Soil organic amendments for climate-smart agriculture
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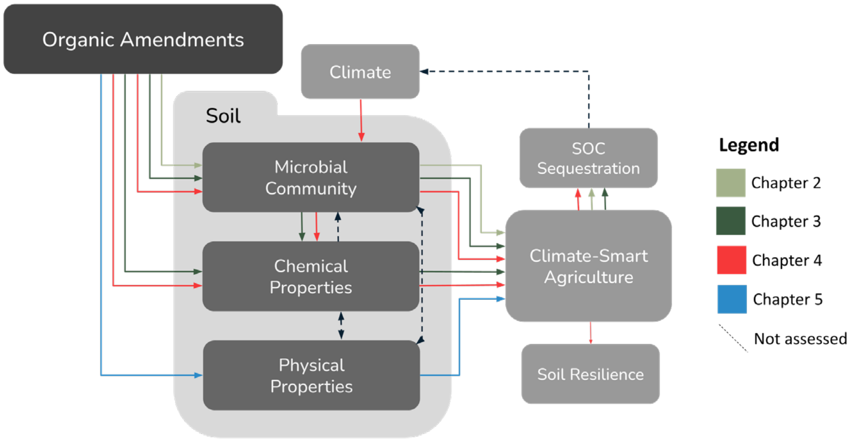

Organic Amendments
Climate
Soil
Microbial Community
Chemical Properties
Physical Properties
SOC Sequestration
Climate-Smart Agriculture
Soil Resilience
Legend
Chapter 2
Chapter 3
Chapter 4
Chapter 5
Not assessed

CHAPTER 1

General Introduction

1.1 Application of soil fertilizers and amendments

In order to maintain soil fertility and thereby sustain crop productivity, agricultural systems depend on external inputs in the form of soil amendments and fertilizers. These amendments and fertilizers ensure that elements lost or extracted from a production system, such as through leaching or crop harvests amongst others, are compensated for so that any degradation in fertility is offset or diminished. As a means of improving crop access to nutrients and water, and thereby boosting crop productivity, soil external inputs have come to play an integral role in our food production systems.

Over the past decades, the widespread application of fertilizers has contributed greatly to improving crop productivity and closing crop yield gaps (Mueller et al. 2012). Global fertilizer consumption rates have increased to 2.5 Tg annually over the past decades and reached 20 Tg for phosphorus and 109 Tg for nitrogen in 2021 (FAO 2023). These demands are projected to further increase as changing diets of the growing populations drive food demands upwards (Fukase and Martin 2020). By 2050, food demands will amount to 10.7-12.0 Tg resource-based cereal equivalents (Fukase and Martin 2020), which will further increase fertilizer demand to 26 Tg for phosphorus (Mogollón et al. 2018) and 232 Tg for nitrogen (Bodirsky et al. 2014) – 130% and 213% of 2021 demands, for phosphorus and nitrogen respectively.

Fertilizers, however, can comprise a wide range of different substances, which are generally distinguished based on either their synthetic or organic origin. Synthetic fertilizers are artificially produced, readily dissolvable chemicals, whereas organic fertilizers can encompass any soil amendment which consist of predominantly organic matter (e.g. compost, animal manure and plant residues). While nutrients supplied by synthetic fertilizers are readily available for crop uptake, organic fertilizers typically have to be mineralized by soil microorganisms before their nutrients become available to plants (Marzi et al. 2020; Masunga et al. 2016). However, in contrast to their synthetic counterparts, organic fertilizers contain large amounts of carbon and can, therefore, offer many additional benefits, such as potentially offsetting greenhouse gas emissions (GHG) and improving soil structure and thereby crop access to water (Diacono and Montemurro 2010). The use of organic waste products or organic residues as organic fertilizers can furthermore contribute to closing resource loops at local scales. By building soil fertility, mitigating climate change and developing circular organic waste streams, the use of organic amendments in agricultural systems can contribute to aligning the agricultural sector with the ambitions of the United Nations Sustainable Development Goals (SDGs; Gomiero, Pimentel, and Paoletti 2011b; Rumpel, Lehmann, and Chabbi 2018; UN General Assembly 2015). Soil and its sustainable management is reflected in 11 of the 17 SDGs, but the application of organic amendments most clearly links to SDG 12 (Responsible Consumption and Production) and

13 (Climate Action). With an increasing urgency to fulfil the SDG ambitions, organic amendments demonstrate a significant potential to take a more prominent role in agriculture than they do today.

1.2 Organic amendments in agriculture – A brief history

The application of organic amendments to arable land constitutes a traditional soil improvement and nutrient recycling strategy that is historically practised in agricultural societies around the world (Parr and Hornick 1992). Its antiquity is exemplified by archaeological sherds found in the Middle East, which provide evidence for the transport of organic waste from urban centres to agricultural fields already in the 3rd millennium B.C.E. (Wilkinson 1982). The practice of collecting, transporting and applying organic amendments in agriculture was furthermore widespread, having been discovered and disseminated among cultures in ancient Europe, South America and Asia (Foxhall 1998; Glaser 2007; Marten and Vityakon 1986). Despite its long agronomic history and cultural universality, however, the application of organic amendments had mostly diminished as a common practise among the world's largest agricultural producers by the end of the 20th century.

The 20th century marked a decline in the use of organic amendments with the discovery of the Haber-Bosch process and subsequent industrial production of synthetic nitrogen fertilizers (van Zwieten 2018). At that time, nitrogen was the principle limiting nutrient stunting crop growth. In combination with an accelerated mechanization, the development of high-yield crop varieties, and the normalization of pesticide use, the world experienced an agricultural revolution marking the greatest improvement in global food security in recorded history (Khush 2001). Later to be coined the 'green revolution', the world would more than double its production of major crops within just three decades, e.g. for primary cereals from 877 Tg in 1961 to 1,788 Tg in 1984 (FAOSTAT, 2022). Yet the introduction of efficiently storable and more easily distributable fertilizers also resulted in the slow recession of the use of organic fertilizers. Instead, the use of synthetic fertilizers – easier to dose and more conveniently applied within the new agro-industrial system – more than quadrupled from 30 Mt in 1960 to 140 Mt in 2000 (IFDC 2004). In large part due to the popularity of synthetic fertilizers, humans now fix more atmospheric dinitrogen than all natural processes combined and thereby exert significant influence on global nitrogen cycles (Fowler et al. 2013). In the end, the green revolution would save hundreds of millions of people from likely starvation; however, its toll on soils and the environment, and therefore long-term food security, would only become apparent in later years (Lal 2009).

1.3 Industrialized agriculture and its challenges

Contemporary, industrialized agriculture is a critical contributor to widespread soil and environmental degradation (Gomiero et al., 2011). Practices defining this type of agriculture still largely conform to those ideas propagated in the previous century, involving, among others, i) intensive synthetic fertilizer use, ii) monocultures, iii) removal of crop residues for fodder, iv) excessive tillage, and v) the disproportionate use of agrochemicals (Lal 2004). Especially fertilizer use (and misuse) is problematic as crops typically integrate less than half of the nitrogen fertilizers applied (Smil 1999). The remainder, meanwhile, is lost to the environment at rates much higher than natural ecosystems can sustain (Van Drecht et al. 2003). The environmental repercussions of fertilizer (mis)use threaten local ecosystems and biodiversity due to the resulting eutrophication and acidification of soils and surface waters. Meanwhile, intensive tillage further impairs future food security through declines in soil organic matter content and associated water and nutrient retention capacities (Balesdent, Chenu, and Balabane 2000; Bescansa et al. 2006). Acidification due to nitrogen fertilizers can also threaten crop production unless properly managed through the application of manure and/or lime where needed (Hao et al. 2019; Xu et al. 2023; Zhu et al. 2018). Finally, also the overuse of toxic agrochemicals has been warranted concern given its evidential adverse effects on both ecosystems (Barmentlo et al. 2018, 2021) and humans alike (Elahi et al. 2019).

Another disadvantage of conventional industrialized agriculture is that it contributes to and suffers from the effects of anthropogenic climate change (Chhetri and Chaudhary 2011). It is estimated that the agricultural sector is accountable for 16–27% of the total anthropogenic greenhouse gas (GHG) emissions (IPCC, 2021). These emissions have various sources and take various forms within the food production system, but the most critical are: nitrous oxide emissions from soils, dejections from grazing animals, methane production by ruminant animals, and indirect emissions due to land-use changes such as land clearing and deforestation (IPCC, 2021). Agriculture also contributes to climate change through the emission of carbon dioxide (CO_2) from soils. Soils constitute the largest pool of terrestrial carbon (Smith 2012; Stockmann et al. 2013), storing over 1550 Pg of carbon in the form of soil organic matter (SOM) derived from the dead biomass of plants, animals and microbes (Batjes 1996). Continuous cropping systems and intensive cultivation practices, however, have led to an accelerated mineralization of this otherwise inert SOM (Post and Mann 2005). In total, it is estimated that cultivated soils have lost some 133 Pg of carbon to the atmosphere this way (Sanderman, Hengl, and Fiske 2017). It should be noted that agriculturally enhanced nitrogen emissions partly compensate for the sector's carbon footprint as these emissions stimulate forests growth and consequently enhance carbon sequestration in trees and forest soils (Vries et al. 2017; de Vries et al. 2009).

Conventional agriculture is not only an important contributor to anthropogenic climate change, it is also a victim as conventional practices exacerbate the vulnerability of our food production systems to climate change effects. Unequivocal evidence warns that a changing climate will increase the prevalence of weather extremes such as droughts and floods, resulting in an increased frequency of crop failures and a worsening of existing yield gaps (IPCC, 2021). Already in 2011, climate change was estimated to have reduced global maize and wheat yields by 3.8% and 5.5%, respectively (Lobell, Schlenker, and Costa-Roberts 2011). Such declines in global food security contribute to malnutrition and acute hunger, and increase socioeconomic and gender inequality (IPCC et al. 2021). The vulnerability of agriculture to the effects of climate change is expected to worsen as the accelerated mineralization of SOM under conventional agriculture can reduce soil water holding capacities and thereby worsen the effects of droughts and precipitation extremes on crop production (Diacono and Montemurro 2010; Wander and Drinkwater 2000). Reducing the vulnerability of our food production systems to the effects of climate change is thus critical to safeguarding future global food security (Campbell et al. 2016).

Given the significant contribution to and vulnerability of the agricultural sector to climate change, there exists a need, a desire, and a large potential for the effective implementation of agriculturally oriented climate change mitigation strategies. Widespread adoption of such strategies, possibly in combination with other practise standards such as conservation, regenerative and/or circular agriculture, may then introduce a new agricultural paradigm to succeed the green revolution, namely the revolution of climate-smart agriculture (CSA; FAO, 2018). Practices constituting CSA are context-specific, depending on local socio-economic, environmental and climate change factors, yet they always aim to address three main objectives, namely: i) sustainably increasing agricultural productivity and incomes; ii) adapting and building resilience to climate change; and iii) reducing and/or removing greenhouse gas emissions (FAO, 2018). Examples of such practices are those that enhance soil water retention and thereby improve crop resilience to droughts, or actively promote soil carbon storage and thereby reduce CO_2 emissions to the atmosphere (Amelung et al. 2020; Lal 2004). It is with the transition to CSA that some traditional agricultural practices may experience a renaissance and, in this context, especially the application of organic amendments appears bound for a revival.

1.4 Renewed potential for organic amendments in agriculture

The application of organic amendments to arable land offers multiple benefits that align with global challenges and ambitions of the 21st century. Foremost, organic amendments may become important instruments in CSA by improving SOM contents and other/associated soil properties that enhance crop production and its climate resilience.

Soil organic matter is widely regarded as a key arbiter and indicator of soil fertility due to its association with improved soil chemical, physical and biological properties (Angelova et al. 2013; Reeves 1997; Romig et al. 1995). Its accumulation can improve a soil's nutrient supply, cation exchange capacity (Magdoff and Weil 2004), its immobilization and neutralization potential of pesticides and the retention (adsorption) of heavy metals and other pollutants (Ahmad et al. 2001; Mohamed et al. 2010; Scheunert, Mansour, and Andreux 1992). Organic amendments can furthermore also improve the supply of plant-available micronutrients (Li et al. 2007). Improvements in soil chemistry through organic amendment applications can therefore benefit crop growth and reduce the impact of harmful substances on crops and ecosystems.

Organic amendments and the accumulation of SOM can also improve soil physical properties such as bulk density (Cercioglu 2017; García-Orenes et al. 2005; Khaleel, Reddy, and Overcash 1981; Tejada and Gonzalez 2008), infiltration capacity and hydraulic conductivity (Eusufzai and Fujii 2012; Meena, Lal, and Yadav 2020; Wanniarachchi et al. 2019), penetration resistance (Celik et al. 2010; Negiş et al. 2020), pore space distribution (Luna et al. 2018), aggregate stability (Abiven, Menasseri, and Chenu 2009; Albiach et al. 2001; Annabi et al. 2011), and water retention (Ankenbauer and Loheide 2017; Eden, Gerke, and Houot 2017; Meena et al. 2020; Rawls et al. 2003; Zhou et al. 2020). These improvements benefit crop production as crops grown on soils of lower bulk densities are facilitated in root penetration and benefit from improved oxygen diffusion into the rhizosphere (Valentine et al. 2012); soils that readily infiltrate water are less susceptible to ponding and land degradation (Hueso-González et al. 2015); soils capable of retaining more water provide crops with greater resilience to drought and thus lower irrigation requirements (Chambal Pandey and Sanjay Shukla 2006; Terleev et al. 2017; Zhang et al. 2006); and soils with high structural stability (i.e. aggregate stability) are, among other effects, aided in nutrient retention through the occlusion of organic matter (Lutzow et al. 2006; Six et al. 2004; Tisdall and Oades 1982). This way, organic amendments can help recuperate soils degraded under conventional industrial agricultural practices that exhibit reduced water retention due to the depletion of SOM (Gomiero et al. 2011a; Lal 2004) or suffer from increased flood risk due to the loss of soil structure caused by intensive tillage and the use of heavy machinery (Hamza and Anderson 2005).

Finally, organic amendments can also benefit soil ecology. Organic matter is a habitat for soil microorganisms that deliver important ecosystem functions due to their role in, for instance, terrestrial food-web networks or their function as critical mediators of global nutrient cycles (Allison et al. 2013; De Vries et al. 2013; Hallin et al. 2009). Improvements in SOM have demonstrated to enhance microbial biomass and diversity (Bending, Turner, and Jones 2002), which have, in return, for instance demonstrated to improve crop resilience to droughts (Prudent et al. 2020).

In addition to benefitting agricultural systems, the application of organic amendments and subsequent accumulation of SOM is also a strategy to offset anthropogenic GHG emissions. SOM consists by approximately 50% of carbon (Pribyl 2010), and by sequestering carbon in the form of SOM, we can reduce the amount that is emitted to the atmosphere. The overall importance of soil carbon sequestration for food security and climate change mitigation was highlighted at the COP 21 in France in 2015, where the '4 per mille Soils for Food Security and Climate' initiative was launched by the French Ministry of Agriculture (http://4p1000.org/). While there exist uncertainties regarding the global potential for carbon sequestration due to concerns regarding associated nitrogen requirements (van Groenigen et al. 2017; de Vries 2018), it is estimated that worldwide application of best management practices could still sequester approximately 0.28 to 0.43 Gt C yr^{-1} (Lessmann et al. 2021) – around 10% of the annual CO_2 flux.

However, not all organic amendments are equally efficient in sequestering carbon due to differences in amendment priming effects. These priming effects describe a change in the natural decomposition rate of carbon already in the soil following the application of an amendment. For the purpose of efficient carbon sequestration, amendments ideally slow down this decomposition, i.e. induce a negative priming effect. However, accelerated rates of decomposition, i.e. positive priming effects, are observed for many, if not most, amendments, thus resulting in less efficient carbon sequestration. On the other hand, synthetic fertilizers do not directly contribute to the accumulation of SOM at all, as they are not composed of organic matter. Instead, they only indirectly impact SOM concentrations by, for instance, enhancing crop yields and thereby crop residue inputs (if these are not removed; Amelung et al. 2020) or by either positively or negatively affecting SOM mineralization rates (Mahal et al. 2019; Russell et al. 2009).

1.5 An opportunity to close resource loops at local scales

In addition to improving soil properties and offsetting GHG emissions, the application of organic amendments may be an effective and sustainable means to dispose organic wastes. This way, organic amendment applications can contribute to achieving other ambitions, such as facilitating circular economic development and closing resource loops at a local scale (Elbersen and Spijker 2014; Rijkswaterstaat (Ministry of Infrastructure and Water Management, the Netherlands) 2020). Manure and composted organic residues are examples of organic wastes that are already, to different extents, commonly recycled in a circular economic fashion. It is estimated that global livestock produces 131.0 Tg N a^{-1} in the form of manure (Zhang et al. 2017), of which approximately 37–61 % is returned as fertilizer to the land surface (Bouwman et al. 2013). And in some places (e.g., Australia and

New Zealand), nearly 40% of all green wastes was composted and reused for agriculture already in the previous century (Biala and Wynen 1998).

In the context of closing resource loops, a second potentially important group of organic amendments are organic residues produced in landscape maintenance. Such organic residues encompass vegetation recovered from public green areas and road verges, weeds and reeds from public waterways, and woodchips produced in the maintenance of national parks and nature reserves. These residues are frequently composted or incinerated instead of being repurposed directly as an organic fertilizer. An estimated 770,000 tonnes of dry organic waste is produced in the maintenance of public green areas in the Netherlands, illustrating the abundance of such residues available for new applications (Elbersen and Spijker 2014). With the further intensification of landscape maintenance, such organic residues may become valuable and untapped sources of sustainable soil improvers that are not only inexpensive but also locally and widely available near most agricultural hotspots.

The application of organic amendments can thus potentially benefit a soil and climate change mitigation efforts in different ways. However, the exact soil impacts of an organic amendment depend largely on its interaction with the soil microbial community (Ernakovich et al. 2021; Fang et al. 2020; Geyer et al. 2016; Kögel-Knabner 2017; Lejon et al. 2007; Yanardağ et al. 2017). The decomposition of organic amendments is driven by soil microorganisms, which represent more than 95% of the biomass in most soils (Wardle and Giller 1996). Soil microorganisms, of which the vast majority are heterotrophs, metabolize organic matter in order to satisfy their energy and nutrient needs in their endeavour to survive and reproduce. Over the course of their decomposition activities, microorganisms directly or indirectly drive changes in soil chemical and physical properties through, for example, their transformation of organic compounds into biomass and the production of enzymes. Microorganisms drive multiple pathways through which organic amendments can affect a soil, such as by trophic regulation (e.g. attraction of protists, nematodes, microarthropods, and other predators as well as their predators), and/or by binding soil particles through their mycelium or production of extracellular polymeric substances. The microbial inability to decompose certain organic amendment fractions, as well as the accumulation of microbial biomass and other microbial products after death (i.e. necromass), further determines how much carbon is retained in a soil to form SOM (Kallenbach et al. 2015; Lehmann and Kleber 2015; Liang et al. 2019). Microorganisms can thus be regarded as the architects of a soil (Young and Crawford 2004), whose influence over their soil habitat can conveniently benefit our crop production and carbon sequestration ambitions (section 1.4).

The response of a soil microbial community to organic amendments, or other changes in their environment, is complex. Each community consists of an overwhelming abundance and diversity of taxa that can theoretically each exhibit their own unique responses to changes in their environment (e.g. the application of an organic amendment). Illustrative of this abundance and diversity is the biological profile of a single gram of soil, which can contain in the order of >10^9 individual cells and >10^6 distinct taxa belonging to all three domains of the phylogenetic tree (Bacteria, Eucarya and Archaea; Curtis & Sloan, 2005; Gans et al., 2005). As with all living beings, the performance and behaviour of each soil microorganism is influenced by the compatibility of its physiological traits with environmental factors such as soil properties (e.g. texture and structure), moisture and temperature conditions, presence of toxins, pathogens or predators, and resource availability. These factors can differently stimulate or inhibit a microorganism, impacting its growth, death, metabolic efficiency (Manzoni, Taylor, et al. 2012), enzyme production (Baldrian 2009), and/or antagonistic or synergistic profiles (Perez, Dill-Macky, and Kinkel 2008). These changes can impact the interactions between microbial communities and organic amendments and thereby impact soil functions.

Since soil microorganisms play a critical role in the decomposition of organic matter, understanding the mechanisms driving changes in microbial properties and processes is important to understanding the impacts that organic amendments can have on a soil. Organic amendments consist of different organic compounds, of different energy concentrations, which are furthermore variably physically and chemically accessible to different microorganisms for decomposition.

Predicting the impact of environmental changes on the multiple facets defining microbial functioning is an enormously complex task, but is, fortunately, moderately simplified due to some functional redundancy within microbial communities (Allison and Martiny 2008). To this extent, a number of empirical and conceptual studies have demonstrated the importance, as well as complexity, by which changes in microbial properties, such as community structure, biomass and metabolism, can affect soil carbon transformations through changes in microbial necromass accumulation, mineralization rates, shifts in carbon-use efficiency and/or variations in metabolic quotients (Allison et al. 2013; De Graaff et al. 2010; Francioli et al. 2016; Kallenbach et al. 2019; L. J. Li et al. 2018; Marschner, Kandeler, and Marschner 2003; Mooshammer, Wanek, Hämmerle, et al. 2014; Sinsabaugh et al. 2015; Wieder, Bonan, and Allison 2013; Zhao et al. 2016). Consequently, there exist numerous conceptual and methodological frameworks for describing the complex composition of organic matter and its interaction with soil microorganisms. The more extensively developed models are typically based on stoichiometry, i.e., the ratio of carbon to nitrogen or phosphorus concentrations (Manzoni, Taylor, et al. 2012), or molecular structure, i.e., concentrations of humic substances, nucleic acids, peptides and amino acids, phenols, sugars and polysaccharides, lipids, lignin, cellulose and other carbohydrate fractions (Box 1) – though other characterization frameworks exist as well (Kögel-Knabner 2017). The composition of organic amendments, whether defined by stoichiometric, molecular, or other characterizations, in relation to microbial community, is important in determining the course of microbial-organic amendment interactions and subsequent impacts on a soil.

Box 1 | Dominant Theories on the Microbial Regulation of Decomposition

Stoichiometry - Rules of stoichiometry, i.e. maintaining constant C:N:P ratios are a major factor in determining organic amendment impact on soil microbial communities (Manzoni et al., 2008; Spohn, 2016). When the stoichiometry of the organic amendment mismatches that of microbial demands, microbial activity will adapt to maintain constant C:N:P ratios in their biomass (stoichiometric homeostasis). To accomplish this, microbes regulate their enzyme production and enzymatic stoichiometry to improve the mobilization of substrates containing the limiting elements (Sinsabaugh et al., 2016).

Energetics - The theory of energetic regulation of microbial activity, instead, proposes that microbial exoenzyme production initially targets high-energetic molecular compounds that require minimal energy investment to oxidize (e.g. sugars and amino acids), followed by lower energetic compounds that offer a less favourable return on enzyme investment (e.g. phenols, lignin, fatty acids and alkyl monoesters; Molenaar et al., 2009; Moorhead et al., 2013).

KNOWLEDGE GAPS

The application of landscape residues and other organic amendments to agricultural soils can potentially improve crop production and its climate change resilience, offset anthropogenic GHG emissions, and contribute to closing resource cycles at a local scale, as described in the previous sections. Yet, widespread adoption of organic amendment application practices is inhibited by uncertainties regarding the benefits and risks thereof. Fundamentally, these uncertainties are derived from a lack of understanding of the relationships and interactions between organic amendment properties, microbial processes and soil improvements (Vogel et al. 2014) but also relate to more practical questions such as those pertaining to the persistence of soil improvements in dynamic agricultural settings.

1.5.1 Impacts of organic amendments properties on microbial community dynamics, priming and soil carbon sequestration

Changes in microbial activity following organic amendment application have been shown to variably stimulate or inhibit the mineralization of carbon stored in the form of SOM – a phenomenon coined the priming effect (Kuzyakov, Friedel, and Stahr 2000). The priming effect influences the efficiency by which carbon is sequestered with the application of organic amendments. Positive priming effects result in the accelerated decomposition of SOM[1], and negative priming effects will slow it down and are, therefore, much more desirable. However, it is difficult to predict and control the direction and magnitude of the priming effect, as it is influenced by many factors such as those related to different properties of the organic amendment applied, the local soil conditions, as well as the soil microbial community (Aye et al. 2018; Blagodatsky et al. 2010; Chen et al. 2014; Hamer and Marschner 2002; H. Wang et al. 2015). While priming effects undoubtedly have implications for the efficacy of soil carbon sequestration initiatives, our limited understanding of the processes driving priming effects, its relationship with the various different properties of organic amendments and its subsequent limited inclusion in soil models all contribute to uncertainties around the effect of organic amendment applications in agriculture.

Defining relationships between organic amendment properties and microbial dynamics and evaluating these relationships in the context of changing soil properties would contribute to our understanding of how we may use organic amendments to the benefit of agriculture and climate change mitigation and thereby aid the design of effective organic amendment application strategies. However, establishing such relationships requires the identification and characterization of organic amendment properties relevant to steering microbial dynamics. Both stoichiometric and energetic characterizations of organic amendment composition are frequently used to explain changes in soil microbial dynamics; yet, while both are scientifically well-established, it remains unclear which characterization framework and which organic amendment properties are most suited for predicting the various organic amendment impacts (Ernakovich et al. 2021; Fang et al. 2020; Geyer et al. 2016; Kögel-Knabner 2017; Lejon et al. 2007; Yanardağ et al. 2017). Identifying which

[1] Decades of priming research have shown that soils incubated with organic amendments always contain more carbon at the end of an experiment than the same soil incubated by itself, and thus the application of organic amendments is, despite priming effects, unlikely to result in the depletion of soil carbon (Kögel-Knabner 2017).

organic amendment characterizations demonstrate the closest relationships with changes in microbial and soil properties can elucidate which mechanisms dominate their interaction.

Knowledge gap: It is unclear which organic amendment properties and characterizations most closely relate to changes in soil microbial properties and processes driving soil carbon transformations and priming effects.

1.5.2 Impacts of organic amendments on the response of soil microbial communities to climatic extremes and their carbon transformations

Since organic amendments impact soil microbial properties and processes, they may also potentially alter the way microbial communities respond to environmental stresses such as droughts (Manzoni, Schimel, and Porporato 2012) and extreme heat events (Riah-Anglet et al. 2015). Altered microbial stress responses can translate to changes in microbial carbon and nitrogen transformations (e.g. more rapid mineralization or stabilization), and thus affect the value that different organic amendments can have in building soil climate resilience or resistance. Given the increasing prevalence of environmental stress events with onsetting climate change (IPCC, 2021), including extreme temperature events, understanding the interactions between microbial dynamics, temperature and impacts on soil elemental balances is becoming increasingly relevant. Yet, these interactions and how we can use organic amendments to manipulate them remain limitedly explored and understood.

Knowledge gap: It is unknown whether different rates of temperature change have an impact on soil microbial communities and their soil processes and whether organic amendments can influence this potential (in)sensitivity.

1.5.3 Temporal variability in the impacts of organic amendments on soil properties

The application of organic amendments may play an important role in climate-smart agriculture, given their potential improvement of various soil properties, but the value of these improvements for agricultural systems depends not only on the type and magnitude of the improvement but also on the rates at which these improvements develop and/or are able to persist in a dynamic agricultural setting (i.e. its temporality). For instance, the contribution of an organic amendment to improving crop productivity and resilience to the effects of climate change will largely depend on whether soil improvements have been achieved by, or are present at, a relevant time in relation to the cropping cycle and the occurrence of seasonal dynamics such as weather extremes. Improvements in soil infiltration capacity are, after all, of limited value when they are present in dry summers but absent in winters when flood risks are typically greater. The temporality of soil improvements by organic amendments is certainly affected by field management practices (Hu et al. 2018), but is also largely influenced by the quantity and quality of the organic amendment applied. However, the existence and degree of temporal variability in soil properties in relation to differently composed organic amendments remain limitedly explored in dynamic agricultural settings.

Knowledge gap: We lack insight into the temporal variability of organic amendment impacts on agricultural soil properties, resulting in uncertainty on whether soil improvements develop rapidly enough and/or are persistent enough such that they are present at a relevant time in relation to the cropping cycle or season.

1.6 OBJECTIVES AND RESEARCH QUESTIONS

As outlined above, there still exist large uncertainties in determining the value of different organic amendments for application in climate-smart agriculture. The aim of this thesis is therefore to enhance our conceptual and numerical understanding of the impacts of organic amendments on soil carbon dynamics and the physical properties of agricultural soils in order to improve our capacity to design effective organic amendment application strategies. To achieve this, we define three research objectives exploring interfaces between amendments, microbial communities and climate and weather effects (Figure 1.1):

1. Determine how different organic amendment properties and characterizations relate to changes in soil microbial communities and their carbon interactions;
2. Evaluate how differently composed organic amendments affect the microbial response to changes in soil environmental conditions, e.g. rate of temperature change;
3. Assess the effect of organic amendment quantity and quality on the temporality in the hydrological and physical improvement of dynamic agricultural soils.

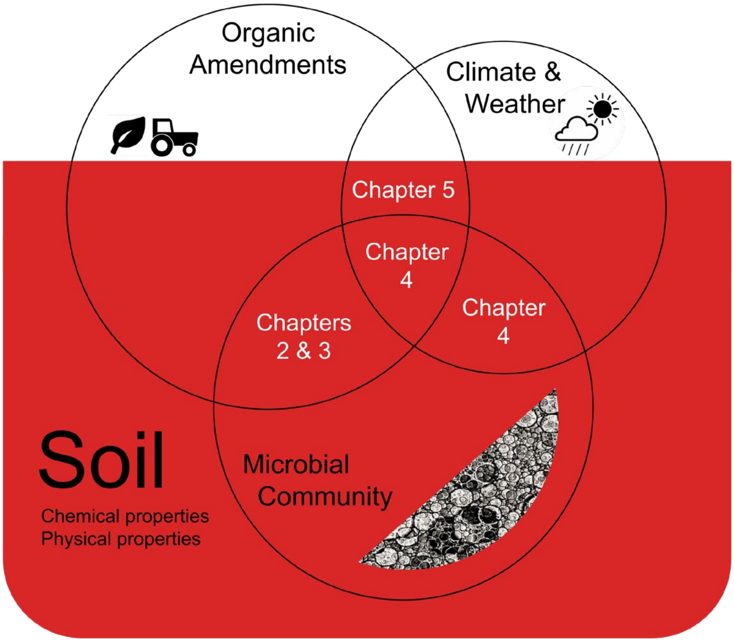


Figure 1.1. Research objectives and their respective foci on the interfaces between organic amendments, soil properties, microbial communities and climate & weather effects.

In the context of these objectives, the subsequent chapters of this thesis address the following research questions:

1. Which organic amendment properties and characterizations demonstrate closest relationship with changes in soil priming effects and microbial properties, and how do soil priming effects relate to specific changes in soil microbial dynamics? (Objective 1; Chapter 2)
2. Can we accurately simulate microbially mediated changes in soil carbon fractions, including priming effects, following the application of different organic amendments? (Objective 1; Chapter 3)
3. Is the rate of temperature change a significant microbial stressor, and do organic amendments affect microbial sensitivity thereto? (Objective 2; Chapter 4)
4. What is the temporal (seasonal) variability in soil hydro-physical improvements in response to rates and composition of applied organic amendments? (Objective 3; Chapter 5)

All chapters investigate various impacts of organic amendments, but Chapter 2 (experimental) and 3 (modelling) focus on the impacts of the microbial community and soil chemical properties, Chapter 4 explores the changes in impacts on microbial and soil chemical properties for climatic extremes (temperature) and Chapter 5 focuses on the impacts on physical soil properties (Figure 1.2)

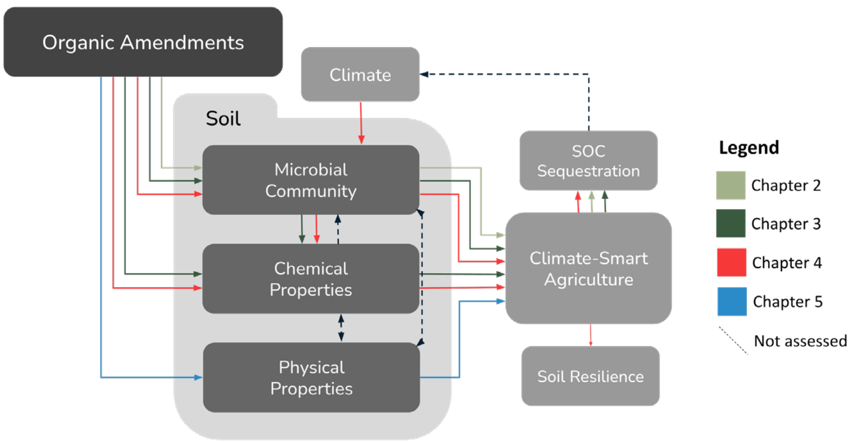


Figure 1.2. Conceptual overview of organic amendment impacts and their relationships as treated in the subsequent chapters of this thesis.

1.9 OUTLINE OF THIS THESIS

This chapter so far has introduced the potential importance of organic amendments for climate-smart agriculture and highlighted several knowledge gaps that currently hinder their widespread application.

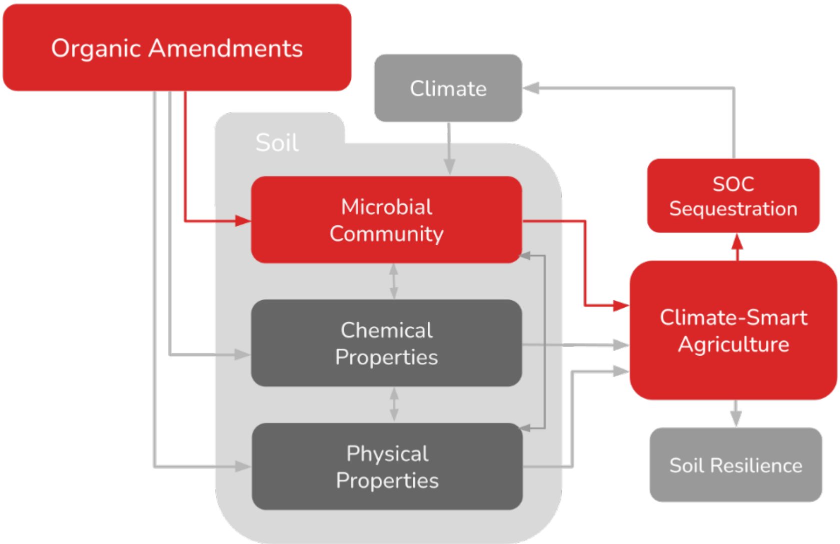
In **Chapter 2**, we address research question 1 through a soil incubation study where we applied wood chips, waterway residues, and isotopically labelled unprocessed, composted and Bokashi fermented road-verge grasses to a podzol soil. We performed stoichiometric and energetic characterizations of the composition of organic amendments applied and monitored for 150 days the changes in concentration of different soil carbon fractions and various microbial parameters, namely microbial community size, structure, carbon respiration and nitrogen mineralization activity, and metabolic quotients. For the isotopically labelled amendments, we furthermore calculated changes in carbon-use efficiency and priming effects. The strength of the relationship between organic amendment characterizations, changes among microbial parameters, and changes in priming effects were determined through Pearson correlation analysis and quantified through linear regression.

In **Chapter 3**, we address research question 2, where we synthesize the data acquired from the incubation experiment described in Chapter 2 to develop a mechanistically grounded, functional, multi-compartmental model to simulate soil carbon dynamics, including priming effects, following the application of compositionally diverse organic amendments.

In **Chapter 4**, we address research question 3 through an incubation experiment where we amended a podzol with wood chips, waterway residues, and isotopically labelled unprocessed, composted and Bokashi fermented road-verge grasses. Sixty days after the application of organic amendments, we exposed the incubation pots to temperature treatments in the form of either a gradual, a rapid or no temperature pulse. At four sampling moments, we measured changes in soil microbial and chemical properties, namely microbial biomass, bacterial to fungal DNA ratio, carbon respiration and nitrogen mineralization activity, carbon-use efficiency, metabolic quotients, priming effects, and various solubility fractions of organic carbon and nitrogen pools. We compared the results between different temperature treatments and sampling times to determine whether the soils experienced detectable stress and whether organic amendments influenced this stress response.

In **Chapter 5**, we address research question 4, where we investigate the temporal effects of organic amendments, including manure, compost, grasses, waterway residues, and their combinations, on soil aggregate stability, bulk density, water retention, and hydraulic conductivity. We achieved this through field experiments at two agricultural sites, where hydro-physical properties were measured twice per year after two and three years of repeated organic amendment applications. Results were compared between sites, seasons and amendment treatments to assess differences in the intra-annual variability in soil response for these factors.

In **Chapter 6**, we revisit the research objectives that conceived this study, discuss our developed insights on the functional and mechanistic relationships that define the nexus of interactions between organic amendments, soil microbiology, and soil carbon dynamics, and present the implications thereof for the value of different rurally-available organic amendments in the context of climate-smart agriculture.


Organic Amendments
Climate
Soil
Microbial Community
SOC Sequestration
Chemical Properties
Climate-Smart Agriculture
Physical Properties
Soil Resilience