ISWA
International Solid Waste Association

QUANTIFYING THE BENEFITS OF **APPLYING QUALITY COMPOST TO SOIL**

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A NOTE ON UNITS & ABBREVIATIONS

The following units have been used in this report:

Mass of compost and soil

This is expressed in metric tonnes, equivalent to one thousand (1,000) kilograms. This may be abbreviated to t.

Compost mass is also expressed in the following ways:

- **Fresh mass** – this is compost as it is produced and contains water.
- **Dry mass** – this is compost that has been dried in an oven to evaporate off the water.

Unless otherwise stated, it has been assumed that compost is about 60% dry mass and 40% water.

Percentages

These are expressed on a mass/mass (m/m) basis, with 1% m/m being equivalent to 1 kg in 100 kg, or 1 tonne in every 100 tonnes. For example, for compost having a 60 % (mass/mass) dry mass, this means that 60 kg out of 100 kg is dry compost; whilst 40 kg out of 100 kg is water (i.e. 40% m/m).

Surface area

The assumed surface area is the hectare, equivalent to ten thousand (10,000) square meters.

Time scales

A period of one year has been assumed for most of the calculations. This may be referred or abbreviated to as:

- yr
- per annum (pa), which means every year.

Rates of application or increase in soil organic carbon levels

These have generally been expressed in the following ways:

- tonnes ha^{-1} $year^{-1}$ – this means the number of tonnes for every hectare over a one-year period
- kg C ha^{-1} yr^{-1} t^{-1} dry mass – this means the number of kilograms of carbon for every hectare over a one-year period for every tonne of compost measured on a dry mass basis. This could also be read as: kilograms of carbon per hectare per year per tonne of dry compost.
- per – means for each

Symbols and abbreviations

- **Carbon** - The chemical symbol for carbon, C, has also been used.
- **Soil Organic Carbon** – SOC
- $^{-1}$ this means 'per'. For example: 1 t ha^{-1} also means one tonne per hectare, or 1 tonne/hectare.

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Executive summary

KEY FINDINGS

Carbon Sequestration Potential

- Compost applied to soil at a rate of 30 tonnes ha^{-1} $year^{-1}$ (fresh mass) could increase soil organic carbon levels by between 10 – 25 tonnes $hectare^{-1}$ over a 20-year period.
- This is equivalent to an increase in soil organic carbon levels between 0.40-0.55 % (m/m) over 20 years depending upon the density of the receiving soil.

Carbon Dioxide Equivalents

For every tonne of compost applied to a hectare of soil:

- 184 kg of carbon dioxide equivalent may potentially be sequestered (compost dry mass basis), equivalent to 18% of its mass.
- 110 kg of carbon dioxide equivalent may potentially be sequestered (compost fresh mass basis), equivalent to 11% of its mass.

Compost Value (Carbon & Nutrients)

An economic evaluation of the role of compost with regard to its potential to sequester carbon in soil and its total plant macro-nutrient content, suggests that it has significant monetary value:

Value	Range (€ $tonne^{-1}$ fresh mass)
Carbon value through sequestration	3.50 - 8.10
Total nutrient value	17.70 – 20.10
TOTAL	**21.20 – 28.20**

The calculated cumulative value (in today's money) is equal to:

- 10-year timeframe: € 6,354
- 20-year timeframe: € 11,359

AVAILABLE WATER CAPACITY

- Compost applied to soil at a rate of 30 tonnes ha^{-1} $year^{-1}$ (fresh mass) over 20 years could increase the available water capacity by 38 cubic meters per hectare in the top 0-30 cm of soil.
- This is equivalent to 3.8 litres of water over one square meter of soil (in the top 0-30 cm horizon).

GLOBAL IMPLICATIONS

If all organic waste produced globally in cities and towns were collected separately and converted into quality compost:

- 34 million tonnes of carbon dioxide equivalents could potentially be sequestered in soil annually.
- This is approximately 0.7-1.7% of the annual 2-5 giga tonnes CO_2-eq that global soils are technically able to sequester.
- An estimated 5.2 tonnes compost $hectare^{-1}$ $annum^{-1}$ fresh mass would be required to raise SOC levels by 0.4% a year in line with the '4 per 1000' initiative and this would cover about 60 million hectares, or 4% of total global cropland.
- The global estimate of compost value based on its carbon sequestration potential and nutrient content is in the region of 6.6 – 8.8 billion Euros a year.

This report presents estimates of the potential benefit of applying quality compost to soil, from a carbon sequestration, nutrient and financial point of view. Its aim is to help fill an information gap about the benefits of organic matter in compost when applied to soil.

Increases in soil organic carbon (SOC) levels following annual compost application were made using three assumed carbon sequestration rates:

- **Low:** 30 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass;
- **Medium:** 50 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass; and
- **High:** 70 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass.

The modelling suggests that at a typical compost application rate of 30 tonnes ha^{-1} $year^{-1}$ (fresh mass) after 20 years SOC levels could increase by:

- **Low:** 10.8 tonnes $hectare^{-1}$
- **Medium:** 18.0 tonnes $hectare^{-1}$
- **Medium:** 25.2 tonnes $hectare^{-1}$

The modelling also suggested that over a 20-year period, SOC levels could be increased (in absolute terms) by between 0.40-0.55 % (m/m) depending upon the density of the receiving soil. This has significant implications in the restoration of soils low in organic matter. The effect was also greatest in soils with low densities, such as clayey soils.

When soil organic carbon was converted into carbon dioxide equivalents, at the medium sequestration rate, for every tonne of compost (measured on a dry mass basis) applied to a hectare of soil, 184 kg of carbon dioxide equivalent may potentially be sequestered. This is equivalent to 110 kg of carbon dioxide equivalent for every tonne of compost measured on a fresh mass basis, equivalent to 11% of its mass.

Extending these calculations globally, an estimated 34 million tonnes of carbon dioxide equivalents could potentially be sequestered in soil annually if all organic waste produced in towns and cities were converted into quality compost. This estimate is approximately 0.7-1.7% of the annual 2-5 giga tonnes CO_2-eq that global soils are technically able to sequester.

An estimated 5.2 tonnes compost $hectare^{-1}$ $annum^{-1}$ fresh mass would be required to raise SOC levels by 0.4% a year in line with the '4 per 1000' initiative. When considered on a global scale, the theoretical 311 million tonnes of compost that could be produced annually and spread at a rate of 5.2 t ha^{-1} $year^{-1}$ would cover about 60 million hectares, or 4% of total global cropland.

Pricing the carbon in compost using World Bank figures, indicates that every tonne of compost (fresh mass) can be valued in carbon sequestration terms at between EURO 3.50-8.10 per tonne.

Estimates were also made of the total macro-nutrient content of compost using published figures for two types of compost derived from either green waste only or a mixture of green and food waste feedstocks. The total nutrient value of compost (when expressed on a dry mass basis) falls in the region of €23 -30 per tonne, or between €17-20 per tonne on a fresh mass basis.

Taken together, the total carbon and nutrient value of compost is estimated to lie in the region of €21.20 – 28.20 per tonne (fresh mass). The global estimate of compost value based on its carbon sequestration potential and nutrient content is in the region of 6.6 – 8.8 billion Euros a year.

Potential increases in available water capacity with increasing SOC levels were found to be quite low: a 30 tonne per hectare per annum application of compost (fresh mass) over 20 years at the medium sequestration rate (50 g SOC per tonne of compost on a dry mass basis), would only increase the available water capacity by 37.8 cubic meters per hectare in the top 0-30 cm of soil; which is equivalent to 3.78 litres of water over one square meter of soil (in the top 0-30 cm horizon).

As the benefits of annual compost use is cumulative, an estimated value of € 6,400 (in today's money) over a ten-year period was calculated.

NOTE: Please refer to the main text for the assumptions made in arriving at these calculations.

2

Introduction

Soil is a complex mixture of minerals, organic matter, air and water. Globally, there are many different types of soil, with each being a product of the underlying geology, the prevailing climatic conditions and the types of plants and animals that live and grow on and within it.

Soil covers most of the earth's surface, supports almost all terrestrial life and can take many thousands of years to form; however, it can also be destroyed very quickly through poor land management practices, urban development and the effects of climate change.

Globally, it is thought that around a third of the world's soil is moderately to highly degraded due to erosion, nutrient depletion, acidification, salinisation, compaction and chemical pollution. The poor condition of many soils around the world is a cause for significant concern. This is because soil is not only the source of almost all of the world's food, but it is also an important store of carbon and provider of ecosystem services.

The loss of soil organic matter is cited as one of the main reasons why a great deal of agricultural land is becoming progressively less productive. The Dust Bowl in 1930s America highlights the catastrophic effects that can occur when soil organic matter levels are allowed to fall below critical thresholds; a process that happened over the period of about a decade. With a global population of just under eight billion people and projections of nine billion by 2050, the need to protect soil and maximise sustainable food production is of relevance to everybody today.

This report is part of a project initiated by ISWA investigating the benefits of applying quality compost and digestate to soil. The **first ISWA report**[1] estimated global organic wastes arisings to be in the region of a billion tonnes a year: equivalent to around 0.35 kg / capita / day. As organic wastes are composed of discarded food residues, garden clipping and trimmings, as well as other plant and animal-derived wastes, they are, therefore, overwhelmingly derived from soil. Unfortunately, only a fraction of this waste is currently recycled through composting and anaerobic digestion and returned to soil.

The **second ISWA report**[2] summarised the benefits of applying quality compost and digestate to soil and was based on a review of published peer-reviewed scientific papers and governmental reports. The authors concluded that anaerobic digestate can be best classified as an organic fertiliser, as it contains plant nutrients that are present in a form readily available for crop uptake; however, the long-term benefits to soil of anaerobic digestate are less clear cut than those of compost, and it is thought that it has a negligible effect on soil organic matter in the long term.

Compost, on the other hand, can be classified as an organic soil improver. Generally, it has lower plant nutrient levels than anaerobic digestate, but has been shown to increase soil organic matter levels thereby helping to improve soil structure and function. As some of this organic matter remains in the soil, it is essentially 'locked up' and taken out of the atmosphere; applying compost to soil is therefore a means of sequestering carbon.

[1] Ricci-Jürgensen, M., Gilbert, J. and Ramola, A. (2020) Global Assessment of Municipal Organic Waste Production and Recycling. ISWA, Rotterdam.

[2] Gilbert, J., Ricci-Jürgensen, M. and Ramola, A. (2020) A Summary of the Benefits of Compost and Anaerobic Digestate When Applied to Soil, ISWA, Rotterdam.

THE IMPORTANCE OF QUALITY COMPOST

This report calculates the benefits to soil of applying compost derived from organic solid wastes.

It is important to note that the benefits described in this report may only be realised if the compost is of high quality; meaning it is not contaminated. Physical and chemical contaminants, such as plastics, glass, metals, heavy metals and organic substances, might pollute soil and have the potential to accumulate over time following repeated application of contaminated compost. This is not sustainable, and neither is it desirable.

Quality compost should only be derived from clean organic (bio-waste) feedstocks which have been kept and collected separately from other wastes. In addition, it is also important to ensure that composting (and any associated anaerobic digestion processes) are quality assured, with the end products being tested regularly to monitor quality. Quality standards exist in many parts of the world, so readers should consult those that are most relevant to their local situation.

Due to the different characteristics and potential contamination levels in mixed waste derived compost/digestate, sewage sludge and biochar, these materials have been excluded from the scope of this document.

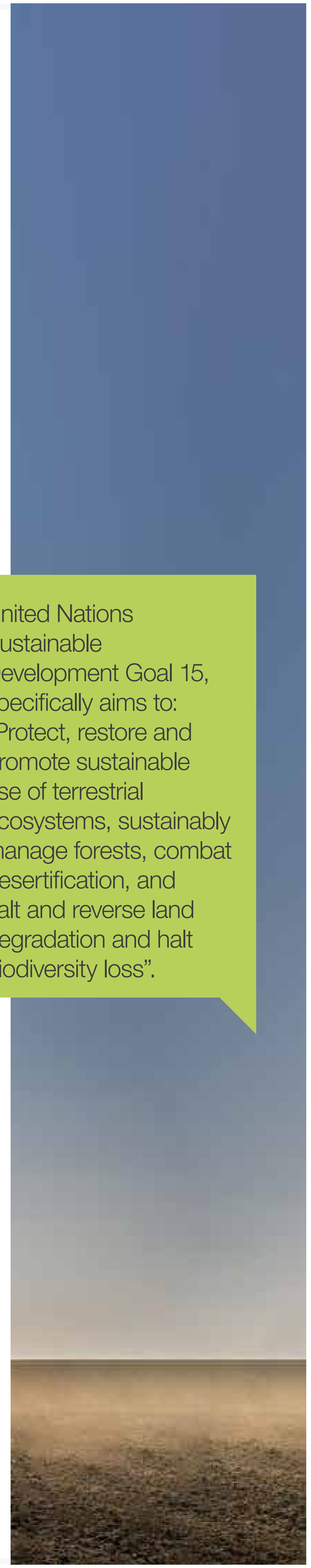
The **third ISWA report**[3] of this project summarised the status and threats to soils in five different countries located in different regions of the world. All five countries (Australia, Brazil, Chile, Italy and the United Kingdom) were found to suffer from varying degrees of soil erosion and loss of soil organic matter. In all five, agricultural productivity was identified as being adversely affected by soil degradation, with Chile being the worst affected.

This report builds on the literature review summarised in Report 2 and presents estimates of the potential benefits of applying quality compost to soil, from a carbon sequestration, nutrient and financial point of view. Its aim is to help fill the information gap about the benefits of organic matter in compost when applied to soil and should be read in the context of estimated organic waste arisings (Report 1) and threats to soil (Report 3)[4].

Soil dynamics need to be evaluated in the most appropriate timescale; the assumed models for compost application to soils, developed in the current report, took into account two different timeframes: 10 and 20 years.

The **ten-year timeframe** was chosen as this is the period from the date of publication of this report (2020) to the Sustainable Development Goals[5] (SDG) set by the United Nations (2030). Goal 15, specifically aims to: "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss", whilst target 15.3 aims to "combat desertification, restore degraded land and soil" by 2030. The benefits of applying compost to soil can therefore be benchmarked against this target.

A **twenty-year timeframe** was also chosen as this is the period of time over which soil organic matter levels of degraded soils have been shown to benefit the most following organic matter application, before reaching a new equilibrium (Figure 1).



United Nations Sustainable Development Goal 15, specifically aims to: "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss".

[3] Ricci-Jürgensen, M., Gilbert, J. and Ramola, A. (2020) Summary of the State of Soils in Five Countries. ISWA, Rotterdam.

[4] Please note: The scenario modelling carried out by ISWA was a desk-top exercise based on results reported in peer-reviewed scientific publications by other researchers; it did not involve any direct field or laboratory research by ISWA.

[5] https://sustainabledevelopment.un.org/

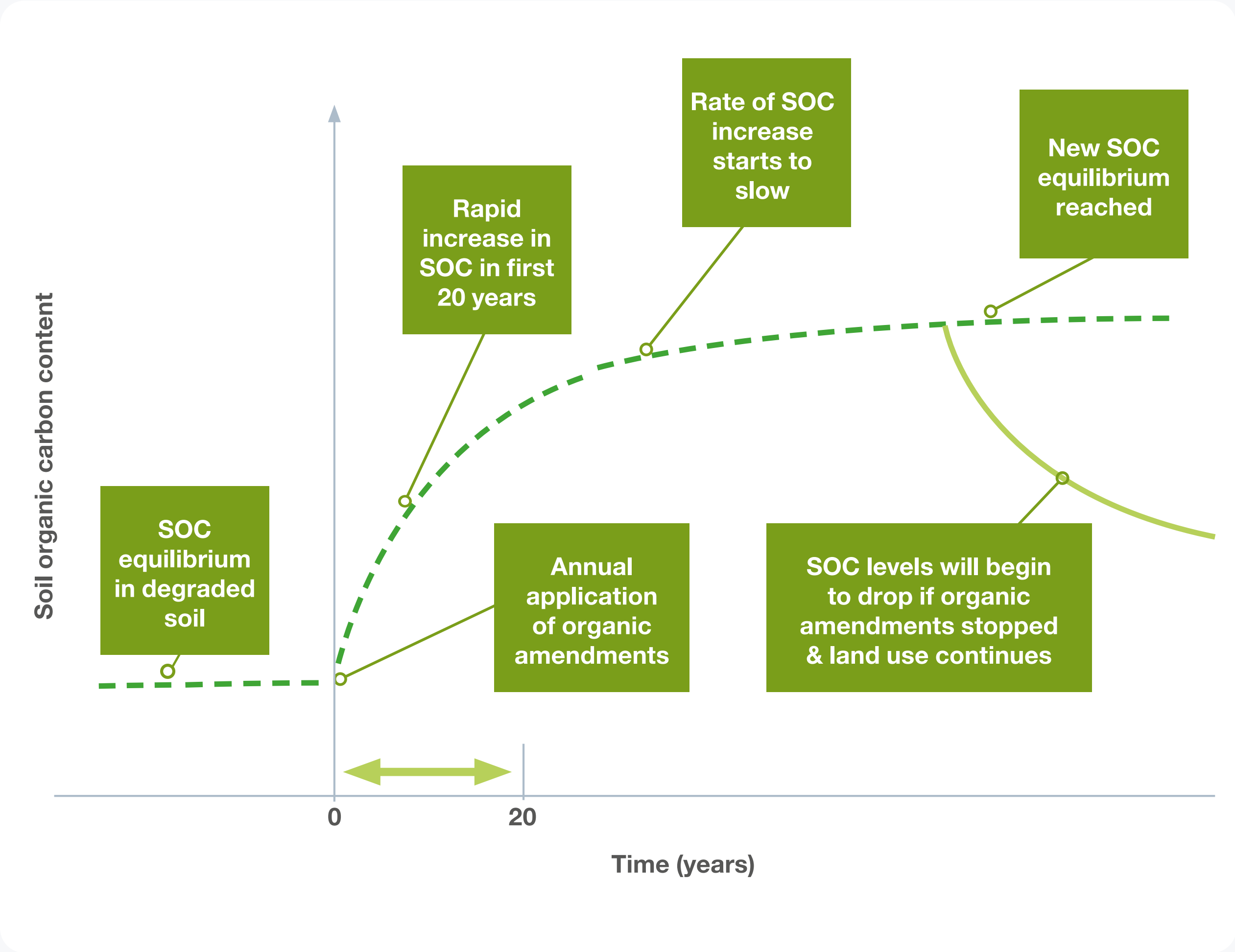


Figure 1 - **Schematic graph showing typical changes in soil organic carbon content following application of organic amendments**

This report is aimed at ISWA members, waste planners and managers, policy officers and other stakeholders with an interest in the link between sustainable waste management and sustainable land and agricultural practices.

In line with the terms of reference of the project agreed by ISWA, the focus has been on recycling organic solid wastes from municipal origin (i.e. produced by households and commercial activities) into compost, but excludes sewage sludge and biochar. This paper has only modelled the potential effects of compost and not anaerobic digestate, as the latter is best classified as an organic fertiliser and not a soil improver.

In addition, this report intentionally does not constitute a life-cycle assessment or greenhouse gas inventory analysis; it therefore does not, for example, take into account externalities such as inorganic fertiliser manufacture, processing or transport emissions.

3 Methodology and assumptions

3.1 OVERALL APPROACH

This section sets out the methodology and assumptions used to calculate potential increases in soil organic carbon and total plant macro-nutrients following the application of quality compost[6] to soil. A number of different scenarios have been modelled based on typical soil physico-chemical properties and compost application rates published in peer reviewed scientific literature.

A comprehensive summary of the benefits of applying compost to soil, including carbon sequestration rates, has been published previously by ISWA[7], from which the data used in this report have been derived. No direct field or laboratory research (primary research) was therefore carried out.

The calculations in this report are based on projected changes in soil organic carbon (SOC) and not soil organic matter; the differences are described in the text box.

The benefits modelled included estimates of the potential:

- Sequestration of carbon that may be stored in soil following compost application;
- Quantity of total plant macro-nutrients applied to soil;
- Increase in available water capacity due to soil organic carbon increases; and
- Monetary benefits associated with potential SOC and nutrient increases.

Unfortunately, due to the complexity of soils and the ecosystem services they perform, a quantification of the benefits of changes in soil biological activity and physical properties following compost application have not been made in this study. These important benefits, however, should not be disregarded and should be considered to be additional to those reported in this document.

In addition, this report does not constitute a life-cycle assessment, as this would have required a much wider and complex series of analyses: for example, does not take into account avoided emissions of composting rather than dumping or landfilling untreated organic waste, alternative treatment through anaerobic digestion, or organic waste collection, processing and transport emissions. It also does not consider wider impacts, such as SOC losses due to harvesting crops or changes in land use. What is does do, however, is help plug an information gap of the carbon benefits of applying compost to soil; a benefit that is currently either overlooked or only partly considered in life cycle assessments.

DEFINITIONS

Soil Carbon

This is the total amount of carbon in a soil, and includes both organic carbon (derived from plants and animals) as well as inorganic carbon (usually present as carbonates and bicarbonates).

Soil Organic Carbon (SOC)

This is the carbon present in organic forms, and is derived from living things such as plants, animals and microbes.

Soil Organic Matter (SOM)

This is the soil organic carbon plus the hydrogen, oxygen and nitrogen that are part of the organic compounds. Scientists usually use the following equation to convert SOC to SOM:

SOIL ORGANIC MATTER (%) = SOIL ORGANIC CARBON (%) x 1.72

[6] This paper has only modelled the potential effects of compost and not anaerobic digestate, as the latter is best classified as an organic fertiliser and not a soil improver.

[7] Gilbert, J., Ricci-Jürgensen, M. and Ramola, A. (2020) A Summary of the Benefits of Compost and Anaerobic Digestate When Applied to Soil, ISWA, Rotterdam.

3.2

Projected timescales

Two timeframes were chosen to evaluate increases in soil organic carbon:

- **10 years** - to meet the Sustainable Development Goal target 15.3 to combat desertification and restore degraded land and soil by 2030, assuming a baseline year of 2020; and
- **20 years** - as this is thought to be the timeframe over which the soil organic carbon content of degraded land increases at its fastest rate following compost addition (see Figure 1).

It was assumed that the rates of SOC increase (and hence carbon sequestration) remained the same over both the modelled 10- and 20-year timeframes.

3.3

Soil organic carbon

To evaluate the benefits of organic matter applied to soil as quality[8] compost, three scenarios (low, medium and high) were modelled based on assumed rates of soil organic carbon increases following compost application (Table 1).

These assumptions were based on data published by Powlson *et al.* 2012, who calculated that soil organic carbon increases of between **50-70 kg C ha^{-1} yr^{-1} t^{-1} dry mass** applied as compost are possible; and were similar to a rate of 70 kg C ha^{-1} yr^{-1} t^{-1} dry mass suggested by Ros *et al.* 2006 (quoted in Powlson *et al.* 2012) in Austria over 12 years.

A low scenario of 30 kg C ha^{-1} yr^{-1} t^{-1} was chosen, as this may better reflect SOC increases in parts of the world with low SOC formation rates, such as the tropics. The medium and high scenarios correspond with the rates suggested by Powlson *et al.*, and may reflect SOC formation rates in degraded soil in temperate climates. Further information on soil organic carbon formation is detailed in the ISWA Report 2[9].

Scenario	Assumed increase in SOC (kg of SOC per tonne of compost measured on a dry mass basis per hectare per year)
Low	30 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass
Medium	50 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass
High	70 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass

Table 1 - Modelled soil organic carbon increase rates

3.4

Compost application rates and moisture content

Three compost application rates to soil were modelled, as shown in Table 2. It was assumed that compost has a typical dry mass content of 60% on a mass/mass basis (40% moisture m/m), as these are typical levels found in biowaste-derived compost (i.e. the input feedstocks are both green waste and food waste).

Annual application rate (tonnes hectare^{-1} year^{-1}) Dry mass basis	Annual application rate (tonnes hectare^{-1} year^{-1}) Fresh mass basis
6	10
18	30
30	50

Table 2 - Modelled compost application rates

The modelling assumed that the same quantity of compost would be applied to the same area of land annually (i.e. every year) over both a ten- and twenty-year period.

[8] Quality compost is a product manufactured from separately collected organic waste that has been composted in a quality assured process.

[9] Gilbert, J., Ricci-Jürgensen, M. and Ramola, A. (2020) A Summary of the Benefits of Compost and Anaerobic Digestate When Applied to Soil, ISWA, Rotterdam.

3.5

Soil density

Soils with different bulk densities were modelled for two reasons:

Firstly, compacted, eroded soils tend to have a high density, which makes them less productive; therefore, by modelling theoretical soil organic carbon increases on soils with different densities, an indication can be gleaned of the potential benefits compost may have on different soil types, including compacted soils.

Secondly, soil organic carbon levels are often quoted on a percentage basis; that is, the mass of SOC per total mass of soil. In order to estimate potential increases in SOC levels, it was therefore necessary to make assumptions about the density of the receiving soil.

Three soil densities were thus modelled to represent soils with a low density (e.g. clayey soils), medium density soils (e.g. silty soils) and high density soils (e.g. sandy soils); this is shown in Table 3.

For modelling purposes, it was assumed that the density of the receiving soil would not change following compost application over both the ten and twenty-year time horizons. However, this is a somewhat erroneous assumption, as it is generally acknowledged that soils with high SOC levels tend to have lower bulk densities than those with low SOC levels[10], meaning that compost amendments would, in general, serve to lower the soil's bulk density. As data relating to the rate at which soil density may reduce following compost application was unavailable, it was therefore not possible to include this variable in the model.

Scenario	Soil density (tonnes m^{-3})	Example Soil Texture
Low	1.1	Clayey
Medium	1.3	Silty
High	1.5	Sandy

Table 3 - Soil density scenarios

[10] See, for example: USDA Natural Resources Conservation Service, Soil Quality Indicators, June 2008

3.6

Soil depth and area of compost application

A soil depth of 30 cm (0.3 metres) was assumed, as this is the maximum depth that most agricultural ploughs reach[11]. It is also the depth that soil organic carbon changes occur in the short-term following compost application (see Report 2, Section 5), and is the depth that most SOC levels are measured experimentally and reported in the scientific literature.

An area of one hectare (equivalent to 100 metres by 100 metres or 10,000 m^2) was chosen as the assumed area of land onto which compost would be spread. Thus, application rates have been quoted as compost mass (in metric tonnes) per hectare.

3.7

Plant nutrient content and fertiliser prices

The plant macro-nutrients modelled were:

Total nitrogen (N)	Phosphorus (as P_2O_5)	Potassium (as K_2O)

In addition, as compost tends to have an alkaline pH, it has the potential to reduce the acidity of soils, and this is expressed as a fraction of the neutralising value of calcium oxide (CaO). Neutralising values were also included in the model. The compost nutrient concentrations used in the fertiliser calculations were those quoted by Bhogal *et al.*, 2016[12] and are shown in Table 4. The authors summarised laboratory results of two different types of compost (green waste- and green/food waste-derived compost) and are the average (mean) of 21 samples for each compost type.

Compost type	Total N (kg/t DM)	Total P_2O_5 (kg/t DM)	Total K_2O (kg/t DM)	Neutralising value (%CaO)
Green compost (n= 21)	13.7	5.1	9.9	3.33%
Green/food compost (n=21)	17.9	6.3	9.8	3.90%

Table 4 - Nutrient levels of different composts expressed on a dry mass basis

The average (mean) dry mass content (mass/mass basis) for these composts were:

- Green waste-derived compost (n= 21) **70%**
- Green/food compost waste-derived compost (n=21) **66%**

Fertiliser prices were calculated using the mean of monthly spot prices from January 2017 – October 2019 in the UK using data supplied by the Agriculture and Horticulture Development Board[13] for N, P and K. The price of CaO was based on a personal communication (A Banks, 2019) and based on an agricultural quotation for Superlon lime with a neutralising value of 55% (% calcium as CaO). All prices were converted from British Pounds Sterling (GBP) to EUROS and are shown in Table 5.

Fertiliser	Ammonium nitrate	Triple super phosphate	Muriate of potash (KCl)	CaO
% nutrient in fertiliser (mass/mass)	34.5% N	46% P_2O_5	60% K_2O	55% NV
Price per tonne as fertiliser	€ 280.44	€ 340.86	€ 303.24	€ 87.78
Price per tonne as nutrient	€ 812.87	€ 741.00	€ 505.40	€ 159.60

Table 5 - Assumed fertiliser prices

[11] Compost may be spread on the surface of soil and left to allow incorporation during crop seeding or sewing, or it may be tilled into the soil using a plough (or plow).

[12] Bhogal A, Taylor M, Nicholson F, Rollett A, Williams J, Newell Price P, Chambers B, Litterick, A and Whittingham, M. (2016) Work Package 1 Final report (2010-2015) DC-Agri; field experiments for quality digestate and compost in agriculture. Waste and Resources Action Programme. Available at: http://www.wrap.org.uk/content/digestate-and-compost-agriculture-dc-agri-reports (Accessed 28 June 2019).

[13] https://ahdb.org.uk/GB-fertiliser-prices; latest update, 4 December 2019 [accessed 17 December 2019]

3.8

Economic modelling

British pounds sterling (GBP; £) and US Dollars (USD; $) were converted to EUROS (€) based on the average exchange rates over the past three years (as of December 2019).

The conversion factors used were:

- 1 £ (GBP) = **1.14 € (EURO)**
- 1 $ (USD) = **0.88 € (EURO)**

Carbon pricing was based on the median values suggested by the World Bank[14] as being needed to initiate behavioural and infrastructure change to meet the Paris climate change accord. These are:

- USD 60 per tonne of carbon dioxide (CO_2) by 2020; and
- USD 75 per tonne of carbon dioxide (CO_2) by 2030.

A straight-line increase for carbon pricing of USD 1.5/year was applied between 2020 and 2030 (10-year horizon), and between 2030 and 2040 (20-year horizon). All carbon prices were subsequently converted to EUROS.

A 3.0% discount rate was applied to future cash flows. This compares with the US Federal Reserve secondary rate of USD 2.75% and the UK Treasury's Green Book suggested rate of 3.5% (December 2019 rates).

3.9

Available water capacity

Soil available water capacity changes due to increases in SOC levels were calculated using a value quoted by Minasny & McBratney (2018)[15] in their meta review of published data.

They suggested that for every 1% (mass/mass) increase in SOC levels the available water capacity would increase by 2.1% (m/m); that is, there would be a gravimetric increase of 2.1 grams of water per 100 grams of soil for every 10 g increase in soil organic carbon per kg of soil. (This is the same as 2.1 g H_2O 100 g^{-1} soil for every 10 kg tonne^{-1} SOC.) This is a conservative estimate and is much lower than increases in available water capacity suggested by other authors.

[14] High-Level Commission on Carbon Prices. 2017. Report of the High-Level Commission on Carbon Prices. Washington, DC: World Bank. License: Creative Commons Attribution CC BY 3.0 IGO

[15] Minasny B and McBratney AB (2018) Limited effect of organic matter on soil available water capacity. European Journal of Soil Science 69: 39–47.

4.1 SCENARIO MODELLING – CARBON

4.1.1

Soil organic carbon levels and sequestration rates

The calculated increases in soil organic carbon (SOC) levels for one hectare of soil following different rates of compost application over both ten and twenty-year periods are shown in Table 6. The data show that at a typical compost application rate of 30 tonnes ha^{-1} year^{-1} (fresh mass) increases in SOC levels of over 10 tonnes ha^{-1} are possible after 20 years at the lowest sequestration scenario, rising to just over 25 tonnes ha^{-1} at the highest sequestration scenario rate (Figure 2).

As the model assumes that there is a directly proportional increase in SOC levels with increasing compost application rates, this means that as more compost is applied to soil, more of the total amount of carbon applied will be sequestered.

In practice, however, an upper sequestration limit is likely to be reached, although there is a paucity of data in the published literature to identify how high this upper carbon sequestration rate may be. Additionally, agricultural compost application rates in many countries are calculated on the basis of nutrient levels in the receiving soil and/or crop nutrient demands[16], meaning that nutrient concentrations will be the rate-limiting value.

Time (y)	Application rate dry mass (t ha^{-1} year^{-1})	Application rate fresh mass (t ha^{-1} year^{-1})	SOC increase (tonnes ha^{-1})		
			LOW (30)	MEDIUM (50)	HIGH (70)
10	6	10	1.8	3.0	4.2
20	6	10	3.6	6.0	8.4
10	18	30	5.4	9.0	12.6
20	18	30	10.8	18.0	25.2
10	30	50	9.0	15.0	21.0
20	30	50	18.0	30.0	42.0

Table 6 - Modelled increases in SOC levels at different compost application rates and SOC increase rates

[16] For example, in parts of the European Union, compost application rates are restricted based on their total nitrogen content if the soil to which they are applied falls in a designated 'nitrate vulnerable zone'. This is due to the Nitrates Directive (91/676/EEC), which aims to reduce pollution caused by agricultural nitrate run-off into surface and ground waters.

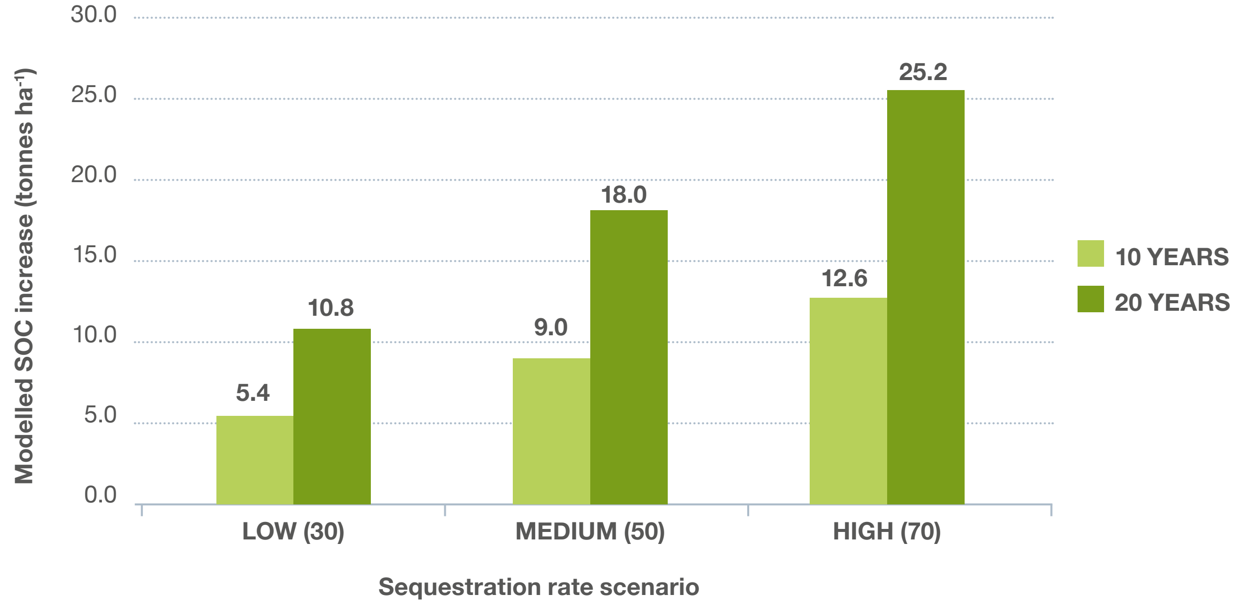


Figure 2 - Modelled SOC increases following annual compost application of 30 tonnes per hectare (fresh mass) over 10 and 20 years

It is only when estimated soil organic carbon levels are converted from a mass basis (as tonnes per hectare) to a percentage basis (that is, the fraction of organic carbon in soil on a mass/mass basis) that the significance of these changes start to become apparent.

Figure 3 shows how the SOC levels change after annual compost application rates of 30 tonnes (fresh mass) a year over 10 and 20-year periods at different soil densities. (The medium sequestration rate of 50 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass was assumed.)

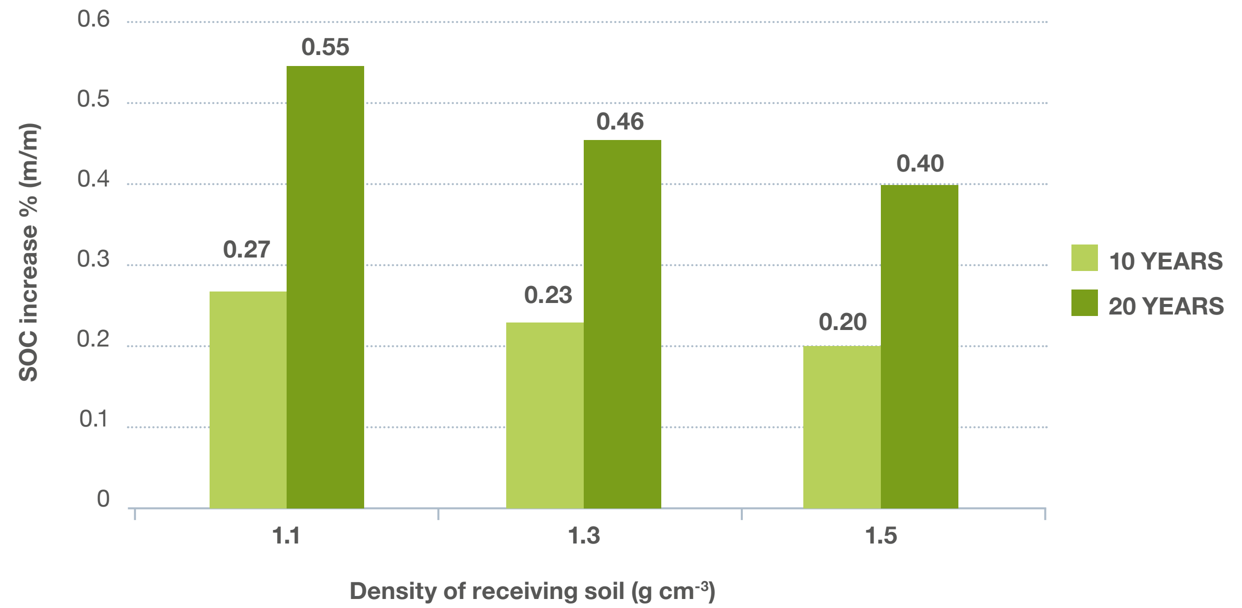


Figure 3 - Modelled changes in the fraction of SOC following 30 tonnes hectare^{-1} year^{-1} assuming a medium (50) sequestration rate at different soil densities

What this shows is that over a 20-year period, SOC levels can be increased (in absolute terms) by between 0.40-0.55 % (m/m) depending upon the density of the receiving soil. This has significant implications in the restoration of soils with a low content of organic matter. The effect was also greatest in soils with low densities, such as clayey soils.

The European Soil Bureau[17] has classified European soils on the basis of their SOC content (Table 7). An SOC level of below 2% is generally acknowledged to be a critical level[18], below which soil productivity becomes impaired – this means that its capacity to grow crops (food) is diminished.

Classification	SOM content (% m/m)
Very low	<1.0%
Low	1.1-2.0%
Medium	2.1-6.0%
High	>6.0%

Table 7 - Classification of soils based on their organic carbon content

As significant areas of the world have SOC levels in the low or very low categories, it is clear from this modelling that an annual application of quality compost could help raise SOC levels and thereby increase agricultural productivity. Therefore, some soils with low SOC levels (in the range of 1.5-2.0 %), could theoretically be improved over a 20-year period and thereby re-classified as having medium SOC levels (due to an increase in SOC content of between 0.4-0.5 %). Higher compost application rates and the highest sequestration rate would show proportionally greater increases.

The greatest relative benefits (that is, the proportional increase in SOC) are gained on low density soils having low initial SOC levels.

Table 8 and Figure 4 shows modelled relative SOC increases on soils of different densities at two initial SOC levels of 1% and 2%. What this shows is that on a low-density soil with a low SOC level, the application of compost over a 20-year period can increase SOC levels by 55%.

It is worth noting that these calculations have been based on an assumed soil depth of 30 cm, as this is the top layer of soil for which most research is reported. However, there is some recent evidence to suggest that soil organic carbon levels in soils following compost application are increased at depths of up to two metres[19]. This is an important observation and warrants further investigation.

Initial SOC level of receiving soil (% m/m)	Density of receiving soil (g cm^{-3})					
	1.1	1.3	1.5	1.1	1.3	1.5
	Timeframe (10 years)			Timeframe (20 years)		
	Relative increase in SOC levels					
1%	27%	23%	20%	55%	46%	40%
2%	14%	12%	10%	27%	23%	20%

Table 8 - Modelled relative increases in SOC levels in soils of different densities receiving compost at 30 t hectare^{-1} year^{-1} assuming a medium (50) sequestration rate

[17] Jones, R.J.A., Hiederer, R., Rusco, E., Loveland, P.J. and Montanarella, L. (2004). The map of organic carbon in topsoils in Europe, Version 1.2, September 2003: Explanation of Special Publication Ispra 2004 No.72 (S.P.I.04.72). European Soil Bureau Research Report No.17, EUR 21209 EN, 26pp. and 1 map in ISO B1 format. Office for Official Publications of the European Communities, Luxembourg.

[18] Loveland, P.J. and Webb, J. (2003) Is there a critical level of organic matter in the agricultural soils of temperate regions: A review. Soil and Tillage Research 70(1):1-18. DOI: 10.1016/S0167-1987(02)00139-3

[19] Tautges NE, Chiartas JL, Gaudin ACM, O'Geen AT, Herrera I and Scow KM (2019) Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. Global Change Biology 00: 1-14. DOI: 10.1111/gcb.14762

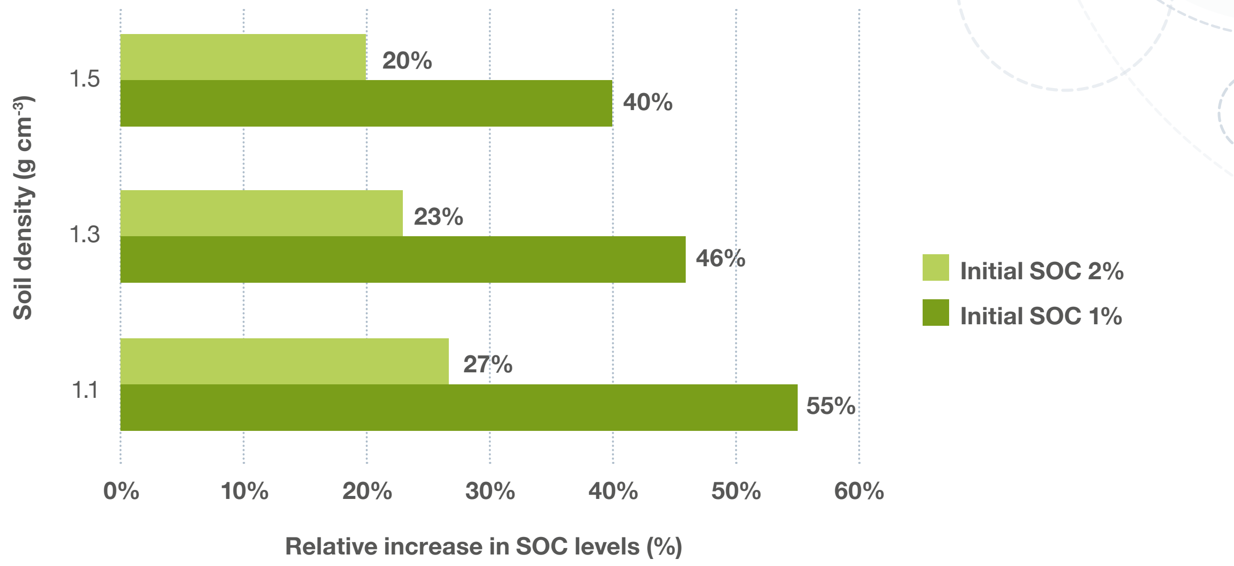


Figure 4 - Modelled relative increase in SOC levels in soils of different densities receiving compost at 30 t hectare^{-1} year^{-1} over a 20-year period assuming a medium (50) sequestration rate

4.1.2

Carbon dioxide equivalents

Increasing a soil's organic carbon content not only improves its productivity and ability to carry out ecological services, but it also acts as a carbon sink, sequestering carbon from the atmosphere. This is an area of significant scientific and policy interest as countries seek to implement climate change policies and reduce atmospheric carbon dioxide[20].

The amount of organic carbon sequestered in soil due to compost application can be converted into carbon dioxide equivalents (CO_2e) by multiplying the mass of organic carbon by a factor of 3.67[21].

The estimated carbon dioxide equivalents for each of the three sequestration scenarios are shown in Table 9.

Assuming a medium rate of SOC formation of 50 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass, for every tonne of compost (measured on a dry mass basis) applied to a hectare of soil 184 kg of carbon dioxide equivalent can be sequestered. This is equivalent to 110 kg of carbon dioxide equivalent for every tonne of compost measured on a fresh mass basis, equivalent to 11% of its mass.

Looking at the modelled scenarios with three different application rates for compost on soil and for three different SOC sequestration rates (Table 10), this suggests that there is - at the highest rate of compost application and at the highest rate of SOC increase - a potential to sequester just over 150 tonnes of CO_2 eq per hectare over a 20-year period;

The cumulative increase in sequestered carbon expressed as carbon dioxide equivalents at the medium sequestration rate of 50 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass over a 20-year period following 30 tonnes of fresh compost is shown in Figure 5. Comparing this with the schematic graph outlined in Figure 1 in the introductory section of this report, illustrates the significant potential that compost application may have on soils low in organic matter. Figure 6 illustrates how this may be applied to low organic matter, degraded soil[22].

It is worth noting that this isn't the total amount of organic carbon applied to the soil as compost but is the amount of organic carbon that is converted into a stable form and hence remains in the soil for long periods of time. The total amount of organic carbon applied in compost will therefore be greater, although the less stable organic molecules will be oxidised over time[23] due to the actions of micro- and macro soil fauna, providing them with valuable food and nutrients.

SOC Scenario	LOW	MEDIUM	HIGH
Sequestration rate (kg of SOC per tonne of compost measured on a dry mass basis per hectare per year)	30	50	70
CO_2 equivalent (kg per tonne compost dry mass)	110	184	257
CO_2 equivalent (kg per tonne compost fresh mass)*	66	110	154

Table 9 - Estimated carbon dioxide equivalent sequestration rates per tonne of compost

* Assuming compost has a moisture content of 40%(m/m)

	Sequestered carbon in carbon dioxide equivalents (tonnes $hectare^{-1}$)					
	Timeframe (10 years)			Timeframe (20 years)		
Annual compost application rate (fresh mass) to 1 ha of soil (t ha^{-1} yr^{-1})	LOW 30	MEDIUM 50	HIGH 70	LOW 30	MEDIUM 50	HIGH 70
10	6.6	11.0	15.4	13.2	22.0	30.8
30	19.8	33.0	46.2	39.6	66.1	92.5
50	33.0	55.1	77.1	66.1	110.1	154.1

Table 10 - Calculated amounts of sequestered carbon for the modelled scenarios expressed in carbon dioxide equivalents

[20] See for example, the 4 per 1000 initiative: www.4p1000.org

[21] This is the stochiometric ratio of one carbon plus two oxygen atoms (i.e. CO_2) to every one atom of carbon.

[22] This has been shown solely for illustrative purposes and does not mean that the modelled compost application and sequestration rates shown will necessarily be required to improve the SOC levels of degraded soils.

[23] This is thought to follow a first-order decay rate, meaning that the labile (less stable) organic carbon is metabolised at a rate proportional to its concentration i.e. the more there is, the faster it decreases.

Figure 5 - Calculated quantities of sequestered carbon (expressed in carbon dioxide equivalents) over a 20-year period following 30 tonnes a year of compost (fresh mass) applied to 1 hectare of land at the medium sequestration rate

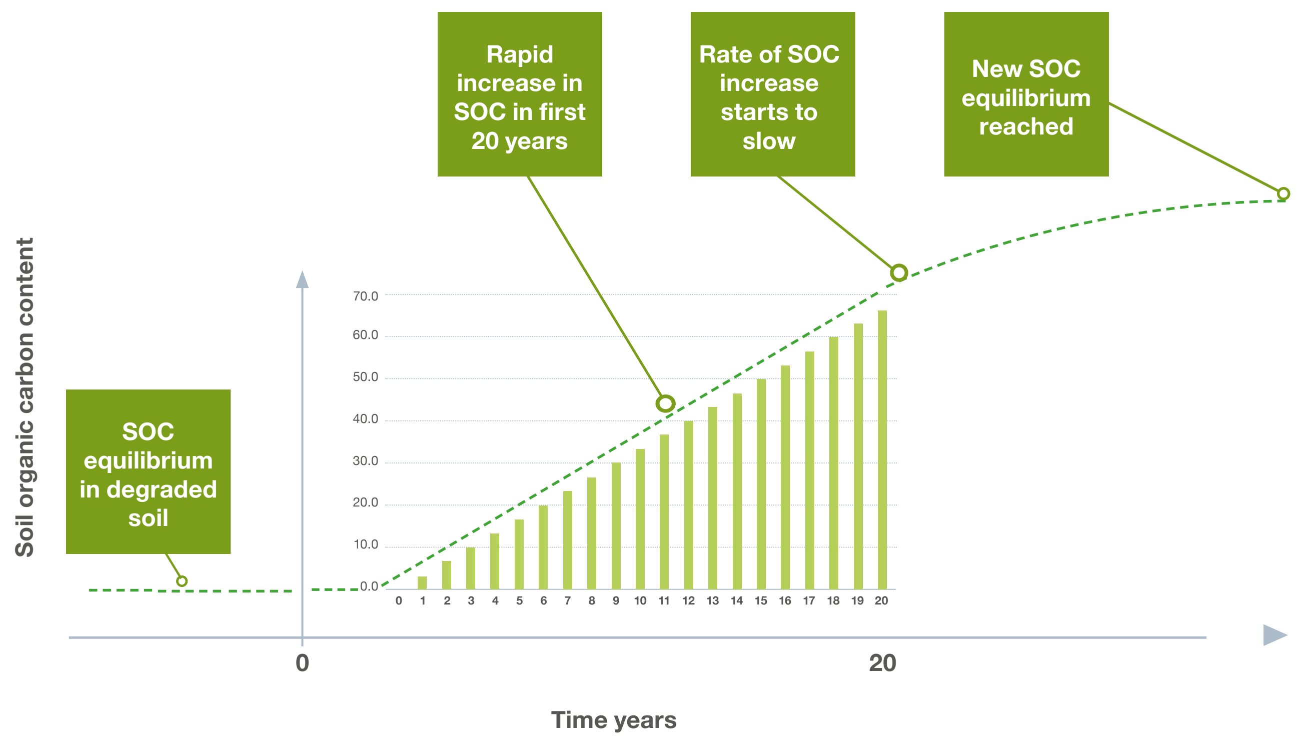


Figure 6 - Illustration showing how an annual application of compost has the potential to improve the SOC levels of a degraded soil over a 20-year period

4.1.3

Carbon accounting and cumulative value

As the previous section has shown, it is possible to sequester carbon in soil through the annual application of quality compost. A price can therefore be placed on this and used to estimate an economic potential.

World Bank estimates for the price of carbon dioxide required to initiate behavioural and infrastructure change to meet the Paris climate change accord have been used (see Section 3.8). Assuming that the median cost of carbon dioxide in 2020 is EUR 52.80 per tonne, then this suggests that every tonne of compost (fresh mass) can be valued in carbon sequestration terms at between EURO 3.50-8.10 per tonne (rounded to the nearest 10 cents; Table 11).

SOC sequestration rate scenario	LOW 30	MEDIUM 50	HIGH 70
CO_2 eq (kg tonne^{-1} compost dry mass)	110	184	257
CO_2 eq (kg tonne^{-1} compost fresh mass)	66	110	154
Price per tonne compost dry mass (2020 value)	€ 5.81	€ 9.72	€ 13.57
Price per tonne compost fresh mass (2020 value)	€ 3.49	€ 5.81	€ 8.14

Table 11 - Estimated monetary value of compost in terms of carbon dioxide sequestration (2020 carbon pricing at EUR 52.80 per tonne of carbon dioxide)

Using these figures, an estimate can be made of the potential value of this carbon in today's money due to annual compost application over both the 10- and 20-year timescales. These have been modelled for the three different SOC sequestration rate scenarios and the three different compost application rates using a 3% discount rate; Table 12.

What this shows is that significant potential exists should the carbon sequestrated in soil following quality compost application be accounted for by an economic instrument aimed at reducing carbon dioxide emissions.

	LOW			HIGH		
Compost application rate (t ha^{-1} yr^{-1} fresh mass)	LOW (30)	MEDIUM (50)	HIGH (70)	LOW (30)	MEDIUM (50)	HIGH (70)
10	€ 336	€ 563	€ 786	€ 642	€ 1074	€ 1500
30	€ 1009	€ 1688	€ 2357	€ 1926	€ 3221	€ 4499
50	€ 1682	€ 2813	€ 3929	€ 3206	€ 5368	€ 7498

Table 12 - Estimated value of carbon sequestered in soil in 10- and 20-year time horizons in today's money

4.2 SCENARIO MODELLING – NUTRIENTS

Compost contains not only carbon, which helps increase soil organic matter levels, but also useful plant macro-nutrients, such as nitrogen, phosphorus and potassium.

Unlike anaerobic digestate, in which plant macro-nutrients are primarily available in a soluble form and are therefore readily available for plant uptake[24], the nutrients in compost are often complexed with organic molecules. This means that they are released gradually over time through the actions of micro- and macro-organisms; thus, repeated application of compost to soil can help improve its overall fertility, creating a so-called 'nutrient bank'[25].

4.2.1

Fertiliser equivalent values

Nutrient calculation tools, such as those used by agronomists, often only consider the concentration of plant nutrients available for crop uptake in the first year following compost application[26].

This underestimates the total nutritional value of the material and therefore fails to estimate the value it adds to soil, especially in the long term.

For these reasons, estimates were made of the total macro-nutrient content of compost using published figures for two types of compost derived from either green waste only or a mixture of green and food waste feedstocks (as detailed in Section 3.7); the results are shown in Table 13.

	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)	Limestone powder*	TOTAL
Price per tonne as nutrient	€ 812.87	€ 741.00	€ 505.40	€ 159.60	--
DRY MASS					
Price per tonne of green waste-derived compost (dry mass)	€ 11.14	€ 3.80	€ 3.00	€ 5.31	**€ 23.25**
Price per tonne of green/food waste-derived compost (dry mass)	€ 14.53	€ 4.67	€ 4.96	€ 6.22	**€ 30.39**
FRESH MASS**					
Price per tonne of green waste-derived compost (fresh mass)	€ 7.80	€ 2.66	€ 3.50	€ 3.72	**€ 17.68**
Price per tonne of green/food waste-derived compost (fresh mass)	€ 9.59	€ 3.08	€ 3.27	€ 4.10	**€ 20.05**

Table 13 - Estimated fertiliser value of the total macro nutrients in two compost types

* Values adjusted to 100% neutralising value to enable like-for-like comparisons to be made.

** Assumed mean dry mass of 70% for green waste-derived compost and 66% for food/green-waste derived compost.

The data shown in Table 13 show that the total nutrient value of compost (when expressed on a dry mass basis) falls in the region of €23 -30 per tonne, or between €17-20 per tonne on a fresh mass basis.

[24] This is why digestate is a useful organic fertiliser.

[25] This was discussed in: Gilbert, J., Ricci-Jürgensen, M. and Ramola, A. (2020) A Summary of the Benefits of Compost and Anaerobic Digestate When Applied to Soil, ISWA, Rotterdam.

[26] See, for example: www.wrap.org.uk/content/compost-calculator [accessed 26 March 2020]

Although this study does not constitute a life cycle assessment, it is worth looking briefly at the avoided carbon dioxide emissions associated with fertiliser manufacture. Using data published by Kool et al. (2012)[27], the data in Table 14 suggest that the nutrients in one tonne of compost (expressed on a dry mass basis) offset in the region of 100 kg of carbon dioxide equivalents simply by displacing synthetic fertilisers. Even though they don't take into account processing emissions associated with compost production (which would be required to complete a like-for-like analysis), they do serve to illustrate the potential environmental value compost has by simply substituting conventional fertilisers.

	Total N	Total P_2O5	Total K_2O	
Green compost (kg tonne^{-1} dry mass)	13.7	5.1	9.9	-
Green/food compost (kg tonne^{-1} dry mass)	17.9	6.3	9.8	-
Global average for manufactured fertiliser (CO_2-eq kg^{-1})	5.66	1.36	1.23	
				TOTAL
Green compost (kg CO_2-eq tonne compost dry matter^{-1})	78	7	12	97
Green/food compost (kg CO_2-eq tonne compost dry matter^{-1})	101	9	12	122

Table 14 - Carbon dioxide displacement of inorganic fertilisers through compost use (per tonne dry mass)

[27] Kool, A., Marinussen, M. & Blonk, H. (2012) LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilisation - GHG Emissions of N, P and K fertilizer production. Blonk Consultants, Netherlands.

4.2.2

Cumulative value

By following a similar approach to that for carbon sequestration detailed in Section 4.1.3, an estimate can be made of the potential value of these plant macro-nutrients in today's money following annual compost application over both the 10- and 20-year timescales. The model assumes a 3% discount rate, and the estimates are shown in Table 15.

Notably, the model assumes that the price of fertilisers remains stable and does not increase or decrease from the assumed baseline. Given the variability in fertiliser prices in the past it is perhaps unrealistic to assume that this would be the case moving forward; although any assumption about potential future increases would be highly speculative.

Notwithstanding these limitations, the data suggest that the total quantity of nutrients applied to soil in compost represent a sizeable financial value; for example, the model estimates a fertiliser value of over €8,000 in food- and green waste-derived compost applied at 30 tonnes per hectare (fresh mass) over 20 years; this is almost twice the estimated value of carbon sequestered in soil over the same time horizon.

Time (y)	Application rate fresh mass (t ha^{-1} year^{-1})	Total application rate (tonnes fresh mass hectare^{-1})	Total present value of cash flows (€ hectare^{-1})
	GREEN WASTE-DERIVED COMPOST		
10	10	100	€ 1,190
20	10	200	€ 2,075
10	30	300	€ 3,570
20	30	600	€ 6,226
10	50	500	€ 5,950
20	50	1000	€ 10,377
	GREEN & FOOD WASTE-DERIVED COMPOST		
10	10	100	€ 1,555
20	10	200	€ 2,713
10	30	300	€ 4,666
20	30	600	€ 8,138
10	50	500	€ 7,777
20	50	1000	€ 13,564

Table 15 - Estimated total value of macro plant nutrients applied to soil following annual application of compost over 10 and 20 years (expressed in today's money)

4.3 SCENARIO MODELLING – AVAILABLE WATER CAPACITY

Available water capacity (AWC; see box) is the metric commonly used to measure a soil's ability to hold water.

MEASURING SOIL WATER HOLDING CAPACITY

Soil scientists use the term **'Available Water Capacity'**. This is defined as:

Available Water Capacity (AWC) = The amount of water (cm^3 water/100 cm^3 soil) retained in the soil between the **Field Capacity (FC) and the Permanent Wilting Point (PWP).**

The **field capacity** is the volumetric fraction of water in the soil at soil water potentials of 10–33 kPa.

The **permanent wilting point** is the volumetric fraction of water in the soil at soil water potential of 1500 kPa.

It is generally acknowledged that soils with medium and high levels of organic carbon (see Table 7) are better able to retain water than soils with low SOC levels. This has important agronomic and ecosystem implications, affecting not only soil productivity and resistance to drought, but also water catchment and release rates following precipitation[28]. It is thought that this is due to both a change in the porosity of the soil and the ability of the organic matter itself to hold onto water; greater increases in the available water capacity generally occur in soils with a medium to coarse texture, compared to finer-textured soils[29].

However, the scientific evidence correlating changes in available water capacity with varying levels of soil organic carbon are uncertain, and there appears to be significant variation in published estimates. For this study, the summarised rate quoted in Chapter 3.9 was used (i.e. a gravimetric increase of 2.1 grams of water per 100 grams of soil for every 10 g increase in soil organic carbon per kg of soil).

The results are presented in Table 16 for the three assumed rates of compost application (10, 30 and 50 tonnes per hectare a year) over 10 and 20-year timeframes at the low, medium and high sequestration rates of organic carbon.

What this exercise shows is that the calculated increases in available water capacity are quite low. For example, a 30 tonne per hectare per annum application of compost (fresh mass) over 20 years at the medium sequestration rate (50 g SOC per tonne of compost on a dry mass basis), would only increase the AWC by 37.8 cubic meters per hectare in the top 0-30 cm of soil; this is equivalent to 3.78 litres of water over one square meter of soil (in the top 0-30 cm horizon).

However, these calculations are based upon changes in the stable soil organic carbon pool which will be sequestered over long periods of time; what they don't take into account is the potential positive effect of labile carbon in the compost, which will almost certainly have a water holding capability.

In addition, it assumes that all of the organic matter would be incorporated into the soil below the surface. Where compost has been applied to the surface and not incorporated into the soil mass by ploughing, it would not be unreasonable to assume that it may well act as a surface mulch and help retain soil water through reducing evaporative losses.

These uncertainties illustrate the complexity of the subject, and suggest that further field-based experiments are required to gain an improved understanding of the effects of compost on soil available waster capacity.

Time (y)	Application rate dry mass (t ha^{-1} year^{-1})	Application rate fresh mass (t ha^{-1} year^{-1})	Increase in AWC in the 0-30 cm horizon (m^3 hectare^{-1})		
			LOW (30)	MEDIUM (50)	HIGH (70)
10	6	10	3.8	6.3	8.8
20	6	10	7.6	12.6	17.6
10	18	30	11.3	18.9	26.5
20	18	30	22.7	37.8	52.9
10	30	50	18.9	31.5	44.1
20	30	50	37.8	63.0	88.2

Table 16 - Modelled increases in available water capacity following annual compost application for 10 and 20-year scenarios at the three rates of organic carbon sequestration

[28] The effects of SOC levels on soil function are summarised in: FAO 2017. Soil Organic Carbon: the hidden potential. Food and Agriculture Organization of the United Nations. Rome, Italy; and Gilbert, J., Ricci-Jürgensen, M. and Ramola, A. (2020) A Summary of the Benefits of Compost and Anaerobic Digestate When Applied to Soil, ISWA, Rotterdam.

[29] Huntington, T.G. (2007) Available Water Capacity and Soil Organic Matter. In Encyclopedia of Soil Science, Second Edition. Taylor and Francis: New York, 139-143.

4.4 GLOBAL IMPLICATIONS

In order to contextualise these findings, an assessment was made of the potential implications of carbon and nutrient application to soil in selected countries and globally.

4.4.1 Carbon sequestration potential

Four of the five countries whose state of soils were summarised by ISWA[30] were chosen as examples. Using the estimated quantities of organic waste they produce[31], the potential carbon that may be sequestered in each country and globally was made (Table 17)[32].

Country	Estimated annual organic waste arisings (million tonnes annum^{-1})	Estimated compost[a] (million tonnes annum^{-1} fresh mass)	Potential increase in soil organic carbon[b] (tonnes annum^{-1})	Carbon dioxide sequestration (tonnes annum^{-1} CO_2-eq)	Equivalent number of passenger vehicles driven for one year[c] (thousands)	Equivalent number of homes' electricity use for one year[c] (thousands)
Australia	3.1	1.0	31,000	**113,667**	25	19
Brazil	39.9	13.3	399,100	**1,463,367**	316	248
Italy	8.0	2.7	80,000	**293,333**	63	50
UK	9.3	3.1	92,800	**340,267**	74	58
GLOBAL	935	311.7	9,350,000	**34,283,333**	7,407	5,804

Table 17 - Estimated annual potential carbon sequestration (CO_2-eq) due to compost application to soil in selected countries and globally

a Assumes that the conversion of organic waste to compost is approximately one-third and that the moisture content of the compost is 40% (mass/mass)

b Assumes the medium sequestration rate of 50 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass

c www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

[30] Summarised in: Ricci-Jürgensen, M., Gilbert, J. and Ramola, A. (2020) Summary of the State of Soils in Five Countries. ISWA, Rotterdam.

[31] Ricci-Jürgensen, M., Gilbert, J. and Ramola, A. (2020) Global Assessment of Municipal Organic Waste Production and Recycling. ISWA, Rotterdam.

[32] This calculation assumes that bio-waste would be composted, with a yield of one-third compost produced per unit mass of bio-waste. In practice, a fraction of this bio-waste would be treated in an anaerobic digester; however, by post-composting the residual digestate, this fraction would be accommodated within the 33% conversion factor and is therefore consistent with the assumptions made.

The calculations suggest that **in the region of 34 million tonnes of carbon dioxide equivalents could potentially be sequestered in soil annually** if all organic waste produced were converted into quality compost. This estimate is approximately 0.7-1.7% of the annual 2-5 giga tonnes CO_2-eq that global soils are technically able to sequester (Paustian *et al.*, 2019[33]).

To put this into context, 34 million tonnes of CO_2-eq is broadly equivalent to:

- The total emissions from one year's driving of 44% of the total number of new passenger vehicles registered in the EU28 in 2017[34] (16.8 million vehicles in total); or
- The electricity used by households in London and the South-East of England in 2017 (5.9 million households)[35].

The potential for soil to sequester carbon, is now starting to be recognised by policy makers. A recent example is the 'SOS soil initiative'[36] which calls on EU policy makers to develop instruments to move Europe towards implementing sustainable, climate-proof land management practices.

The outcomes of the calculations of this report can be linked also to other global campaigns, such as the '4 per 1000' international initiative launched by France in 2015 at the United Nations Climate Change Conference. It aims to increase soil carbon stocks by 0.4% (or 4‰) per year, in the top 30-40 cm of soil in order to reduce anthropogenic carbon dioxide[37]. Using the methodology outlined in this report, applying 30 tonnes per hectare of compost (fresh mass) to soil with an initial SOC content of 1% (mass/mass), and a density of 1.3 tonnes/hectare to a depth of 30 cm and assuming the medium (50) sequestration rate, the SOC stock could be increased by 2.3% per year; this is approximately six times the annual increase supported by the '4 per 1000' initiative. Hence to achieve the 4‰ increase in soil organic carbon, an estimated 5.2 tonnes of compost (fresh mass) would need to be spread onto one hectare of this example soil (using the assumptions outlined above). These are summarised in Table 18.

These estimates also broadly agree with those of Poulton *et al.* (2018)[38] who summarised data from a range of long-term experiments. One experiment, where compost was applied at 40 t hectare^{-1} annum^{-1} to soil over ten years and on which various arable crops were grown, resulted in an annual increase of soil organic carbon of 3.6% (or 36 ‰); this compares with the estimated 2.3% per annum increase at our theoretical 30 t per ha scenario shown in Table 18.

Compost application rate (tonnes hectare^{-1} annum^{-1} fresh mass)	Increase in SOC stock (% m/m)	Potential global landbank for compost (million hectares)	Fraction of total global cropland (%)
30.0	2.3%	**10.4**	1%
5.2	0.4%	**60.0**	4%

Table 18 - Estimated annual quantities of compost applied annually to soil to achieve an increase of 4‰ in soil organic carbon stocks and landbank equivalents

[33] Paustian K, Larson E, Kent J, Marx E and Swan A (2019) Soil C Sequestration as a Biological Negative Emission Strategy. Front. Clim. 1:8. doi: 10.3389/fclim.2019.00008

[34] https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=road_eqr_carmot&lang=en [accessed 30 March 2020]

[35] https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/adhocs/005374totalnumberofhouseholdsbyregionandcountryoftheuk1996to2015 [accessed 31 March 2020]

[36] Launched in 2019 by the European Compost Network (ECN) and the Italian Composting and Biogas Association (CIC) during the annual ISWA conference. https://www.saveorganicsinsoil.org/

[37] See: www.4p1000.org

[38] Poulton, P., Johnston, J., Macdonald, A., White, R. & Powlson, D. (2018) Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. Global Change Biology; 24: 2563–2584. DOI: 10.1111/gcb.14066

[39] http://www.fao.org/economic/ess/environment/data/land-use/en/ [accessed 31 March 2020]

[40] Cropland accounts for about one-third of total global agricultural land; ibid.

Although these estimates do not take into account the location of organic-waste arisings, compost production and proximity to cropland, they illustrate that potential demand for compost by farmers growing crops[40] outstrips theoretical supply by a factor of between 25 to 100-fold.

Looking more specifically at the four countries studied by ISWA, applying compost at a rate of 5.2 tonnes hectare^{-1} annum^{-1} (fresh mass) would only be sufficient to raise the SOC stocks of a small fraction of degraded agricultural land by 4‰. The calculations are shown in Table 19 and suggest that for Australia it would be 0.5% and for Italy 14% of their total degraded agricultural land. This illustrates the point that a range of measures will be required to start to address soil organic matter losses.

Country	Estimated area of degraded land (million hectares)	Estimated compost production (million tonnes annum^{-1})	Potential land bank when compost is spread at 5.2 tonnes ha^{-1} annum^{-1} (million ha)	Approximate fraction of degraded agricultural land
Australia	40	1.0	0.2	0.5%
Brazil	48	13.3	2.6	5.3%
Italy	4	2.7	0.5	14.1%
United Kingdom	6	3.1	0.6	9.9%

Table 19 - Estimated fraction of degraded agricultural land in four countries to which quality compost could be applied to increase soil organic carbon stocks by 4‰.

Table 18 Assumptions:

- Initial SOC level of receiving soil = **1%**
- Density of receiving soil = **1.3 t m^{-3}**
- Carbon sequestration rate = **50 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass**
- Soil depth = **0.3 m**
- Theoretical global compost production = **312 million tonnes annum^{-1} (fresh mass)**
- Global cropland = **1.6 billion hectares in 2016**[39]

[39] http://www.fao.org/economic/ess/environment/data/land-use/en/ [accessed 31 March 2020]

[40] Cropland accounts for about one-third of total global agricultural land; ibid.

4.4.2

Market value

In most cases, compost is marketed as a low value, high volume product. Unless it is bagged, blended into technical growing media, or formulated into added-value products, it is generally only sold for between EURO 0 to 15 per tonne (excluding transport and spreading costs).

By placing a value on the carbon it sequesters in soil and the total plant macro-nutrients it contains, it becomes clear that the true value of compost is not being realised through marketing alone (Table 20).

Looking at the four countries listed in Table 17, the global estimate of compost value based on its carbon sequestration potential and nutrient content (in today's money) is in the region of 6.6 – 8.8 billion Euros a year (Table 21).

Value	Range (€ tonne^{-1} fresh mass)
Carbon value through sequestration	3.50 - 8.10
Total nutrient value	17.70 – 20.10
TOTAL	**21.20 – 28.20**

Table 20 - Estimated total carbon and nutrient values (minimum and maximum) of one tonne of compost (fresh mass)

Country	Estimated compost (million tonnes annum^{-1} fresh mass)	Total value range of carbon (million €)[a]	Total value range of nutrients (million €)[a]	TOTAL of carbon and nutrient values (million €)[a]
Australia	1.0	4 – 8	18 - 20	21 - 28
Brazil	13.3	47 - 108	253 - 267	282 - 375
Italy	2.7	9 - 22	48 - 54	57 - 76
United Kingdom	3.1	11 - 25	55 - 62	66 - 87
GLOBAL	**311.7**	**1,091 - 2,525**	**5,517 – 6,265**	**6,607 – 8,789**

Table 21 - Estimated value of compost based on carbon sequestration potential and total nutrient content in selected countries and globally

a Based on compost fresh mass

Estimated values rounded to the nearest integer

When annual compost applications of 30 tonnes (fresh mass) per hectare are considered over 10- and 20-year timeframes (see Chapter 4.1 and 4.2), the potential value (in today's money) is significant in terms of carbon sequestration and nutrients applied to soil (Table 22).

When compared with an average current market value for compost of € 7.50 per tonne (fresh mass), these calculations suggest that compost is currently only sold for about 30% of its true value (in today's money) in carbon and nutrient terms over the 10 and 20-year timeframes.

These values, if recognised by local authorities and monetised to farmers, would easily put the agricultural sector into the (economic) position to purchase compost at an average market price of EURO 20 per tonne of compost (fresh mass), excluding transport and spreading costs.

Value	Total present value of cash flows 1-10 years	Total present value of cash flows 1-20 years
Carbon value through sequestration	€ 1,688	€ 3,221
Total nutrient value	€ 4,666	€ 8,138
TOTAL	**€ 6,354**	**€ 11,359**
Comparison with current compost purchase at € 7.50 per tonne (fresh mass)	€ 1,919	€ 3,347
% OF POTENTIAL VALUE CURRENTLY REALISED	**30%**	**29%**

Table 22 - Estimated cumulative value of the carbon and nutrient value in compost over 10- and 20-year timeframes (in today's money)

Assumptions:

Green & food waste-derived compost

Application rate = **30 tonnes^{-1} hectare year^{-1} (fresh mass)**

Carbon sequestration rate = **50 kg SOC ha^{-1} yr^{-1} t^{-1} dry mass**

Conclusion

To the best of the authors' knowledge, this is the first time that an economic assessment of both the carbon and nutrient value of compost has been made, taking into account theoretical carbon sequestration rates in soil.

The modelling illustrates the potential positive impact quality compost can have on soil organic carbon (SOC) levels; at a global level it has potential to sequester in the region of 34 million tonnes of carbon dioxide equivalents annually, if all organic waste produced by human settlements (i.e. the organic fraction of MSW) were to be collected separately and converted into quality compost. Although the challenges of separate collection, quality assured treatment and manufacture of quality compost should not be overlooked, this potential is significant and could increase the levels of SOC in about 4% of the world's croplands by 4‰.

In recent years, there has been an increase in the understanding and concern about soil erosion and its implications for food security. The manifesto 'SOS Soil' launched in 2019, reinforces the request by compost producers for a global commitment to preserve and protect soils starting from the adoption of legislative measures and actions in the European Union (EU)[41]. The loss of agricultural productivity in the EU, for example, has been estimated to cost EURO 1.25 billion a year, equivalent to a 0.43% reduction[42]. The estimates in this report provide a mechanism for agronomists and decision makers about municipal solid waste policies to start to evaluate further the carbon and nutrient value of compost, and to specify it as a product to mitigate some of the detrimental effects of soil erosion and climate change.

What this investigation was unable to do, however, was place a value on the wider range of ecosystem services, structural and biological benefits that quality compost is known to confer to soil. Estimates have been made of ecosystem service losses due to soil erosion[43] and these methodologies have potential to be applied in reverse to estimate beneficial improvements to degraded soil following compost application. However, at present, many of these benefits are described in the scientific literature in qualitative terms, where the implications in economic, carbon and/or nutrient terms have yet to be correlated. It is a complex issue, that warrants further research.

Overall, some of the issues highlighted in this report suggest that research to improve knowledge and understanding of composts' benefits to soil could be focussed on the following areas:

- **The rate at which organic carbon compounds are degraded**, including the rate of conversion of relatively unstable organic molecules to stable humic substances, both during composting and once compost has been applied to soil;
- **The effect** that both unstable and stable carbon in compost may have on available water capacity (AWC), as published literature suggests that changes in soil organic carbon levels (meaning mostly stable carbon) only effects relatively small changes in AWC;
- **The depth** to which compost application affects SOC levels in the 0-2 metre horizon; and
- **The biological effects of compost** on macro- and micro-organisms, and the implications for carbon and nutrient cycling.

Notwithstanding, the repeated application (i.e. in a time horizon of 10 to 20 years) of quality compost to soil has potential to systematically increase soil organic carbon levels, thereby sequestering carbon and improving soil functionality. By acknowledging the function of quality compost in terms of carbon sequestration and nutrient pool, the estimated values of between EURO 21 – 28 per tonne of compost (fresh mass) should be used to market it more effectively to farmers and agronomists.

As the benefits of annual compost use is cumulative, an estimated value of € 6,400 over a ten-year period, should be used to communicate compost's role in meeting the United Nations' Sustainable Development Goal Target 15.3 (to "combat desertification, restore degraded land and soil"). Compost, a soil amendment rich in organic carbon, clearly has an important role to play alongside other land use and management practices. With an estimated global potential value of €6 – 8 billion annually in product alone, the composting sector needs to be recognised for the important role it has to play in sequestering carbon and improving degraded soils.

[41] www.saveorganicsinsoil.org

[42] Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L. & Bosello, F. (2018) Cost of agricultural productivity loss due to soil erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models. Land Degradation & Development 29: 471-484. DOI: 10.1002/ldr.2879

[43] See, for example: Graves, A.R., Morris, J., Deeks, L.K., Rickson, R.J., Kibblewhite, M.G., Harris, J.A. Farewell T.S. & Truckle, I. (2015) The total costs of soil degradation in England and Wales. Ecological Economics 119: 399-41. doi.org/10.1016/j.ecolecon.2015.07.026

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