 t DM ha⁻¹ biowaste compost (23% C) over 50 years results in the sequestration of 110 t C ha⁻¹, which represents 42% of carbon added with compost. Therefore, using compost at 22.8 t DM ha⁻¹ for 50 years could achieve GHG emission abatements of 403 t CO₂-e ha⁻¹, 350 kg CO₂-e t⁻¹ applied compost dry matter, and 1,537 kg CO₂-e t⁻¹ applied compost carbon.

Based on a number of assumptions, the CENTURY model predicted the following carbon sequestration rates per tonne of dry matter compost in the USA:

- initial three years of compost application: 305 to 400 kg carbon, equivalent to between 1,122 and 1,467 kg CO₂-e
- initial ten years of compost application: 226 to 259 kg carbon, equivalent to between 829 to 950 kg CO₂-e
- after 34 years, with compost application for the initial 10 years only: between 85 and 155 kg carbon, equivalent to between 311 and 570 kg CO₂-e
- after 100 years: between 141 and 198kg carbon, equivalent to between 518 and 725 kg CO₂-e.

Using the same CENTURY model base data, a sequestration rate of 70 kg C t⁻¹ fresh matter composted product (surface applied mulch and incorporated soil conditioner) was used in Australia. Considering different moisture contents, it is expected that 117 kg C (428 kg CO₂-e) is sequestered per dry tonne of applied soil conditioner over a 100-year time frame, and 88 to 93 kg C (321–342 kg CO₂-e) per dry tonne of applied mulch.

Notwithstanding the significant short to medium-term carbon sequestration gains following compost use, the IPCC framework for estimating greenhouse gas fluxes is based on a 100-year time horizon and will only consider compost carbon as 'sequestered' if it remains locked in the soil for at least 100 years. As indicated previously, turnover times of different organic matter compounds can differ widely, and the proportion and estimated half-life times for different

* Favoino, E. and D. Hogg (2008). "The potential role of compost in reducing greenhouse gases." *Waste Management & Research* 26(1): 61 - 69.

compost carbon pools largely determine long-term carbon sequestration rates. In 2001, a major UK study adopted a compost carbon turnover time in soil of 40 years, and calculated the decay of the carbon added each year (a) according to the equation $y = a \cdot e^{-kt}$, where y is the amount of carbon remaining after t years and k is the first-order decay rate constant, i.e. $1/\text{turnover time}$.

With reference to manure-based data, the carbon still bound to soil after 100 years has been estimated to represent 2% to 10% of the input in compost, with recent suggestions that between 9% and 14% of compost carbon is sequestered, depending on soil type and crop rotation. As stable organic matter has a turnover time of 100 to 1000 years the proportion of compost-derived carbon that becomes part of the stable soil carbon fraction can be considered as 'sequestered' in the realm of the IPCC framework and for the purpose of international carbon trading, and be credited either as avoided downstream CO₂ emission to the waste management system, or as carbon sequestration gain to the land manager. Accordingly, if C_{input} (kg) is the carbon content in compost and C_{bind} is the fraction that is or will become 'stable', then the carbon sequestration, expressed as CO₂ (CO_{2,bind}, kg) can be calculated as:

$$\text{CO}_{2,\text{bind}} = C_{\text{input}} \times C_{\text{bind}} \times 44/12$$

If the carbon content in compost is in the order of 100–285 kg t⁻¹ DM for garden organics compost, and 191–470 kg t⁻¹ DM for food organics compost, and if between 2% and 14% of compost carbon are sequestered, between two and 66 kg C t⁻¹ DM compost could be bound in soil, equivalent to 7–242 kg CO₂-e t⁻¹ DM compost. Carbon sequestration is thus in the order of 2 to 79 kg CO₂-e t⁻¹ for food organics and 3 to 73 kg CO₂-e t⁻¹ for garden organics, assuming mass losses during the composting process of 60% and 30% respectively.

3.4.2 Mineralisation and use of nitrogen

The supply of mineral nitrogen through compost use can affect the level of nitrous oxide emissions from soil, the potential for nitrous oxide emissions due to nitrate being leached into groundwater, and emissions associated with fertiliser production when compost partially or totally substitutes for mineral nitrogen fertiliser. Apart from soil characteristics, soil moisture and temperature regimes, the supply of nitrogen from compost is primarily governed by its total nitrogen and carbon content and its C:N ratio, while compost maturity is of lesser importance.

When considering nitrogen mineralisation and nitrogen use efficiency data associated with compost use, it is helpful to note that:

- nitrogen availability measured with plants might be higher than in incubation tests without plants
- the presence of plants can modify nitrogen availability in soil
- nitrogen availability of commercial composts might be higher than for composts made on a smaller scale
- small differences in nitrogen release might not be detected when plants were used as indicators.

3.4.2.1 Nitrogen mineralisation

Although available publications often show similar nitrogen mineralisation effects and trends, results are difficult to compare because of divergent trial conditions, the high number of possible variables, or inadequate descriptions of trial conditions. In addition, laboratory incubation test results cannot be transferred directly to field conditions.

In any case, the following generic conclusions regarding nitrogen mineralisation following compost use can be drawn from the available information:

- use of immature compost often results in nitrogen immobilisation shortly after compost use
- total nitrogen mineralisation from immature compost is often lower than from mature compost
- composting of manure results in markedly reduced nitrogen mineralisation
- the average minimum and maximum mineralisation rates ranged between 4.6per cent and 19.5per cent of added total nitrogen in the most favourable temperature and moisture conditions
- mineralisation rates were higher in sandy soils than in clay soils.

Incubation of fresh and mature biowaste compost at temperatures between five and 25°C showed the influence temperature has on nitrogen mineralisation (Figure 4). Cumulative net release of NO₃ from fresh compost ranged from 1.8% of the initial nitrogen content at 5°C to 14.3% at 25°C during 112 days. However, net nitrogen release occurred only after a time lag of between 14 days at 25°C and 84 days at 5°C, when approximately 30% of compost carbon was mineralised. In contrast, in mature compost around 10% of the initial nitrogen content was released as NO₃ after 14 days, regardless of temperature, most likely representing the mineral nitrogen content in the mature compost. Cumulative net release of NO₃ from mature compost ranged between 9.8% at 5°C and 16% at 25°C.

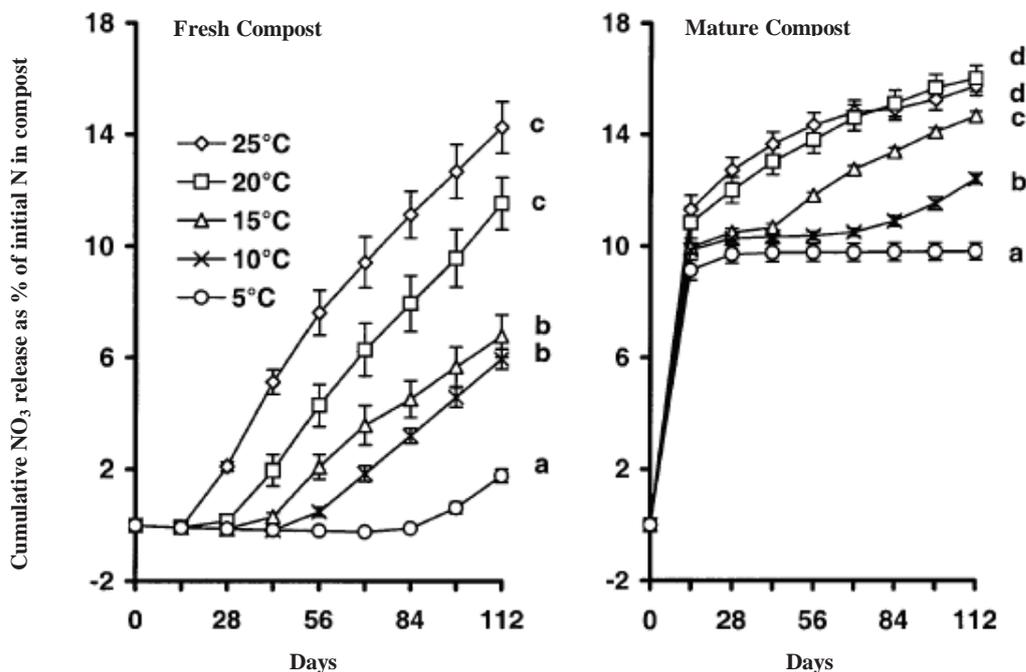


Figure 4 Cumulative release of NO₃-N from fresh (left) and mature (right) biowaste compost at various temperatures. Treatments with the same letter assigned are not significantly different (p<0.05) (Source: Chodak et al. 2001)*.

The report provides various examples where uncomposted material, along with composted products, resulted in nitrogen immobilisation, at least for the first few weeks following soil amendment. Although nitrogen immobilisation following the use of recycled organic products is usually an undesirable outcome, this effect can be employed as a means of 'mopping up' excess nitrogen from high nitrogen crop residues, and hence prevent nitrogen loss and nitrate leaching. Net nitrogen mineralisation from sugar beet and brassica leaves, for example, was reduced by up to 90% when soil was amended with paper waste that had a C:N ratio of 520:1. When leek residues were incubated with straw, garden organics composts (high and low C:N ratio) and tannic acid, all added materials (except for the compost with low C:N ratio) resulted in significant immobilisation of the residual nitrogen released from the vegetable residues. The addition of molasses after 15 weeks, which aimed at enhancing mineralisation, resulted in 73% of nitrogen that was initially immobilised by compost with high C:N ratio, to be remineralised.

3.4.2.2 Nitrogen use efficiency

Not all mineral nitrogen that becomes available in the soil from fertiliser, organic soil amendments or plant residues is absorbed and utilised by plants. Hence, not all compost-derived mineral nitrogen will be absorbed and utilised by plants, resulting in relatively low nitrogen use efficiency.

The following generic observations were made mainly in European climates about plant uptake of nitrogen derived from compost use:

- trial results must be differentiated between those that used mineral fertiliser as a supplementary source of nitrogen, and those that did not
- use of mineral nitrogen fertiliser usually reduces the efficiency of plants in utilising compost-derived nitrogen
- rotations that contain crops with high nitrogen demand can increase nitrogen use efficiency
- the longer the growth period of crops (e.g. corn versus wheat or leafy vegetables), the higher the nitrogen use efficiency
- nitrogen use efficiency in field trials ranged from 2.6% to 10.7% (average of minimum and maximum values respectively) during the first year after compost application
- subsequent (three or more years after compost application) nitrogen availability depends largely on site and production-specific conditions but is generally in the range of 2–3% of added compost nitrogen
- continuous compost use will increase nitrogen use efficiency in the initial year after compost application, with a maximum of 40% measured after 21 years of compost use
- mineralisation from mature composts usually occurs faster than from fresh composts, and fresh compost as well as those with high C/N ratio usually incur temporary nitrogen drawdown.

Results obtained during 9 and 12 year compost application trials at 5 sites in Germany confirm that, as an average across all sites, years and compost products used, only around 5% to 10% of nitrogen added with compost is utilised by crops. The long-term trials with three or four cropping cycles showed very clearly that nitrogen use efficiency increased from less than 5% during the first three-year crop cycle, to levels between 5% and 15% during subsequent cropping cycles. These medium-term trials confirmed the above generic observations that:

- the highest nitrogen use efficiency is achieved when no additional mineral nitrogen is used (plant uptake approximately 5% in the first crop cycle, and between 8% and 15% in subsequent crop cycles)
- increasing humus levels and microbial activity with continued compost use result in increased mineralisation and growing release and use of compost nitrogen
- a higher nitrogen use efficiency can be achieved when compost is used in crop rotations that have high nitrogen demand (average compost nitrogen use efficiency was 13–16% for high nitrogen demand rotations, and 7–10% for crop cycles with lower nitrogen demand, when no mineral fertiliser was used).

Nitrogen supply from occasional applications of moderate compost quantities often need not be accounted for in nitrogen budgets unless N immobilisation or optimum mineralisation conditions occur. When compost is used regularly for four or more years between 5–12% or possibly even 15% or more of nitrogen applied with compost, will be utilised by crops annually. Over a three-year crop cycle, approximately 20–35% of compost applied nitrogen will support plant growth. Such high nitrogen supply from compost use has to be accounted for in nitrogen budgets of individual fields and farms, so that monetary savings can be made, and agronomic and environmental problems prevented. Conversely, when garden organics composts and immature composts are used, nitrogen use efficiency should not be overestimated (about 5%). This will prevent unjustified fertiliser reduction that might adversely impact on crop yield or quality. In addition to estimating nitrogen release from compost, mineral soil nitrogen levels should also be assessed regularly.

A long-term (13 yrs) field trial in Austria showed relatively low nitrogen use efficiency. On average, approximately 6.5%, 3.7% and 3.4% of the total nitrogen applied through biowaste compost at annual application rates of 8, 15 and 22 t FM ha⁻¹ respectively was used. Nitrogen use efficiency for compost remained unchanged (3–6%) when nitrogenous fertiliser (26–57 kg N ha⁻¹) was applied in addition to compost.

Trials on sands of low natural fertility in Australia confirmed that very little nitrogen initially supplied with compost (garden organics+10% chicken manure) was available to plants. However, at the conclusion of two trials, around 18% of nitrogen applied with compost was either utilised by crops or leached. However, application of unmaturing compost for the seventh time resulted in the additional release of approximately 300 kg N ha⁻¹, presumably due to a priming effect that stimulated mineralisation of soil nitrogen reserves. This effect highlighted the potential risk of compost contributing to nitrate leaching, particularly on sandy soils, and in the early phases of compost use before the soil microbiology has had time to fully adapt to elevated compost inputs.

As only a relatively small proportion of the total nitrogen applied with compost is mineralised and used by plants over the first few years after application, continuous compost use leads to substantial increases in soil nitrogen levels. This has been confirmed by most compost related research, since, as soil organic matter has a C:N ratio of around 10:1, it is inevitable that increasing organic matter levels also increases soil nitrogen levels. If it is assumed that, on average, 10% of total nitrogen applied with compost is mineralised during the first year after application, 4% in the second year and 2% in the following years, it is possible to model both the potential soil nitrogen accumulation following annual compost application, as well as the increasing nitrogen mineralisation potential. If, for example, 8 t DM ha⁻¹ of compost containing 1.6% N (in dry matter (DM)) is applied annually, and nitrogen losses are disregarded, annual nitrogen mineralisation from compost use (ca. 130 kg N ha⁻¹) will match the amount of total nitrogen added with compost after about 100 years (Figure 5). This equilibrium can be reached considerably faster in environments where higher mineralisation rates can be expected.

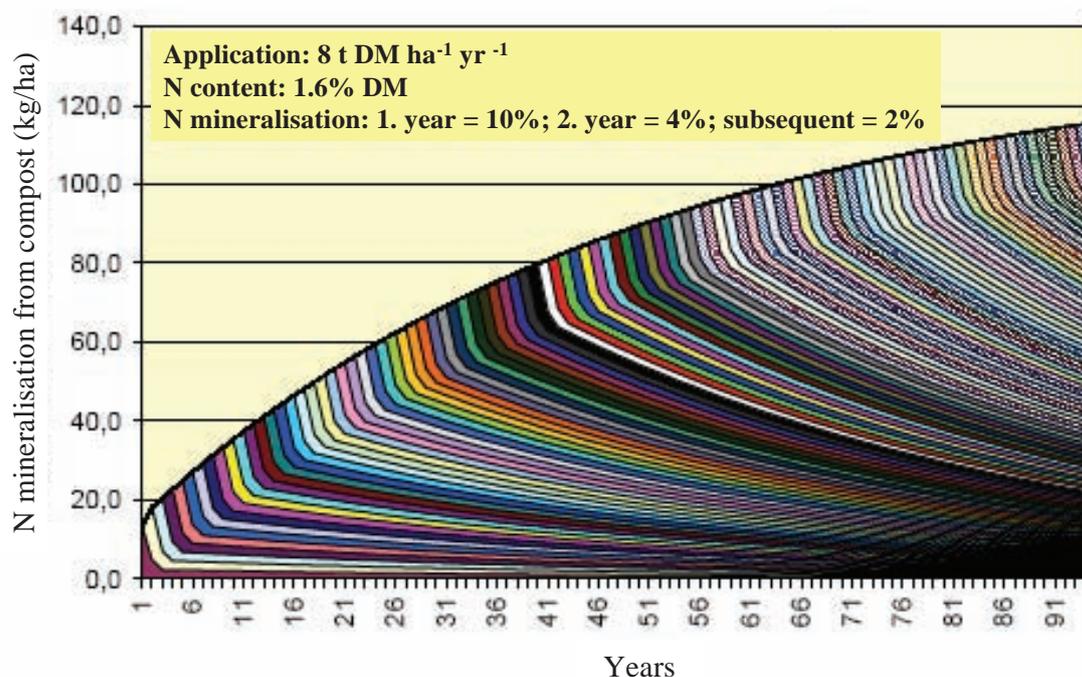


Figure 5 Expected increasing nitrogen mineralisation potential following long-term annual compost application at 8 t DM ha⁻¹ (Source: Amlinger et al. 2003b*).

3.4.2.3 The risk of nitrate leaching from and for compost use

Untimely mineralisation and release of nitrogen is often raised as a potential problem associated with compost use, despite the fact that most nitrogen applied with compost is organically bound and only a small proportion is immediately available, or becomes available gradually after application. Concerns have also been expressed about nitrate leaching, which has been seen as a potential threat to groundwater quality. Quite a number of trials have shown that compost use does not pose a risk to groundwater quality through nitrate leaching, or reduces such risks compared to land application of uncomposted materials. However, there are also occasions where compost use on sandy soils can cause unexpected high release of nitrogen, probably due to the long-term build-up in soil nitrogen from previous compost and manure applications contributing to the surge of nitrates. However it is reported that if compost is applied regularly, it will take between 40 and 100 years before nitrogen supply through compost use will be balanced with plant nitrogen uptake. Problems may be caused if nitrogen supply through compost use is not accounted for in farm nutrient budgets, and that mineral fertiliser application rates are therefore not reduced, despite additional nitrogen inputs.

Many countries have regulations to protect the quality of ground and surface water, and to restrict the use of organic soil amendments, as well as overall nutrient applications. These regulations can cover the use of compost, even though it is only responsible for only a very small part of agricultural non-point source pollution of ground and surface water. The way in which the European Union's Nitrates Directive has been (and still is) implemented is presented in the report to demonstrate and exemplify potential implications for farmers, and for the use of organic soil amendments.

* Amlinger, F., S. Peyer and P. Dreher (2003b). Kenntnisstand zur Frage des Stickstoffaustrags in Kompostdüngungssystemen (Current Knowledge Regarding Leaching of Nitrogen in Agricultural Systems that Use Compost). E. a. W. M. Federal Ministry for Agriculture and Forestry, Austria. Vienna: 91.

3.4.3 GHG emission savings through fertiliser replacement

Compost use can supply at least some of the mineral nitrogen that would otherwise have to be provided through mineral fertilisers, as well as most, if not all, of the crop's phosphorous, potassium and trace element requirements. Substituting the use of mineral fertiliser through compost use offers the opportunity of reducing GHG emissions caused by the manufacturing and transportation of fertilisers. In order to estimate the potential for reducing GHG emissions, the typical nutrient contents of compost has to be established, as well as the level of GHG emissions that are associated with the manufacturing and transportation of various fertilisers.

Based on limited information available, it was estimated that 'typical' garden organics compost in Australia contains 11 kg N t⁻¹ DM, 2 kg P t⁻¹ DM, 5.5 kg K t⁻¹ DM, and 275 kg C t⁻¹ DM. GHG emissions associated with the production of mineral fertilisers vary greatly, but in considering dominant fertiliser use practices in Australia, GHG emission factors that are equivalent to 3,500 kg CO₂-e per tonne of nitrogen, 350 kg CO₂-e per tonne of phosphorous, and 300 kg CO₂-e per tonne of potassium were used for estimating potential GHG savings by replacing mineral fertilisers with nutrients supplied in compost in Australia. Consequently, if 10 t ha⁻¹ DM of garden organics compost is used continuously and 40% of the applied nitrogen is utilised by crops (replacing the use of urea and single superphosphate) GHG emissions of approximately 180 kg CO₂-e can be avoided (Table 2). GHG savings are higher if compost with higher nutrient density is used, or if mineral fertilisers with higher carbon intensity are replaced. The 50% or less nitrogen use efficiency of mineral fertilisers, which requires the application of at least twice the amount of nitrogen that is replaced by compost use, has not been taken into account.

Table 2 Potential for avoiding GHG emissions associated with the production of mineral fertiliser if compost displaces their use

Nutrient element	Nutrient content (kg t ⁻¹ DM)	Crop uptake	Fertiliser nutrients replaced (kg t ⁻¹ DM)	Fertiliser GHG emissions (kg CO ₂ -e t ⁻¹)	Avoided GHG emissions (kg CO ₂ -e t ⁻¹ DM compost)
Garden organics compost					
Nitrogen (N)	11	40%	4.4	3,500	15.4
Phosphorous (P)	2	100%	2.0	350	0.7
Potassium (K)	5.5	100%	5.5	300	1.7
Total					17.8
Biowaste compost					
Nitrogen (N)	15	40%	6.0	3,500	21.0
Phosphorous (P)	3	100%	3.0	350	1.1
Potassium (K)	8	100%	8.0	300	2.4
Total					24.5

3.4.4 Nitrous oxide emissions following compost use

Although a considerable number of experiments sought to determine the effects of organic soil amendments use on (i) nitrous oxide emissions, (ii) the mechanisms that govern emissions and (iii) the magnitude of emissions following the use of different products, no conclusive and universally applicable results have yet emerged in this area. Although authors in the UK have put forward an emissions factor for garden organics compost of less than 0.04% of total nitrogen applied, and have calculated net reduction in nitrous oxide nitrogen emissions of 0.1 kg ha⁻¹ (49 kg CO₂-e ha⁻¹) when applied at a rate that delivers 250 kg N ha⁻¹, most research conducted so far has delivered inconclusive and conflicting results. In any case, at this point in time it appears impossible to derive and use a generic nitrous oxide emission rate following the use of garden organics and biowaste compost.

3.4.5 Potential additional GHG savings following compost use

Apart from sequestering carbon, substituting the use of mineral fertiliser, and possibly reducing nitrous oxide emissions, the use of compost offers additional opportunities for reducing GHG emissions directly and indirectly. These include:

- reducing/avoiding the use of micronutrients
- reducing/avoiding the use of agricultural lime
- reducing/avoiding the use of gypsum
- avoiding the use of humic substances on their own as soil improvement treatment
- reducing need for irrigation and the associated use of fuel/electricity
- reducing the use of tractor fuel due to improved tillth
- reducing erosion and loss of soil and nutrients
- reducing the use of biocides
- increasing yields, and hence improving the efficiency per unit of input.

3.4.6 Combined effects of using compost on climate change mitigation

Both the medium (20 and 50 yrs) and the long-term (100 yrs) time frames need to be considered in regards to the sequestration of compost-derived carbon. From a global warming potential (GWP) point of view, it makes relatively little difference if compost use is considered under a 20 or 100-year time frame, as:

- GWP of CO₂ (i.e. degradation of biogenic carbon in soil) equals one across all time horizons
- GWP of methane (72 over 20 years and 25 over 100 years) is not relevant as methane is not emitted from soils, rather the opposite
- GWP of N₂O differs very little between the 20 year time frame (289) and the 100 year time frame (298).

Interim climate change mitigation measures, such as carbon sequestration following compost use, are of particular importance. They provide opportunities to implement low-cost measures that are available immediately and deliver a wide range of other environmental, agronomic and societal benefits.

Consequently, it was assumed that 45% of carbon applied with compost is retained over a 20-year period, 35% over a 50-year period and 10% over a 100-year period. Hence, the use of mature garden organics compost as agricultural soil conditioner at a rate of **10 t DM ha⁻¹** will sequester carbon that is equivalent to reducing GHG emissions by:

- **5,046 kg CO₂-e over 20 years**
- **3,532 kg CO₂-e over 50 years**
- **1,009 kg CO₂-e over 100 years.**

The use of **10 t DM ha⁻¹** of mature garden organics compost as agricultural soil conditioner is expected to replace the use of mineral fertiliser (N, P, K), which saves **178 kg CO₂-e** of GHG emissions.

By combining the two GHG emission savings options, mature garden organics compost is used at **10 t DM ha⁻¹** as agricultural soil conditioner:

- **around 5,224 kg CO₂-e can be saved in GHG emissions within a 20-year time frame**
- **around 3,710 kg CO₂-e can be saved in GHG emissions within a 50-year time frame**
- **around 1,187 kg CO₂-e can be saved in GHG emissions within a 100-year time frame.**

An economic compost evaluation model, which included potential GHG emission savings through continuous use of biowaste compost demonstrated that GHG emission savings increase from year to year as compost use continues, reaching a level of 474 kg CO₂-e per hectare on an arable farm after seven years, at an application rate of 10 t DM ha⁻¹. This equated to a monetary value of \$18.06* per hectare in the seventh year, based on marginal costs for avoiding GHG emissions in Germany (without carbon trading), which at the time were €24.00 or \$38.09* per tonne CO₂-e.

Although increasing compost application rates result in increased GHG emission savings, the increase in GHG emission savings was not proportional to the increase in application rates. This resulted in declining marginal monetary benefits of saved GHG emissions per tonne of compost:

- 5 t DM ha⁻¹ €1.23 or \$1.95* t⁻¹ DM compost
- 10 t DM ha⁻¹ €1.14 or \$1.81* t⁻¹ DM compost
- 20 t DM ha⁻¹ €0.90 or \$1.43* t⁻¹ DM compost.

*Converted at exchange rate as of 1.7.2005: \$1.00 = €0.63 (see <http://www.rba.gov.au/statistics/hist-exchange-rates/2003-2006.xls>)

4 Findings, conclusions and recommendations for further work

4.1 Findings

This report, which has assessed whether and to what extent the use of compost can assist in mitigating climate change, has clearly demonstrated that using compost saves GHG emissions by the following direct and indirect means:

- reducing methane emissions from landfill
- reducing GHG emissions through improved manure management
- sequestering biogenic, compost derived carbon in the soil
- replacing the use of mineral fertilisers
- reducing methane emissions from soil, or increasing soil methane absorption
- reducing nitrous oxide emissions from soil
- improving plant biomass production, resulting in increased sequestration of plant carbon
- supplying auxiliary GHG emission savings (e.g. reduced need for irrigation, reduced erosion, reduced liming, reduced nitrate leaching).

Consequently, using compost is an important tool in reducing both waste management and agricultural GHG emissions, and in helping to mitigate climate change.

More precisely, the following key findings were made:

- **Reduction of methane from landfill**
The Australian organics recycling industry diverted at least 3.7 Mt of organic residues from landfill in 2007–08, preventing the generation of methane that is equivalent to ~4.28 Mt CO₂-e. The saving in methane when organic materials are recycled is nearly equivalent to the amount of methane recovered from landfill (4.5 Mt CO₂-e).
- **Reduction of methane emissions through improved manure management**
Composting improves manure management practices, as it reduces methane emissions compared to other manure management options (stockpiling, lagoons), and the use of composted manures has higher climate change mitigation effects than the use of raw manures.
- **Sequestration of compost derived carbon**
Based mainly on European and North American data, it is estimated that the use of garden and biowaste compost as soil conditioner will result in the following carbon sequestration rates:
 - 20-year accounting time frame: 40–55% of carbon applied with compost
 - 50-year accounting time frame: 30–50% of carbon applied with compost
 - 100-year accounting time frame: 0–14% of carbon applied with compost.

Using characteristics of Australian garden organics composts, it is assumed that 45% of carbon applied with compost will be retained over a 20-year period, 35% over a 50-year period, and 10% over a 100-year period. The use of mature garden organics compost as agricultural soil conditioner at a rate of 10 t DM ha⁻¹ will sequester carbon that is equivalent to reducing GHG emissions by 5,046 kg CO₂-e over 20 years; 3,532 kg CO₂-e over 50 years; or 1,009 kg CO₂-e over 100 years.

Reduction of mineral fertiliser use

Again, based on the characteristics of Australian garden organics composts it is estimated that the use of mature compost as agricultural soil conditioner at a rate of 10 t DM ha⁻¹ will replace the use of mineral fertiliser (N, P, K) to the extent that saves 178 kg CO₂-e of GHG emissions.

Combined GHG emission savings

When mature garden organics compost is used at 10 t DM ha⁻¹ as agricultural soil conditioner, the following GHG emissions can be saved:

- ~ 5,224 kg CO₂-e within a 20-year accounting time frame
- ~ 3,710 kg CO₂-e within a 50-year accounting time frame
- ~ 1,187 kg CO₂-e within a 100-year accounting time frame.

National Carbon Accounting System

The National Carbon Accounting System (NCAS) has been developed by the Australian government to report on land-based GHG emissions and sinks. The NCAS reports on all carbon pools (biomass, dead organic matter and soil carbon) and all principal greenhouse gases by making use of integrated ecosystem modelling combined with remotely sensed data. The terrestrial ecosystem model (Full Carbon Accounting Model) is based on 25 m grid resolution data and incorporates various sub-models, one of which is Roth-C soil carbon model. The NCAS provides an ideal framework for integrating the use of compost and other organic soil amendments into the National Carbon Inventory. Including the use of compost into the National Carbon Inventory will reduce Australia's net GHG emissions.

4.2 Conclusions

Using compost as an agricultural and horticultural soil amendment:

- can contribute to mitigating climate change directly and indirectly
- provides opportunities for implementing low-cost measures that are immediately available
- is one of the fastest means of improving soil carbon levels
- is ideally suited as a mitigation measure in productive agricultural soils
- fits easily into the Australian NCAS
- can attract carbon credits
- delivers many agronomic benefits and enhances long-term agricultural production
- also delivers environmental and societal benefits.

4.3 Further work

Based on the findings of this report, the following work should be carried out to maximise the use of compost with the associated GHG savings, and also to provide farmers with a tool for gauging how management practices impact on soil humus levels:

- adjust available data from Europe and North America to reflect Australian environmental and farming conditions
- incorporate compost use into the Australian National Carbon Accounting System
- introduce the concept and use of 'Humus Balance'.

Additional recommendations for future work are documented in the main report.

4.4 References

For a complete list of references please see the full report *The benefits of using compost for mitigating climate change*, available at the Department of Environment, Climate Change and Water NSW website.

