This paper is a based on a desktop assessment aimed at determining the carbon benefits of using locally produced compost/digestate to improve carbon soil stocks. The aim was also to identify material gaps and to make recommendations for further research.

The paper was produced by Felix Finlayson-Hood, a student at the University of Canterbury, who combined knowledge from his chemistry degree with his interest in the environment and agriculture and experience of growing up in a rural area.

The research was initiated by the WasteMINZ Organic Materials Sector Group and was funded by Marlborough District Council as part of a summer student scholarship in 2022/2023. The Organic Materials Sector Group gratefully acknowledges their support.

Please note this research has not been peer reviewed through scientific journals.

The potential for organic amendments to increase the carbon stocks in New Zealand soils

Felix Finlayson-Hood

Executive Summary

- There is increasing global interest in raising soil carbon stocks for both agricultural and climatic benefits. Potentially, New Zealand could be a leader in the field by reusing organic wastes as soil amendments to increase soil carbon stocks. These amendments could be applied raw or processed prior to application.
- Mineral associated organic matter (MAOM) is the most persistent fraction of organic matter in soil and the largest fraction in most soils. The ability of a soil to stabilise carbon in the form of MAOM is strongly correlated with soil specific surface area (A_s). The carbon stabilisation capacity of a soil and its carbon saturation deficit can be estimated from simple measurements of soil physical properties and use to determine its sequestration potential.
- This report calculated the potential benefits, in terms of soil carbon, of using New Zealand's organic wastes as soil conditioners instead of disposing of them to landfill.

- In most cases, repeated application of organic amendments would result in an increase in soil carbon stocks, but these may not be converted into persistent MAOM. So, the increases in stock may decrease over time unless repeated application is used to sustain higher stocks.
- Organic amendments may result in a trade-off effects of increased nitrous oxide (N_2O) emissions from soil.
- Organic amendments may contain physical, chemical, or biological contaminants which may pose threats to agricultural production, or environmental and human health.
- Organic amendments present a feasible route to improve soil quality, but appropriateness may vary across both site and amendment.

Introduction

New Zealand's biological wastes contain organic carbon and critical plant nutrients such as nitrogen (N) and phosphorus (P). However, they may also contain chemical, or biological contaminants. Often the economic value of nutrients are wasted if the raw materials are incinerated or disposed of into landfill. A common barrier to more productive use of these materials is a mismatch between the chemical and biological properties of the waste material to provide benefits to agricultural systems to which they could be applied.

Soil organic matter (SOM) and its carbon component (SOC) influence soil properties both physicochemically and biologically. SOM and SOC have high cation exchange capacities (CEC) per unit mass. CEC represents a soil's capacity to retain positively charged cations, including important nutrients such as magnesium (Mg^{2+}), calcium (Ca^{2+}) and potassium (K^{+}). In addition to binding cations, the density of reactive sites on SOM allows the binding of chemical species, both benign and harmful. This can reduce the bioavailability of chemical contaminants[1]. Soil carbon affects the physical structure of soil primarily the amount of carbon adsorbed with minerals to form aggregates. Improvements in aggregation and soil structure are associated with many co-benefits, including reduced erosion, increased pore space providing greater aeration, improved water holding capacity and water permeability, and improved root growth[2]. SOC influences the microbiota that perform essential functions within soil by providing the nutrients needed for growth, and soil fauna biomass[3]. As a result of these influences, SOC is critically important for resilient agricultural systems.

Since 2000, there has been increased focus on the importance of SOC stocks, not just for agricultural reasons but for management of the global climate, such as the "4 per 1000" Initiative introduced at the CoP 21 meeting, as part of the Lima-Paris Plan of Action by the United Nations Framework Convention on Climate Change[3]. Application of biological wastes to soil is a potential component of management strategies; a report by the Composting &

Anaerobic Digestion Association of Ireland claims the composting and soil application of Ireland's household and commercial wastes would produce an emission reduction equivalent to removing 44,000 cars from the roads[4]. In light of these claims, this report aims to determine the potential for New Zealand's biological wastes to increase soil carbon stocks and challenges associated with application of biological wastes to soil.

Organic wastes and their use as amendments

Organic waste comprises any biodegradable material that originates from living or recently living organisms. Organic wastes are varied in nature, ranging from food wastes and crop residues to human wastes. Most wastes are associated with either primary production, processing, or consumption. Depending on the waste stream, organic wastes differ in consistency of composition and volume. For example, grape marc is largely homogenous but only produced during a short period during the year. It is estimated New Zealand's organic wastes from processing seafood[5], wine grapes[6], milk products[7], livestock[8, 9], chicken[5], grains[10], and vegetables[11] to amounts to 2.1 Mt annually. Given the scale of production, diversion of organic waste from landfill will be necessary to achieve New Zealand's current goals of reducing biogenic methane emission, and disposal of waste per capita by 30% by 2030[12, 13].

A soil amendment (or soil conditioner) is applied to soil in order to improve its physical characteristics such as bulk density and water holding capacity. Organic amendments are amendments of biological origin, primarily from plants or animals. Soil amendments differ from fertilisers, which aim to provide nutrients for crop uptake[14]. However, due to their complex nature, organic amendments can act as alternative sources of nutrients. In general, organic materials with a significant dry matter fraction such as composts or solid digestate, influence physical characteristics more than primarily liquid organics such as dairy slurry. These tend to be richer in nutrients, acting more like fertilisers[15]. For the purpose of this report the term organic amendment will broadly refer to materials of organic origin applied to soils. In New Zealand, organic wastes are primarily used as amendments in one of two forms. Wastes may be applied raw (i.e. unprocessed), which is referred to as green spreading. However, m any wastes are processed prior to use as amendments, which is by far the most common method for compost addition.

Composting

Composting involves the degradation of organic wastes by microorganisms in aerobic conditions. This presents a range of advantages:

- The mass of waste is significantly reduced
- Undesirable biological components such as weed seeds are often neutralised by the increased temperature of the process

- There is no risk of the underlying soil becoming anaerobic due to the high biological oxygen demand of undecomposed organic matter.
- If conducted correctly, the product is biologically stable (displays resistance to further aerobic decomposition)[16, 17]

The biological stability of the compost is desirable as application to soil is less likely to deplete resources such as oxygen within the soil, which are consumed when breaking down organic matter.

However, composting processes can lead to several major disadvantages:

- Composition is inconsistent, making nutrient loadings unpredictable
- Undesirable biological components are not always neutralised, presenting a potential source of pathogens and weed seeds
- If not properly finished composts are biologically unstable, which may induce anaerobic conditions in soil
- Composts may contain a range of contaminants such as plastics, pesticides, and heavy metals
- Due to low nutrient content per unit mass, composts are more expensive to transport and apply than the equivalent mass of mineral fertiliser
- Relatively low commercial value
- The composting process can result in significant non-greenhouse gas emissions, including unpleasant odours.

The potential of composts to contaminate soils or induce anaerobicity make composts a risky choice compared to the use of conventional fertilisers, and the lower, inconsistent nutrient value of composts combined with higher transport costs means the benefits may be considered insufficient to offset the risk[18]. Depending on origin, many of the same disadvantages can apply to green spread waste, with a much greater tendency towards anaerobicity due to biological instability.

While most of the above disadvantages are associated with consumption of compost, gaseous emissions are mainly a result of production. Composting results in the emission of ammonia (NH_3) as microorganisms dispose of excess nitrogen in the raw material. Ammonia is a significant atmospheric pollutant; not only is it itself toxic, it acts as a precursor to fine particulate matter ($PM_{2.5}$), which has serious impacts on human health. As a result of ammonia emissions, a Californian life-cycle analysis found composting had a higher social cost than the use of landfill using two different public health cost tools[12]. This highlights the significance of non-greenhouse gas pollutants emitted during composting.

The potential to increase soil organic carbon stocks in New Zealand

The addition of organic material to soil will not necessarily result in accumulation of SOC For any accumulation to occur, two things are necessary: amendments must be converted into stabilised forms of SOC that are resistant to microbial degradation.

SOC components

Soil organic matter (SOC) comprises the carbon content of all organic, non-carbonate carbon compounds. SOC is extremely heterogenous, but can be conceptually divided into two broad categories. Mineral associated organic carbon (MAOC) is the more critical as it is both the larger proportion and the more persistent fraction, and will be the focus of this report. MAOC is adsorbed to the surfaces of soil minerals and typically consists of simple, low molecular weight chemicals[19, 20]. Because organic matter is adsorbed onto the fine fraction of the soil, the term fine fraction OC is often used to describe MAOC. The other category, particulate organic carbon (POC) is unbound to soil minerals, and typically comprises larger and more complex compounds that are less degraded and more closely resemble the material from carbon inputs. A third category, dissolved organic carbon (DOC) is much less significant per unit mass than the other components but is important for the formation of MAOC.

Formation of SOC from soil conditioners

Organic amendments such as compost are a supplementary source of organic matter applied either to the soil surface or incorporated into the soil. Due to the complexity of the soil and climatic conditions and variability in microbiota, formation of SOC from these amendments does not occur by a single mechanism. There are, however, different mechanisms that are considered to dominate the formation of POC and MAOC. POC is primarily formed by the physical degradation of structural matter such as fibrous polymers. As such, POC primarily resembles its parent material chemically. MAOC formation, however, is dominated by inputs from DOC and products of microbial processing. The DOC pathway involves leaching of soluble organic molecules from parent materials derived from amendments applied to the soil surface. These soluble molecules are exposed to mineral surfaces as they descend through the soil profile, allowing the formation of mineral association. Alternatively, large complex residues such as those from amendments that have been incorporated into the soil can be processed by soil microorganisms into smaller, simpler molecules. These then associate in the same manner as DOC. These pathways are also known as abiotic and biotic routes[21]. The biotic pathway is strongly influenced by the C:N (carbon to nitrogen) ratio of the amendment. The C:N ratio of amendments is critical to match the needs of soil microorganisms. While the C:N ratio or microorganism is typically about 8, the organisms prefer substrates with C:N ratios between 25 and 35 to service their metabolic requirements. If there is insufficient N available, the microbial processing that converts amendments into stable SOC is inhibited, limiting its formation[22].

The persistence of SOC formed via soil conditioners

The pool of SOC is dependent on the balance between carbon inputs and outputs. The primary loss is mineralisation via microbial respiration. During this process organic carbon is oxidised to carbon dioxide (CO_2) which is then emitted by the soil to the atmosphere. The climate influences this microbial activity through temperature and moisture levels. In addition, organic matter can be lost via soil erosion, or may be leached from the soil as DOC[23].

This can be considered through the *inhibition limitation and constraint* model, which partitions conditions affecting SOC persistence into three states. Firstly, when microbes are completely inhibited from breaking down OC, such as in frozen or anoxic soils. Secondly, when microbes are limited in the rate they can decompose available OC, and thirdly, when microbial access to OC is constrained, for instance by mineral association or occlusion in aggregates. Soil aggregates can be described in terms of a hierarchy above POC and MAOC, as they comprise both forms[24]. SOC is critical to bind soil aggregates, which in turn provide physical protection to organic matter by occluding it. However, organic matter occluded within aggregates is vulnerable to physical disturbance such as tilling, which disrupts aggregates, exposing them to degradation. As this report focuses on MAOC, microbial access constraint is the primary process discussed, with the exception of the priming effect, a form of limitation discussed below.

The mineralogy factors that can be used to predict the concentration of organic carbon in soil can be used to approximate the stabilisation capacity[*] of a soil and its saturation deficit[†]. Although bulk clay content was considered to be a primary contributor, a broader set of factors can give a more refined prediction, including both the specific surface area (A_s) and its mineral composition[25].

The capacity of the MAOC fraction is correlated with the A_s, as it reflects the area of active surfaces that bind organic matter. A strong influence on the A_s of a soil is the nature of its fine fraction. In general, the greater the fine fraction, the higher the A_s. However, in finer soil fractions there is significant A_s variability associated with other properties that can cause a high clay or silt content not to lead to a high MAOC content. MAOC is considered to be related to A_s by a *monolayer equivalent*[‡]. This reflects that when organic matter does not form perfectly homogenous monolayers on mineral surfaces, with inconsistent thickness and competition with inorganic compounds[26], the loading rate almost never exceeds the value expected of an ideal monolayer[§].

[*] Stabilisation capacity is how much carbon it can stabilise by mineral association.

[†] Saturation deficit is the difference between its stabilisation capacity and current concentration.

[‡] Define monolayer equivalent

[§] 1 mg C m^{-2} is the loading expected of an ideal monolayer.

As MAOC formed on the fine fraction constitutes the majority proportion (86-89%) of SOC in soils under a variety of land uses[27], A_s is a strong indicator of the soil's carbon stabilisation capacity. The silicates that form the majority of clay minerals can be classified as 1:1 or 2:1, depending on their layer structure. 1:1 minerals such as kaolinite have comparatively low values of A_s, whereas 2:1 minerals, such as vermiculite, have much higher values of A_s and CEC. This means that soils with the same fraction of clay may have significantly different surface areas contributing to the sorption of organic matter.

Under differing conditions, factors such as cation content can be important in predicting the SOC content. In drier regions, soils tend to have higher than average alkalinity with a prevalence of exchangeable basic cations such as Mg^{2+} or Ca^{2+}, the most abundant and strongest binding. Divalent cations such as Ca^{2+} can associate strongly with both the negatively charged soil surfaces and the many negative functional groups found in organic matter, forming 'cation bridges' to bind the two together. Due to this role in organic matter association, exchangeable calcium content can be a stronger predictor of SOC than clay content in areas with low precipitation[25].

The concentration of extractable iron (Fe^{3+}) and aluminium (Al^{3+}) in a soil is also a significant factor. The organic compounds that bind to these metals are typically more aromatic, with a higher concentration of carbonyl groups than average for organic compounds found in the soil[28, 29]. High concentrations of Fe and Al from mineral weathering promotes the formation of short range order (SRO) phases. These phases are dense in hydroxyl groups which readily stabilise organic matter[25]. Inner-sphere complexation of Fe and Al is thought to be an important stabilisation mechanism[29], and cation-pi interactions may explain the preference for aromatic compounds at the mineral surface[30].

SOC provides the carbon required by soil microorganisms for growth and reproduction. The fraction of SOC that is readily available for microbial consumption is sometimes referred to as labile carbon[31]. Organic amendments all contain some proportion of carbon that will be labile when applied to soil. On application, this availability of labile carbon stimulates microbial activity. In some cases, this increased activity can facilitate the microbial degradation of comparatively stable SOC already present in the soil. Alternatively, it may divert microorganisms consuming existing stable carbon to the more readily consumable labile fraction, thereby protecting the existing fraction. Due to these competing effects, alongside a suite of additional factors, the short term effect on turnover of native SOC from the addition of organic amendments, known as the 'priming effect', may be positive or negative. While the direction and magnitude of the priming effect is difficult to predict, existing SOC content, the degree of wetness, and the salinity of the soil are all associated with more negative priming effects[32].

New Zealand specific case study

New Zealand researchers[33] have developed a best fit quantile regression model to assess the soil carbon sequestration potential of New Zealand soils under permanent pasture and continuous cropping. This model predicts the concentration of fine-fraction carbon based on the A_s and pyrophosphate-extractable Al concentrations. Additionally the model includes factors that provide a better fit for allophanic soils that are found predominantly in volcanic regions of the North Island. By taking the 90th quantiles of the model as stabilisation capacities and the median values as current concentrations, saturation deficits were determined for different soil orders under both pasture and cropping. Deficit and land area combined contribute to a soil order's sequestration potential, e.g. melanic soils had the greatest mean C saturation deficit of all soils tested, but comprised the second lowest land area nationally. New Zealand contains a range of soil orders, but the largest areas are the Brown, Pallic, and Recent soils with mean C saturation deficiencies of 12, 13, and 14 mg C g^{-1} soil respectively[33].

Generally, SOC stocks can be increased through the application of organic amendments. While the efficacy of amendment application depends on a wide array of variables, especially soil type, climate, management, and type of amendment, SOC stocks can usually be expected to increase with repeated application of appropriate loadings.

However, in experiments attempting to increase the carbon content of soils using compost applications, an initial rapid increase is often observed, which gradually slows until continued application produces little or no further increases in carbon concentration. The carbon stock when this asymptote is reached depends on the aforementioned factors influencing stability and persistence. While this means the asymptotic value may be influenced by changes in management, such as altering tillage practices, limitations on potential stability are still dominated by the mineralogy of the soil[34]. In addition to having practical upper limits, SOC increases from amendment application can be dependent on continual application, with the potential for levels to decrease when application ceases[35]

Potential trade-off effects

Nitrous oxide emission

While there is significant interest globally in the capacity for soils to sequester carbon to mitigate climate change, it is important to recognise that use of organic amendments may influence existing emissions of greenhouse gases, including N_2O. N_2O is a very powerful greenhouse gas, with a global warming potential 298 greater than that for CO_2, and it also depletes stratospheric ozone. N_2O can be produced in soils by multiple pathways, by the processes of nitrification (conversion of ammonium to nitrate) and denitrification (conversion of nitrate to nitrogen gas)[36].

Unlike application of synthetic fertilisers, where N_2O emissions can be well predicted from nitrogen application rates, organic amendments have complex influences on N_2O emissions[37]. For example, mineralisation and nitrification of nitrogen from organic amendments will be a source of N_2O. On the other hand, increased C inputs due to organic amendment promotes microbial growth, increasing the competition for existing ammonium and limiting its availability to nitrifying microorganisms, thus reducing N_2O emissions[37]. Generally, C:N ratios are negatively correlated with N_2O emissions[38]. Thus, there is a risk that attempts to offset carbon emissions by increasing soil carbon via organic amendments may result in increased N_2O emissions. If scaled by widespread application, this could offset any positive effects of increasing carbo stocks because of the higher global warming potential for N_2O.

Contamination from organic amendments

Unlike agrochemicals, which are often synthetic in origin with tightly controlled levels of contaminants, organic amendments are derived from highly varied origins which may increase the risks to contamination.

These contaminants can be broadly be divided into:

- biological contaminants (pathogens, weed seeds etc)
- chemical contaminants (heavy metals, xenobiotics etc)
- physical (plastics, glass etc) contaminants

These contaminants may be damaging to the environment, agricultural production, and human health.

Biological contamination

Biological contaminants are typically pathogens, which can include viruses, bacteria, helminths, and protozoa. Biosolids and animal manures are both major sources of enteric pathogens which can pose a threat to both livestock and humans. *Escherichia coli, Listeria monocytogenes, Campylobacter jejuni* and *coli, Clostridia, Cryptosporidium parvum,* and *Giardia lamblia* are widespread in the manures of various livestock species. The oral route of contamination is most common, which can even occur directly from soil. For example, prions can adsorb to soil minerals in a similar manner to other organic matter, retaining infectivity. The use of organic amendments containing such pathogens can contribute to their spread. If amendments originate offsite this may result in spread between herds. Pathogens can greatly impact stock health and can cause fatalities.

Contaminated food products, such as those containing *Salmonella* can transmit diseases to humans. Similarly, pollution of water resources can lead to another way of transmission. Whilst it was likely not deliberately applied as an amendment, sheep faeces was considered to be the likely origin of the 2016 *Campylobacteriosis* outbreak in Havelock North[39].

Plant-derived organic wastes, if sourced from infected areas, can be infested with plant pathogens, such as *Armillaria mellea* or members of the destructive *Phytophthora* genus responsible for potato blight and Kauri dieback[40]. While untreated wastes may act as a potential source, composting when performed correctly is a viable option for reducing pathogen risk, primarily through the heat released. Composts can be in fact an effective tool in suppression of certain plant diseases, potentially through changes in microbial community structure[41].

Weed species are a significant cost to agricultural systems through lost production and management costs. Grass weeds make up the majority of species whose seeds are commonly found in organic amendments. Contamination can be present from the origin, such as seeds ingested by livestock then found in manure, or can occur afterwards, such as stored wastes colonised by wind-dispersed seeds. A study comparing the relative contamination of amendments found urban and green waste to be the least contaminated, the worst being composted farmyard manure and cattle slurry, with fresh manure tending to be less contaminated[42].

Chemical contamination

Elevated levels of trace elements in soils can pose a serious threat to agricultural production and human health. Although trace elements may be present in various forms with differing mobility and bioavailability, unlike some more complex organic pollutants, trace elements do not biodegrade. This presents a significant challenge for remediation, where immobilisation may be feasible but not removal. Currently New Zealand faces issues associated with the accumulation of cadmium (Cd) from application of superphosphate. The offal of New Zealand livestock over 2.5 years of age can no longer be sold for human consumption due to accumulation of Cd[43].

Trace elements can be associated with organic amendments through a variety of sources. Municipal sewage sludges tend to be enriched in trace elements, not from human excrement or food wastes, but from stormwater or industrial effluents. This results in a highly diverse range of contaminants, which may lead to a variety of environmental risks associated with mobility, toxicity, and bioavailability[44]. Elements commonly found in higher concentrations include Cd, chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), and zinc (Zn). Multiple years of sludge application to soils have been shown to result in decreases in crop yield due to the phytotoxicity of these elements at elevated concentrations, an effect that persisted after application ceased[45]. Composts produced from urban wastes can also be subject to similar sources of contamination, and may suffer from inadequate separation of organic and non-organic source materials.

Trace elements are often used to supplement animal feeds. As trace elements in appropriate concentrations are necessary for many biological functions, this can provide a range of benefits, including disease control and increased animal weight gains. The use of trace elements varies depending on species and local feed deficiencies. Due to limitations in absorption and potentially excessive dosages, animal manures can be enriched in such elements and this can lead to increased inputs to soils[46].

Xenobiotics[**] can include compounds used in the production or processing of organic products, or contaminants introduced from non-organic sources such as in municipal sewage sludge. While these are too diverse to comprehensively cover, key examples include antibiotics and persistent organic pollutants. Antibiotics are very commonly used in animal systems both to reduce disease and as prophylactics and, as with trace elements, significant proportions of the administered doses ultimately reside in manures.

Organic amendments containing antibiotics or antibacterial compounds present a potential hazard when applied to soil due to the development of antibiotic resistance[47]. Organic amendments (primarily biosolids and wastewater) may contain organic pollutants, including persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs)[48]. While all organic pollutants are of concern, POPs are generally very resistant to degradation, bioaccumulate, and are toxic to both wildlife and humans[49].

Physical contaminants

Glass, metal, and plastics are the primarily physical contaminants found in organic amendments. While physical contamination may occur from any source, it is often pronounced in composts from municipal organic materials. It is a common public concern with the use of composts, and standards vary globally. Although concerns are usually associated with contaminants entering the food chain, the physical characteristics of soil can be altered as well, for instance the blocking of pores by inert materials[50]. Microplastics[††] are an emerging contamination issue for organic amendments, especially biosolids. Soil microplastics have been found to alter the composition of subterranean fauna and reduce their overall abundance [52]. Microplastics are capable of both leaching contaminants used in their production such as phthalates, and adsorbing other contaminants on their surfaces.

[**] referring to synthetic compounds foreign to biological systems

[††] Microplastics are particles smaller than 5 mm, and originate primarily from the disintegration of plastic products such as packaging and synthetic clothing (51) Laminzana, B. *Plastic planet: How tiny plastic particles are polluting our soil*. UN Environment Programme, 2021. https://www.unep.org/news-and-stories/story/plastic-planet-how-tiny-plastic-particles-are-polluting-our-soil (accessed 2023 31-03-2023)..

Conclusion

New Zealand soils provide the opportunity to sequester up to a theoretical maximum of 124 Mt of carbon[33]. Continuous application of organic amendments is a feasible option for increasing carbon stocks within the stabilisation limits set by soil mineralogy. This will likely result in reduced returns over time and may require continued application to maintain attained levels. There are additionally potential issues regarding increased soil N_2O emissions and physical, chemical, or biological contamination of soils in response to organic amendment application.

Appendix – Current and emerging management practices

There is currently a diverse range of organic waste management practices used in New Zealand. These include both centralised and decentralised practices.

Landfilling

Landfilling is a method commonly used for general public waste and that from commercial operations, involving the burial of wastes in specially engineered sites. While this is primarily intended for non-organic wastes, landfills usually contain a large organic fraction. This is undesirable for multiple reasons:

- It consumes finite landfill space
- It is a waste of the valuable nutrients contained with the organic material
- It results in harmful greenhouse gas emissions

Although modern landfills capture gas emissions, rogue emissions are inevitable. This is problematic as although landfills emit carbon dioxide (CO_2), the anaerobic conditions favour the formation of methane (CH_4), which has a global warming potential 28 times that of CO_2. Nitrous oxide (N_2O), which has a global warming potential 273 times greater than CO_2, is also emitted. As a result, landfilling is considered to result in the highest emissions of greenhouse gases from organic waste disposal, with emissions of almost 400 kg CO_2 per tonne of organic waste[12].

Stubble Burning

Stubble burning uses controlled combustion to remove stubble and other crop residues after grain harvesting, with the additional purposes of disease and pest control. This occurs primarily in Canterbury due to its concentration of arable farming. Nationally, approximately 425,000 tonnes of residues were burnt in 2012[53]. Stubble burning has been criticised internationally for its contribution to air pollution through producing gaseous contaminants such as nitrogen oxides, sulphur oxides, and carbon monoxide. In addition, combustion produces considerable CO_2 emissions and particulate matter, including black and brown carbon, which contribute to both air pollution and radiative forcing[54]. While there is debate over whether stubble burning negatively impacts soil organic carbon (SOC), it is consistently shown to be less influential than tilling[55]. This is of consequence as most alternatives to stubble burning require some degree of tillage. Additionally, stubble burning may alter the quality of SOC as it reduces inputs of fresh organic matter (OM) but increases inputs of black carbon[56].

Anaerobic digestion

Anaerobic digestion (AD) involves the breakdown of organic matter via bacteria and archaea under anaerobic conditions. While this is technically the same process that organics undergo when sent to landfill, anaerobic digestion usually refers to the process occurring in a purpose-built bioreactor, with the intent to treat waste or produce biogas. The majority of biogas is CH_4 with a large CO_2 fraction and trace gasses making up the rest. Biogas can either be used to produce onsite electricity or combined heat and power (CHP), or purified into biomethane which is suitable for injection into existing gas networks[57].

Anaerobic digestion is widely utilised internationally, and particularly in European countries that have provided incentives, it is an established process for waste and energy systems. In some cases, such as Germany, the emphasis has arguably moved from waste management to energy generation. This is reflected in the fact that in 2015, 10.7% of Germany's arable land was used to produce feedstock crops for biogas[57].

In the past, New Zealand has operated anaerobic digestion plants specifically for the production of gas to augment its natural gas reserves; this, however, was driven by the oil crises of the 1970s and was relatively small-scale. Existing anaerobic digestion facilities in New Zealand are primarily waste treatment facilities rather than biogas producers. These include municipal wastewater treatment plants (WWTPs) and effluent treatment at industrial facilities, such as Fonterra's Tirau plant. Biogas produced by these facilities usually contributes to providing the energy requirements for the treatment or other onsite activities. New Zealand has one biogas focused operation, the newly opened Ecogas Reporoa Organics Processing Facility. When fully operational, this facility is expected to process 75,000 tonnes of organic waste annually, including kerbside organic wastes sorted offsite[58]. Energy and carbon dioxide produced by the facility is planned to be utilised by the nearby T&G tomato glasshouse.

Anaerobic digestion is feasible for most organic wastes, but is not suitable for wastes with high lignin content (e.g. wood waste) due to its chemical recalcitrance, especially to breakdown by most anaerobic microorganisms. Digesters are typically designed to process a specific waste or type of wastes based on the solid fraction of the waste: high solids digesters can be either wet or dry with the later producing slurry, while low solids digesters are always wet[59]. The different systems possess advantages and disadvantages; for instance, dry digesters do not produce a pumpable product but are much more resilient to physical contamination. In addition, to physical contaminants such as plastics, anaerobic digestion can be inhibited by chemical components such as ammonia and metals.

Aside from biogas, the main product of anaerobic digestion is *digestate*, the matter remaining after processing. There are two kinds of digestate, named for the processing stage in which they occur. Acidogenic digestate is a solid comprised of fibrous plant material such as lignin and cellulose, whereas methanogenic digestate is a liquid high in nutrients, especially ammonia[60]. Depending on the design of the bioreactor these may be produced separately or as a whole product (which is often then separated), which resembles livestock slurry in appearance and pumpability[61]. Whole or liquor digestate is commonly applied as a fertiliser by injection or trailing-shoe methods in countries where AD is common[62]. The solid fraction however typically requires further processing such as drying and composting before it can be utilised as an organic amendment. This is due to its high moisture content that makes transport and storage difficult, and because it is biologically unstable in aerobic environments[63].

While AD can produce valuable biogas, manage a range of organic materials, reduces residue odours, it is expensive when compared to composting, and requires a continuous supply of organic material to operate efficiently[64]. Additionally, the digestate (the solid fraction especially) may be of agronomic value, but often requires further treatment and may become a disposal issue in its own right.

References

(1) Kwiatkowska-Malina, J. Functions of organic matter in polluted soils: The effect of organic amendments on phytoavailability of heavy metals. *Applied Soil Ecology* **2018**, *123*, 542-545. DOI: https://doi.org/10.1016/j.apsoil.2017.06.021.
(2) Lin, Y.; Ye, G.; Kuzyakov, Y.; Liu, D.; Fan, J.; Ding, W. Long-term manure application increases soil organic matter and aggregation, and alters microbial community structure and keystone taxa. *Soil Biology and Biochemistry* **2019**, *134*, 187-196. DOI: https://doi.org/10.1016/j.soilbio.2019.03.030.
(3) Rice, C. W.; Fabrizzi, K.; White, P. *Soil Carbon Management, Economic, Environmental and Societal Benefits: Benefits of Soil Organic Carbon to Physical, Chemical, and Biological Properties of Soil*; CRC Press, 2007.
(4) Foster, P. *Ireland has potential to avoid emissions from 44,000 cars by using compost to store carbon in soils*. Composting & Anaerobic Digestion Association of Ireland, 2021. http://www.cre.ie/web/members-news/ireland-had-potential-to-avoid-emissions-from-44000-cars-by-using-compost-to-store-carbon-in-soils/ (accessed 2023 31-03-2023).
(5) Jayathilakan, K.; Sultana, K.; Radhakrishna, K.; Bawa, A. S. Utilization of byproducts and waste materials from meat, poultry and fish processing industries: a review. *J Food Sci Technol* **2012**, *49* (3), 278-293. DOI: 10.1007/s13197-011-0290-7 From NLM.
(6) Fresh Fruit Portal. *NZ horticultural export value grows to NZ$5.5B*. FreshFruitPortal, 2019. https://www.freshfruitportal.com/news/2019/05/27/nz-horticultural-export-value-grows-to-nz5-5b/ (accessed 2023 05-04-2023).
(7) Compassion in World Farming. *Standard Intensive Milk Production*. Compassion in World Farming, https://www.compassioninfoodbusiness.com/awards/good-dairy-award/standard-intensive-milk-production/ (accessed 2023 05-04-2023).
(8) Beef + Lamb New Zealand. *NZ red meat exports top $6.7 billion in 2017-18*. Beef + Lamb New Zealand, 2018. https://beeflambnz.com/news-views/nz-red-meat-exports-top-67-billion-2017-18 (accessed 2023 05-04-2023).
(9) Hall, R. *New Zealand Deer Production Trends*; Global Agricultural Information Network, 2023. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=New%20Zealand%20Deer%20Production%20and%20Trends_Wellington_New%20Zealand_NZ2022-0019.pdf (accessed 04-05-2023).
(10) StatsNZ. *Agricultural production statistics: June 2019 (provisional)*. StatsNZ Tatauranga Aotearoa, 2019. https://www.stats.govt.nz/information-releases/agricultural-production-statistics-june-2019-provisional/ (accessed 2023 05-04-2023).
(11) Horticulture New Zealand. *New Zealand domestic vegetable production: the growing story*; Horticulture New Zealand, 2017. https://www.hortnz.co.nz/assets/Environment/National-Env-Policy/JR-Reference-Documents-/KPMG-2017-NZ-domestic-vegeable-production-.pdf (accessed 05-04-2023).
(12) Nordahl, S. L.; Devkota, J. P.; Amirebrahimi, J.; Smith, S. J.; Breunig, H. M.; Preble, C. V.; Satchwell, A. J.; Jin, L.; Brown, N. J.; Kirchstetter, T. W.; et al. Life-Cycle Greenhouse Gas Emissions and Human Health Trade-Offs of Organic Waste Management Strategies. *Environmental Science & Technology* **2020**, *54* (15), 9200-9209. DOI: 10.1021/acs.est.0c00364.

(13) Ministry for the Environment. Te rautaki para Waste Strategy: Getting rid of waste for a circular Aotearoa New Zealand. Taiao, M. f. t. E. M. M. T., Ed.; New Zealand Government: 2023.
(14) Pennington. *WHY AND HOW TO USE SOIL AMENDMENTS*. https://www.pennington.com/all-products/fertilizer/resources/the-gardeners-guide-to-soil-amendments (accessed 2023 31-03-2023).
(15) Bioenergy Association. *The Production and Use As Biofertiliser of Digestate Derived from Source Segregated Organic Waste*; 2021. https://www.biogas.org.nz/documents/resource/TG08-Production-and-use-of-digestate-as-fertiliser.pdf.
(16) Baffi, C.; Dell'Abate, M. T.; Nassisi, A.; Silva, S.; Benedetti, A.; Genevini, P. L.; Adani, F. Determination of biological stability in compost: A comparison of methodologies. *Soil Biology and Biochemistry* **2007**, *39* (6), 1284-1293. DOI: https://doi.org/10.1016/j.soilbio.2006.12.004.
(17) Breitenbeck, G. A.; Schellinger, D. Calculating the Reduction in Material Mass And Volume during Composting. *Compost Science & Utilization* **2004**, *12* (4), 365-371. DOI: 10.1080/1065657X.2004.10702206.
(18) Sikora, L. J. Benefits and Drawbacks to Composting Organic By-Products. In *Beneficial Co-Utilization of Agricultural, Municipal and Industrial by-Products*, Brown, S., Angle, J. S., Jacobs, L. Eds.; Springer Netherlands, 1998; pp 69-77.
(19) Jilling, A.; Kane, D.; Williams, A.; Yannarell, A. C.; Davis, A.; Jordan, N. R.; Koide, R. T.; Mortensen, D. A.; Smith, R. G.; Snapp, S. S.; et al. Rapid and distinct responses of particulate and mineral-associated organic nitrogen to conservation tillage and cover crops. *Geoderma* **2020**, *359*, 114001. DOI: https://doi.org/10.1016/j.geoderma.2019.114001.
(20) Emde, D.; Hannam, K. D.; Midwood, A. J.; Jones, M. D. Estimating Mineral-Associated Organic Carbon Deficits in Soils of the Okanagan Valley: A Regional Study With Broader Implications. *Frontiers in Soil Science* **2022**, *2*, Original Research. DOI: 10.3389/fsoil.2022.812249.
(21) Lavallee, J. M.; Soong, J. L.; Cotrufo, M. F. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology* **2020**, *26* (1), 261-273, https://doi.org/10.1111/gcb.14859. DOI: https://doi.org/10.1111/gcb.14859 (acccessed 2023/03/30).
(22) Sayer, E. J.; Baxendale, C.; Birkett, A. J.; Bréchet, L. M.; Castro, B.; Kerdraon-Byrne, D.; Lopez-Sangil, L.; Rodtassana, C. Altered litter inputs modify carbon and nitrogen storage in soil organic matter in a lowland tropical forest. *Biogeochemistry* **2021**, *156* (1), 115-130. DOI: 10.1007/s10533-020-00747-7.
(23) Alvarez-Cobelas, M.; Angeler, D. G.; Sánchez-Carrillo, S.; Almendros, G. A worldwide view of organic carbon export from catchments. *Biogeochemistry* **2012**, *107* (1), 275-293. DOI: 10.1007/s10533-010-9553-z.
(24) Cotrufo, M. F.; Ranalli, M. G.; Haddix, M. L.; Six, J.; Lugato, E. Soil carbon storage informed by particulate and mineral-associated organic matter. *Nature Geoscience* **2019**, *12* (12), 989-994. DOI: 10.1038/s41561-019-0484-6.
(25) Rasmussen, C.; Heckman, K.; Wieder, W. R.; Keiluweit, M.; Lawrence, C. R.; Berhe, A. A.; Blankinship, J. C.; Crow, S. E.; Druhan, J. L.; Hicks Pries, C. E.; et al. Beyond clay: towards an

improved set of variables for predicting soil organic matter content. *Biogeochemistry* **2018**, *137* (3), 297-306. DOI: 10.1007/s10533-018-0424-3.
(26) Mayer, L. M.; Xing, B. Organic Matter–Surface Area Relationships in Acid Soils. *Soil Science Society of America Journal* **2001**, *65* (1), 250-258, https://doi.org/10.2136/sssaj2001.651250x. DOI: https://doi.org/10.2136/sssaj2001.651250x (acccessed 2023/03/30).
(27) Gregorich, E. G.; Beare, M. H.; McKim, U. F.; Skjemstad, J. O. Chemical and Biological Characteristics of Physically Uncomplexed Organic Matter. *Soil Science Society of America Journal* **2006**, *70* (3), 975-985, https://doi.org/10.2136/sssaj2005.0116. DOI: https://doi.org/10.2136/sssaj2005.0116 (acccessed 2023/03/30).
(28) Zhao, Q.; Poulson, S. R.; Obrist, D.; Sumaila, S.; Dynes, J. J.; McBeth, J. M.; Yang, Y. Iron-bound organic carbon in forest soils: quantification and characterization. *Biogeosciences* **2016**, *13* (16), 4777-4788. DOI: 10.5194/bg-13-4777-2016.
(29) Kramer, M. G.; Sanderman, J.; Chadwick, O. A.; Chorover, J.; Vitousek, P. M. Long-term carbon storage through retention of dissolved aromatic acids by reactive particles in soil. *Global Change Biology* **2012**, *18* (8), 2594-2605, https://doi.org/10.1111/j.1365-2486.2012.02681.x. DOI: https://doi.org/10.1111/j.1365-2486.2012.02681.x (acccessed 2023/03/30).
(30) Keiluweit, M.; Kleber, M. Molecular-Level Interactions in Soils and Sediments: The Role of Aromatic π-Systems. *Environmental Science & Technology* **2009**, *43* (10), 3421-3429. DOI: 10.1021/es8033044.
(31) Bongiorno, G.; Bünemann, E. K.; Oguejiofor, C. U.; Meier, J.; Gort, G.; Comans, R.; Mäder, P.; Brussaard, L.; de Goede, R. Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. *Ecological Indicators* **2019**, *99*, 38-50. DOI: https://doi.org/10.1016/j.ecolind.2018.12.008.
(32) Bastida, F.; García, C.; Fierer, N.; Eldridge, D. J.; Bowker, M. A.; Abades, S.; Alfaro, F. D.; Asefaw Berhe, A.; Cutler, N. A.; Gallardo, A.; et al. Global ecological predictors of the soil priming effect. *Nature Communications* **2019**, *10* (1), 3481. DOI: 10.1038/s41467-019-11472-7.
(33) McNally, S. R.; Beare, M. H.; Curtin, D.; Meenken, E. D.; Kelliher, F. M.; Calvelo Pereira, R.; Shen, Q.; Baldock, J. Soil carbon sequestration potential of permanent pasture and continuous cropping soils in New Zealand. *Global Change Biology* **2017**, *23* (11), 4544-4555, https://doi.org/10.1111/gcb.13720. DOI: https://doi.org/10.1111/gcb.13720 (acccessed 2023/03/30).
(34) Powlson, D. S.; Bhogal, A.; Chambers, B. J.; Coleman, K.; Macdonald, A. J.; Goulding, K. W. T.; Whitmore, A. P. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: A case study. *Agriculture, Ecosystems & Environment* **2012**, *146* (1), 23-33. DOI: https://doi.org/10.1016/j.agee.2011.10.004.
(35) Clark, M. S.; Horwath, W. R.; Shennan, C.; Scow, K. M. Changes in Soil Chemical Properties Resulting from Organic and Low-Input Farming Practices. *Agronomy Journal* **1998**, *90* (5), 662-671, https://doi.org/10.2134/agronj1998.00021962009000050016x. DOI: https://doi.org/10.2134/agronj1998.00021962009000050016x (acccessed 2023/03/30).

(36) Liu, R.; Hu, H.; Suter, H.; Hayden, H. L.; He, J.; Mele, P.; Chen, D. Nitrification Is a Primary Driver of Nitrous Oxide Production in Laboratory Microcosms from Different Land-Use Soils. *Frontiers in Microbiology* **2016**, *7*, Original Research. DOI: 10.3389/fmicb.2016.01373.
(37) Charles, A.; Rochette, P.; Whalen, J. K.; Angers, D. A.; Chantigny, M. H.; Bertrand, N. Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. *Agriculture, Ecosystems & Environment* **2017**, *236*, 88-98. DOI: https://doi.org/10.1016/j.agee.2016.11.021.
(38) Huang, Y.; Zou, J.; Zheng, X.; Wang, Y.; Xu, X. Nitrous oxide emissions as influenced by amendment of plant residues with different C:N ratios. *Soil Biology and Biochemistry* **2004**, *36* (6), 973-981. DOI: https://doi.org/10.1016/j.soilbio.2004.02.009.
(39) Te Kāwanatanga o Aotearoa | New Zealand Government. Government Inquiry into Havelock North Drinking Water: Section One: Introduction and Context, Part 1 - Overview, key findings and highlights. Affairs, Te Tari Taiwhenua | Department of Internal Affairs, Ed.; Auckland, New Zealand, 2017.
(40) Downer, A. J.; Crohn, D.; Faber, B.; Daugovish, O.; Becker, J. O.; Menge, J. A.; Mochizuki, M. J. Survival of Plant Pathogens in Static Piles of Ground Green Waste. *Phytopathology®* **2008**, *98* (5), 547-554. DOI: 10.1094/PHYTO-98-5-0547 (acccessed 2023/03/30).
(41) Noble, R. Risks and benefits of soil amendment with composts in relation to plant pathogens. *Australasian Plant Pathology* **2011**, *40* (2), 157-167. DOI: 10.1007/s13313-010-0025-7.
(42) Colbach, N.; Tschudy, C.; Meunier, D.; Houot, S.; Nicolardot, B. Weed seeds in exogenous organic matter and their contribution to weed dynamics in cropping systems. A simulation approach. *European Journal of Agronomy* **2013**, *45*, 7-19. DOI: https://doi.org/10.1016/j.eja.2012.10.006.
(43) Kim, N. *Cadmium Accumulation in Waikato Soils*. Waikato Regional Council, 2005. https://www.waikatoregion.govt.nz/services/publications/tr200551/ (accessed 2023 31-03-2023).
(44) Nkinahamira, F.; Suanon, F.; Chi, Q.; Li, Y.; Feng, M.; Huang, X.; Yu, C.-P.; Sun, Q. Occurrence, geochemical fractionation, and environmental risk assessment of major and trace elements in sewage sludge. *Journal of Environmental Management* **2019**, *249*, 109427. DOI: https://doi.org/10.1016/j.jenvman.2019.109427.
(45) Berti, W. R.; Jacobs, L. W. Chemistry and Phytotoxicity of Soil Trace Elements from Repeated Sewage Sludge Applications. *Journal of Environmental Quality* **1996**, *25* (5), 1025-1032, https://doi.org/10.2134/jeq1996.00472425002500050014x. DOI: https://doi.org/10.2134/jeq1996.00472425002500050014x (acccessed 2023/03/30).
(46) Zhang, F.; Li, Y.; Yang, M.; Li, W. Content of heavy metals in animal feeds and manures from farms of different scales in northeast China. *Int J Environ Res Public Health* **2012**, *9* (8), 2658-2668. DOI: 10.3390/ijerph9082658 From NLM.
(47) Hölzel, C. S.; Schwaiger, K.; Harms, K.; Küchenhoff, H.; Kunz, A.; Meyer, K.; Müller, C.; Bauer, J. Sewage sludge and liquid pig manure as possible sources of antibiotic resistant bacteria. *Environ Res* **2010**, *110* (4), 318-326. DOI: 10.1016/j.envres.2010.02.009 From NLM.
(48) Urra, J.; Alkorta, I.; Garbisu, C. Potential Benefits and Risks for Soil Health Derived From the Use of Organic Amendments in Agriculture. *Agronomy* **2019**, *9* (9), 542.

(49) Ministry
for the Environment. *Stockholm Convention on Persistent Organic Pollutants*. Ministry for the Environment, 2022. https://environment.govt.nz/what-government-is-doing/international-action/stockholm-convention-persistent-organic-pollutants/ (accessed 2023 31-03-2023).
(50) Cattle, S. R.; Robinson, C.; Whatmuff, M. The character and distribution of physical contaminants found in soil previously treated with mixed waste organic outputs and garden waste compost. *Waste Management* **2020**, *101*, 94-105. DOI: https://doi.org/10.1016/j.wasman.2019.09.043.
(51) Laminzana, B. *Plastic planet: How tiny plastic particles are polluting our soil*. UN Environment Programme, 2021. https://www.unep.org/news-and-stories/story/plastic-planet-how-tiny-plastic-particles-are-polluting-our-soil (accessed 2023 31-03-2023).
(52) Lin, D.; Yang, G.; Dou, P.; Qian, S.; Zhao, L.; Yang, Y.; Fanin, N. Microplastics negatively affect soil fauna but stimulate microbial activity: insights from a field-based microplastic addition experiment. *Proceedings of the Royal Society B: Biological Sciences* **2020**, *287* (1934), 20201268. DOI: 10.1098/rspb.2020.1268 (acccessed 2023/03/30).
(53) Williams, R.; Poole, N.; Fraser, T.; Grant, D.; Hanson, N.; Orson, J.; Rolston, P.; Sim, J. *Review of the role and practices of stubble burning in New Zealand, including alternative options and possible improvements*; Foundation for Arable Research, 2013. https://www.far.org.nz/assets/files/blog/files/f71f0977-b1e4-4ddd-9b05-85017b37d535.pdf.
(54) Abdurrahman, M. I.; Chaki, S.; Saini, G. Stubble burning: Effects on health & environment, regulations and management practices. *Environmental Advances* **2020**, *2*, 100011. DOI: https://doi.org/10.1016/j.envadv.2020.100011.
(55) Rumpel, C. DOES BURNING OF HARVESTING RESIDUES INCREASE SOIL CARBON STORAGE? *Revista de la ciencia del suelo y nutrición vegetal* **2008**, *8*, 44-51.
(56) Virto, I.; Imaz, M. J.; Enrique, A.; Hoogmoed, W.; Bescansa, P. Burning crop residues under no-till in semi-arid land, Northern Spaineffects on soil organic matter, aggregation, and earthworm populations. *Soil Research* **2007**, *45* (6), 414-421.
(57) BECA. *Biogas and Biomethane in New Zealand: Unlocking New Zealand's Biomethane Potential*; BECA, 2021. https://www.beca.com/getmedia/4294a6b9-3ed3-48ce-8997-a16729aff608/Biogas-and-Biomethane-in-NZ-Unlocking-New-Zealand-s-Renewable-Natural-Gas-Potential-Final.pdf.
(58) Ecogas. *ECOGAS OPENS ITS FLAGSHIP REPOROA ORGANICS PROCESSING FACILITY*. 2022. https://www.ecogas.co.nz/news/ecogas-opens-its-flagship-reporoa-organics-processing-facility (accessed 2023 31-03-2023).
(59) United States Environmental Protection Agency. *Types of Anaerobic Digesters*. 2022. https://www.epa.gov/anaerobic-digestion/types-anaerobic-digesters (accessed 2023 31-03-2023).
(60) ChemEurope. *Digestate*. ChemEurope, https://www.chemeurope.com/en/encyclopedia/Digestate.html (accessed 2023 31-03-2023).
(61) AWSM Farming. *Digestate Spreading*. https://awsmfarming.co.uk/services/farming/digestate/digestate-spreading/# (accessed 2023 31-03-2023).

(62) Lukehurst, C. T.; Frost, P.; Al Seadi, T. *Utilisation of digestate from biogas plants as biofertiliser*; 2010.
(63) Lu, J.; Xu, S. Post-treatment of food waste digestate towards land application: A review. *Journal of Cleaner Production* **2021**, *303*, 127033. DOI: https://doi.org/10.1016/j.jclepro.2021.127033.
(64) Zulkepli, N.; Muis, Z.; Mahmood, N.; Hashim, H.; Ho, W. Cost benefit analysis of composting and anaerobic digestion in a community: a review. *Chemical Engineering Transactions* **2017**, *56*, 1777-1782.