Soil organic amendments for climate-smart agriculture

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CHAPTER 6

Synthesis & Discussion

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6.1 RECAPITULATION

The design of efficient and effective organic amendment application strategies is inhibited by a lacking conceptual and numerical understanding of the various soil responses to different types of amendments. In this thesis, I aimed to further develop this understanding by exploring and quantifying the relationships between amendment properties and the response of soil microbial communities and soil chemical and physical properties (Figure 1). To guide my research towards this aim, I defined three research objectives that each address some aspect of the interfaces between these factors:

> **Objective 1:** To determine how different organic amendment properties and characterizations relate to changes in soil microbial communities and their carbon interactions (Chapters 2 and 3);
>
> **Objective 2:** To evaluate how differently composed organic amendments can affect the microbial response to changes in soil environmental conditions, e.g. the rate of temperature change (Chapter 4);
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> **Objective 3:** To assess the effect of organic amendment quantity and quality on the temporality in the physical improvement of dynamic agricultural soils (Chapter 5).

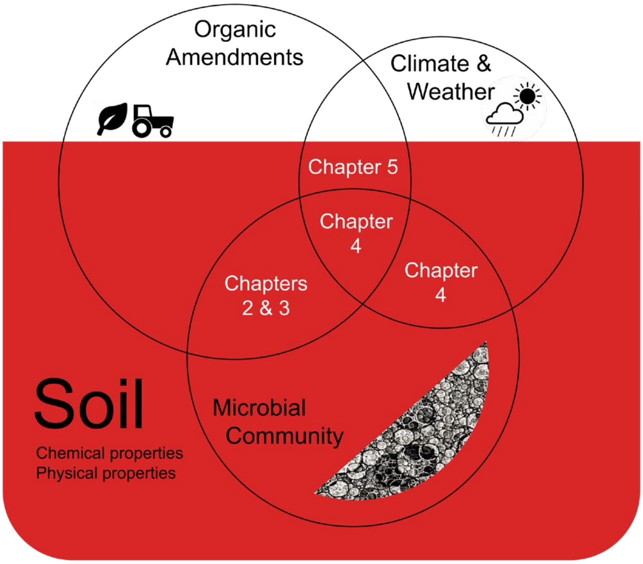

Figure 6.1. Research objectives and their respective foci on the interfaces between organic amendments, soil properties, microbial communities and climate & weather effects.

These objectives culminated in four principal research questions:

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

In previous chapters of this thesis, we presented the outcomes of detailed investigations that address these research questions and objectives. In this chapter, we synthesize our key findings and discuss their implications for the field of soil science and agriculture. The chapter is structured as follows:

> **Section 6.2** integrates and synthesizes the main findings from Chapters 2 to 5, elucidating the relationships between organic amendments, microbial communities, soil properties and the significance of temporal variations in amendment impacts.
>
> **Section 6.3** delves into the theoretical implications of our findings for the study of organic amendment and outlines potential avenues for future research.
>
> **Section 6.4** presents the practical, agricultural implications of our findings for soil managers and farmers.
>
> **Section 6.5** concludes the discussion chapter and this thesis, summarizing the significance of our study in addressing existing knowledge gaps in research on organic amendment impacts and reemphasizes the potential value of organic amendment applications for agriculture.

6.2 MAIN FINDINGS

Investigations from the previous chapters coalesce in a number of key findings. These relate to the impact of rates of temperature change on microbial properties and functioning and the influence of organic amendments thereupon, as well as the identification of relevant chemical amendment properties that drive (i) soil carbon dynamics and microbial activity and (ii) temporal patterns in soil hydro-physical improvements.

6.2.1 Effects of organic amendments on microbially driven soil carbon dynamics

While soil microbial communities are critical mediators of the global carbon cycle, our understanding of the processes and factors affecting microbial carbon transformation is disconnected from the many different forms of organic carbon that may be applied to a soil. In Chapters 2 and 3, I quantified the response of well-established processes and properties affecting soil carbon dynamics, including carbon use efficiencies (Manzoni 2017; Sinsabaugh et al. 2013), priming effects (Chen et al. 2014; Kuzyakov 2010) and metabolic quotients (Fang et al. 2020) and their response to different types of organic amendments of varying chemical compositions for a sandy podzol.

Results showed that the concentrations of hot water extractable to total carbon in organic amendments explained most variation in the priming effects observed for each amendment (research question 1). We also found close association of priming effects with changes in microbial biomass, fungal abundances, carbon use efficiencies and metabolic quotients and show the significance of the dissolvable and hot water extractable carbon concentrations for predicting peak changes in microbial properties. Finally, we show how priming effects and soil carbon dynamics can be modelled with MiPrime, a *microbially mediated* multicompartmental decomposition model that distinguishes between *measurable* pools of endogenous (i.e. soil) and exogenous (i.e. amendment) organic carbon and their dissolvable, hot water extractable and insoluble carbon fractions (research question 2).

6.2.2 Effects of organic amendments on microbial properties and functioning under temperature change

Organic amendments can potentially make microbial communities more or less sensitive to environmental stresses, and even though these changes in sensitivity vary for different organic amendments, studies seldomly relate them back to the properties of the organic amendments applied. In Chapter 4, we investigated the implications of the rate of temperature change as a stressor and assessed the impact of different organic amendments on the microbial response to this change.

Results showed that microbial communities are sensitive to different rates of temperature change (research question 3). The different temperature treatment affected *microbial properties* such as DNA concentrations, ratios of bacterial to fungal DNA, respiration and priming rates, and *microbial functioning* given differences observed in dissolvable, hot water extractable and non-hydrolysable soil carbon and nitrogen fractions. We furthermore demonstrate that organic amendments can affect the microbial sensitivity to the rate of temperature change, but that this effect depends on the type of organic amendment applied. The grasses and fermented grasses amended soils demonstrated larger differences in a number of properties, while compost treatments resulted in smaller differences.

6.2.3 Temporal variability in organic amendment impacts on soil physical properties and its drivers

Organic amendments offer considerable value to agricultural systems in that their application can improve soil physical properties and thereby facilitate crop growth and improve soil resilience to climate extremes. However, impacts on soil hydro-physical properties vary in time depending on the amendments applied, seasonal soil conditions and management practices. In Chapter 5, I investigated the temporal variability in soil hydro-physical improvements for different amendments as a function of application quantity and quality at two live agricultural sites.

Our field experiments demonstrated that soil hydro-physical properties can improve within three years of repeated amendment application and that these improvements were more closely related to application rates than to the chemical composition of amendments. Data acquired through sampling multiple times per year for multiple years furthermore evidenced a significant temporal variability between seasons (research question 4). These temporal differences varied per amendment but could be as great as 10% for bulk density, 100% for infiltration capacity, 45% for aggregate stability and 70% for water retention. Inconsistent trends between the two investigated agriculture sites suggest that the temporal variability in amendment impacts are also strongly influenced by soil type and land management practices. In attempt to relate these observations back to the amendment properties, we found that no single quantity or qualitative amendment property could consistently explain the observed temporal variability.

6.3 SCIENTIFIC IMPLICATIONS AND FUTURE RESEARCH

Key findings summarized in the previous sections shed new light on a number of existing knowledge gaps and open the door to a set of future investigations that may further unravel the complex processes that drive organic amendment-soil interactions. The sections below reflect on the implications of the aforementioned findings and provide recommendations for future research.

6.3.1 Energetic versus stoichiometric characterizations and the composition of organic amendments

In this thesis, I explored how up to 22 different characterizations of the chemical composition of organic amendments relate to changes in soil properties. The outcomes of these investigations revealed that characterizations based on energetic properties (e.g. total, dissolvable, hot water extractable and insoluble carbon and nitrogen contents) were generally better predictors of soil impacts than stoichiometric indexes (C:N ratio, or even C:N ratios of energetic fractions). While both energetic and stoichiometric theories are frequently referenced, our results reveal a consistently greater predictive capacity for energetic characterizations. Stoichiometric indexes were furthermore rarely the best predictor for changes in any of the four investigated hydro-physical properties, at any field site, for any sampling moment (Chapter 5), nor were they strong predictors for peak changes in any microbial response variable for the laboratory incubation experiment (Chapter 2). Instead, application quantity and phosphorus content (Chapter 5), or energetic properties, such as the ratio of dissolvable to hot water extractable carbon (C_{DO}:C_{HW}), and total applied dissolvable carbon (C_{DO}) or nitrogen (N_{DO}; Chapter 2), proved much stronger predictors of soil impacts. Even when hybridizing both stoichiometric and energetic characterizations by determining the carbon to nitrogen ratio (stoichiometry) of different energetic fractions (e.g. C_{DO}:N_{DO}, C_{HW}:N_{HW}, etc.), characterizations based on pure energetic properties generally still performed better. Our findings indicate that energetic properties might have a similarly or more important role in driving changes in soil properties than stoichiometric properties.

While energetic characterizations are frequently used in other studies and models (e.g. YASSO; Liski et al., 2005) and correlate well with amendment impacts, their definition seems largely out of convenience, and our understanding of their composition and functional meaning is limited. Parsimonious wet chemical extraction methods used to derive these fractions are directed at extracting approximate groups of energetically similar polymers (e.g. sugars as dissolvable compounds, and ligneous and wax-like compounds as insoluble). However, these extracts are subject to significant chemical heterogeneity and do not always accurately reflect organic amendment structures or chemical compounds that control and arise from amendment decomposition (Johansson, Kögel, and Zech 1986; McKee et al. 2016; Preston et al. 1997). Analytical techniques such as chemolytic methods, analytical pyrolysis and solid-state ^{13}C NMR spectroscopy have been posed as alternatives but have different levels of resolution and vary in their ability to provide compositional information (Kögel-Knabner 2017). Given the relative strength of correlations observed between the explored proximate fractions and changes in soil properties, it would be interesting to develop these methods further so that we may isolate those polymers most relevant to steering microbial activity and decomposition processes driving specific soil impacts. Until then, it is recommended that studies use different existing methods in complementary ways to better assess which compounds drive amendment impacts.

6.3.2 Connections between microbial properties, microbial functionality and changes in soil chemistry

Soil microorganisms play a critical role in mediating the effects of organic amendments on soil properties. Yet, our findings show that soil chemical and physical changes can occur without detectable changes in soil microbial properties. This seeming disconnect between amendment impacts on soil chemical and physical properties versus impacts on microbial communities is well reflected in Chapter 4 but is likely also present in the other chapters, though masked. Somewhat similar observations have been made in other studies as well, where, for instance, significant differences in mineralization rates and enzyme activities coincided with the absence of significant differences in microbial indicator lipids (Mooshammer et al. 2017). Notably, studies have also found the opposite, with microbial composition being sensitive to external perturbations while its functioning was not ('functional redundancy'; Allison & Martiny, 2008). This functional redundancy within soil microbial populations is best evidenced by the limited set of metabolic pathways shared across a variety of taxonomic groups (Chen et al. 2022; Louca et al. 2018).

Establishing and formalizing relationships that link enzyme production to changes in microbial properties such as biomass, metabolism and diversity is necessary for a holistic understanding of combined microbial and decomposition dynamics. Enzymes form the critical link between microbial communities and the organic substances in their environment and largely define their interaction. Further study of enzyme diversity to explain differences in decomposition trends will further elucidate how different amendments impact a soil (Allison 2012; Allison et al. 2011; Baldrian 2009). Such insights may explain a number of uncertainties related to observed changes noted in Chapters 2, 4 and 5 and thus should be a topic of further investigation in understanding amendment impacts.

Finally, while microbial communities and associated enzyme dynamics are the principal agents of decomposition, abiotic processes are often disregarded despite possibly explaining observed disconnects between microbial properties and soil carbon and nitrogen transformations. Amendments can break down through a number of abiotic mechanisms, including photodegradation, thermal degradation, oxidation by reactive oxidation species, and/or inorganic chemical reactions (Wang, Lerdau, and He 2017). Factors like the prevalence of acids, soil mineral and metal catalysts may facilitate the decomposition of organic substances simultaneous to, or in the absence of, exoenzymatic processes driven by microorganisms. An absence of changes in soil microbial properties despite observing changes in soil chemistry suggests that potentially such abiotic (or non-microbial) drivers may have been operative. Abiotic decomposition processes have received relatively little attention compared to biotic ones. It is necessary that ambiguities surrounding abiotic processes are addressed so that we may better understand their relative contribution to the decomposition of amendments and their resulting impacts.

6.3.3 Physical barriers to organic amendment decomposition

In this thesis, I have explored the relative importance of different characterizations of the chemical composition of organic amendments and their relationships with changes in a number of soil biological, chemical and physical properties. These characterizations often explained a significant amount of the variations observed between treatments. Unexplained variation may derive from any number of factors, but an important one is likely the physical accessibility of amendments.

Microorganisms can only decompose amendments that their exoenzymes can physically reach and have chemical access to. The structural or morphological properties of an amendment, and/or the spatial constraints of a soil, may restrict this access and thereby affect decomposition. By this mechanism, the delayed or slow decomposition of certain organic amendments and their compounds may not necessarily be due to the chemical nature of the amendment, but rather to the microbial communities' limited physical accessibility to it. This accessibility can be influenced by the structure of the amendments, where potentially highly energetic compounds, such as sugars, may be initially protected by a barrier of lignin and, simultaneously, they will be influenced by the soil matrix where mechanisms such as mineral associations, occlusion by soil particles, or the lack of a transport medium such as moisture can influence the rate at which microorganisms can colonize a substrate (Angst et al. 2017; Prescott 2010; Pulleman and Marinissen 2004). While soil physical protection mechanisms have received some attention in other studies, the influence of the physical makeup or morphology of organic amendments has received relatively less attention. It would be valuable if future investigations on organic amendment impacts assess the relative importance of particle size, surface area, or other morphological aspects of amendments for decomposition and its impacts.

6.3.4 Temporal Dynamics of organic amendment impacts

The purpose of this research was to better understand the processes driving soil impacts so that we may better assess the value of different amendments for improving soils. However, assessing the performance of different organic amendments is complex given the substantial temporal variability observed for all soil properties investigated in the laboratory, field and modeling experiments. Not only does this variability add challenges in the interpretation of patterns (given that peaks may have been missed or highly transient changes accidentally captured), but it also complicates any comparison of amendments across studies sampling at somewhat different time frames. The temporality of organic amendment impacts is important, as cropping and weather cycles are also temporally variable. Therefore, organic amendment application strategies should consider this temporality if organic amendments are to achieve their intended effects.

Although amendment composition is used in models to assess temporal differences in soil carbon impacts (e.g. CENTURY model and many others), investigations outlined in Chapter 4 did not confirm such impacts for the temporal differences observed in the hydro-physical properties of our agricultural soil. The effect of amendment composition on the temporal dynamics of soil properties is complex as the slow, intermediate and fast reacting components of an amendment (Figure 6.2) can all be differently sensitive to factors such as temperature, the microbial community, moisture and the presence of other nutrients (co-metabolism). Echoing the recommendation for a further dissection of organic amendment composition based on parsimonious extraction methods (section 6.2.1), it would be valuable to determine the reaction rate of the different components of organic amendments so that we may better understand their individual contributions to the observed temporal variability. It is furthermore recommended that future studies increase their sampling frequency, as the temporal variabilities observed pose obvious concerns around comparisons made and conclusions derived from changes in soil properties measured at fixed yearly intervals (Cercioglu 2017; Ferreras et al. 2006; Tejada and Gonzalez 2008) or only once at the end of an experiment (Singh Brar et al. 2015; Yüksel and Kavdır 2020; Zhao et al. 2009).

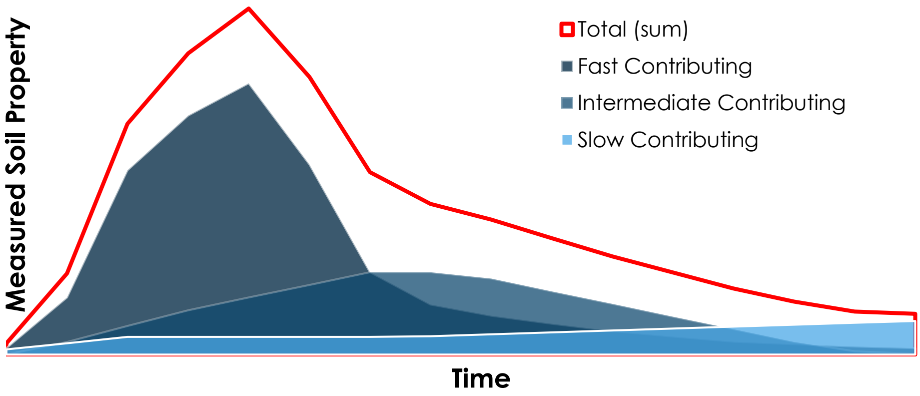

Figure 6.2. Conceptualization of amendment impacts on a soil property as the sum of fast, intermediate and slow contributing compositional amendment components.

Amendment impacts and general decomposition processes can be slow and may persist for many years after amendment application (Diacono and Montemurro 2011). Ultimately, an understanding of longer-term impacts is required as this information is more relevant for the management agricultural systems which similarly operate at longer timescales. This requires that research investigates impacts through long-term experiments (preferably decades). Long-term studies on amendment impacts may present much clearer insights into the effective sequestration and soil improvement potential of different organic amendments, as long-term effects can be substantially different from short-term ones (e.g. for priming effects; Fanin et al., 2020). Long-term studies could furthermore help establish the relative contribution of microbial products and decomposed compounds (e.g. mineral associated organic matter fractions, MAOM; (Cotrufo et al. 2019) versus selectively preserved amendment compounds (e.g. particulate organic matter fractions, POM; (Cotrufo et al. 2019) to stabilizing soil carbon over time and allow for an assessment of equilibrium states achieved by soils following recurrent amendment applications. Such studies could also help distinguish the extent to which observed soil improvements are derived from the d*irect effects* of the organic amendments themselves on soil properties, which are likely more related to changes in POM fractions, or whether they arise *indirectly* as a result of changes in SOM, which are likely more related to changes in MAOM fractions.

6.3.5 Artificial intelligence for analysing soil amendments

The development of effective amendment application strategies is constrained by the extensive complexities of the soil system and a lacking centralisation, consistency and coherency across research studies. There exist multitudes[2] of data on experiments for different amendments, characterized in different ways, applied to different soils, under different soil environmental conditions. Adding another layer of complexity are different means and methods by which organic amendments can be applied, such as the timeliness of application (e.g. application season), single versus repeated applications, shredding of amendments, soil integration or surface application methods, combining different amendments and/or mixing organic amendments with synthetic fertilizers. As with the natural-physical processes explored in this thesis, these application aspects also influence amendment impacts, yet they are significantly more controllable and are therefore warranted more thorough investigation.

Natural-physical processes and application strategy factors combined, the research opportunities are virtually inexhaustive, as any potential combination of relevant variables related to amendments, soil and environmental interactions could result in unique and previously unobserved dynamics of interest. This also complicates deriving any universal relationship for these interactions, as any observed relationship is likely to be highly context-dependent. These context dependencies certainly also explain recurrent reports of contrasting findings. The numerous interfaces with fields of ecology, microbiology, organic chemistry, biogeochemistry and other research fields further complicate research. It is humanly, practically impossible to take into account the innumerable confounding variables and inconsistencies in experimental setup and derive universal, quantified relationships from the volumes of existing studies. However, developments in computing and learning algorithms may soon change this.

Opportunely, at the time of composing this thesis, developers and data scientists have made great strides forward in making accessible artificial intelligence-based tools and algorithms that are of direct practical use for scientific research (e.g. ChatGPT, Consensus, Elicit, Scite, etc.). These tools, while still in their early development, offer new opportunities for future discoveries in soil amendment research as they are able to summarize and extract information from extensive databases of scientific publications and thereby make it more feasible to collate experimental data and other relevant information while making context-specific assumptions to fill in data gaps (e.g. assumptions on the climate data for a field experiment in the tropics). Mass standardization of available data by AI and subsequent integration of this data into comprehensive models could enable the development of more accurate predictive tools for assessing the impact of organic amendments on soil resilience. While having some obvious limitations as well, the power of learning models to scan and acquire, process and fill data could significantly change the field of soil research and aid

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[2] A quick search with keywords ‘soil’, ’organic’ and ‘experiment’ yields over 3,620,000 hits on Google Scholar (November 2023).

agricultural decision-making. It can take full advantage of the information acquired in the past to identify patterns and thereby steer future research.

6.4 AGRICULTURAL AND SOCIETAL IMPLICATIONS

In this section, I discuss the relevance of our findings for the management of mostly podzols and highlight take-aways from our research when designing amendment application strategies. A concise summary of the identified amendment-specific strengths is presented in Table 6.1, supplementing the more general findings described in the succeeding subsections.

Table 6.1. Summary of strengths per amendment when applied to a sandy soil. Note that not all benefits were assessed for every amendment.

Amendment	Benefits
Grasses	Microbial biomass growth (short-term) Increasing soil mineral nitrogen
Compost	Sequestering soil carbon Reducing bulk density Enabling seasonally persistent soil improvements Reduced sensitivity of soils to rapid temperature fluctuations
Bokashi	Reducing soil bulk density Reducing soil fungal growth compared to non-fermented grasses
Wood Chips	Sequestering soil carbon Immobilizing mineral nitrogen
Waterway residues	Increasing infiltration capacity
Grass & Manure	Increasing infiltration capacity Increasing aggregate stability
Bokashi & Manure	Increasing water retention

6.4.1 Application of organic amendments improve soil properties

The outcomes of investigations presented in Chapters 2 to 5 showed that the application of organic amendments, such as grasses, compost, bokashi, wood chips, and waterway residues, will always increase soil carbon and biomass concentrations (Chapters 2 to 4) and nearly always improve soil hydro-physical properties (Chapter 5), though to different extents. Accelerated decomposition of soil endogenous carbon following application of an organic amendment, i.e. priming effects, occurred to some degree for all of the amendments investigated, but these priming effects never resulted in an efflux of carbon greater than what was newly added in the form of the amendment. This reinforces the understanding that priming effects will have implications for the efficiency by which carbon is sequestered (Wang et al. 2022), but that amendments are unlikely to pose a risk to reducing soil carbon as carbon inputs overcompensate for any primed loss at least on the short-intermediate term (Fontaine et al. 2004; Jenkinson 1966; Kögel-Knabner 2017; Ohm, Marschner, and Broos 2011).

Microbial, hydro-physical and other soil properties also improved with the addition of nearly all investigated organic amendments, as shown consistently in the laboratory, field and modelling experiments. Only by exception were potentially agriculturally undesirable impacts observed, such as for i) woodchips reducing mineral nitrogen concentrations in a podzol (Chapter 2), compost and manure reducing winter water retention in a cropped Anthrosol, and Bokashi reducing summer aggregate stability in a cropped podzol (Chapter 5; none tested for statistical significance). In other studies, negative impacts on, for instance, infiltration rates have generally been observed for viscous organic amendments such as slurries, sludges and manures (España et al. 2019; Mamedov et al. 2016). Potentially, these were the result of amendments clogging soil pores and are thus more related to the physical or morphological properties of an amendment rather than its chemical properties. Regardless, our findings showed that the application of amendment are much more likely to improve soil physical properties than harm them and should a physical property be negatively impacted, then many other properties are still improved. These findings are encouraging, as they demonstrate the potential value that most organic amendments have for improving agricultural soils regardless of their specific chemical characteristics or origin.

Given the multifaceted impacts of organic amendments on soil quality indicators, it is recommended that future research further explores the impact of amendment applications directly on crop yields. Such data would contribute to completing our understanding of the potential value of organic amendments, allowing translation of their combined soil hydro-physical, chemical and biological impacts to changes in crop productivity. Assessment of organic amendment impacts on crop productivity would allow for an economic valuation of the benefits of different types of organic amendments – information that will further facilitate their adoption into conventional agricultural practices.

6.4.2 Potential importance of amendment quantity over quality

Findings show relatively high importance of application rate in driving soil improvements. Increased application rates resulted in greater enhancements in, for instance, soil physical properties, and generally demonstrated a closer relationship to the observed changes than variations in amendment chemical composition (Chapter 5). The clearest evidence is provided in Chapter 5, where different organic amendments are applied at different quantities and supplemented with mineral fertilizers to meet the nutrient input recommendations outlined in official guidelines. In the incubation experiments (Chapter 1 and 3), amendment quality differences drove short-term effects which then converged suggesting that application rates dominate intermediate (>3 months) to long term (>6 months) effects. Thus, as a rule of thumb, those aiming to improve their soils are likely better off investing their time and resources in increasing application quantity rather than increasing application quality.

6.4.3 Considerations of temporal variabilities in designing amendment application strategies

Previous chapters show that organic amendment impacts on soil properties can be affected by a strong temporal variability in soil response. For instance, in the incubation experiment, microbial biomass was observed to vary more than 200%, respiration rates more than 400%, nitrogen mineralization 300%, and carbon use efficiencies 300% within a single month after amendment application (Chapter 2). Data from the field experiment demonstrated differences in soil properties following amendment applications on bulk density of around 10%, infiltration capacity of 100%, aggregate stability of 45%, and water retention of 70% between seasons (Chapter 5). This variability was furthermore influenced by external factors such as different rates of temperature change (Chapter 4).

These temporal variabilities have significant implications for the benefits of organic amendment applications for agricultural soils, as expected improvements in mineral nitrogen concentrations or water retention may not yet have developed or already dissipated by the time they benefit crops the most. Experiments showed that no single organic amendment demonstrated an annually persistent improvement in properties, but compost produced the temporally most favourable impacts for most hydro-physical properties even though its impacts were not always the greatest in magnitude. Generally, the amount of amendment applied was of greater influence on improvements and differences between seasons than amendment quality indicators – provided, at least, that nutrient differences are offset through synthetic fertilizers. Our findings show that potential intra-annual variability of organic amendment impacts on soil properties needs to be considered when designing amendment application strategies such that the desired improvements in specific soil functions temporally align with seasonal challenges and different crop requirements throughout the cropping cycle.

6.4.4 Amendment applications to sequester carbon

Carbon sequestration is a principal reason to apply organic amendments to soils (Amelung et al. 2020; Lal 2004), though not all amendments are equally efficient in sequestering carbon given their own inherently limited carbon contents or due to their priming effects. Wood chips have relatively higher carbon concentrations than other amendments and were observed to result in lower cumulative carbon respiration than waterway residues, grasses, and fermented grasses. In short-term experiments, the application of woodchips is thus likely an effective amendment to sequester carbon. However, we did not assess priming effects of wood chips, and it is, therefore, uncertain what priming effect this amendment has on the residual carbon already in the soil. Assessing priming effects by grasses that were untreated, composted and fermented revealed that composted grasses had the lowest respiration rates when compared to other amendments. Relative to wood chips, composted grasses demonstrated relatively greater biomass growth which is understood to benefit carbon sequestration, as subsequent microbial necromass and by-products are significant contributors to stabilizing carbon pools (Kallenbach et al. 2015; Liang et al. 2019; Prescott 2010). However, contrary to our own results, composts have also demonstrated significant priming effects in other studies (San-Emeterio et al. 2023), and therefore quality, maturity and parent substrate of compost are likely important factors that influence its priming effect. Nevertheless, consensus is that compost is generally an effective amendment for accumulating soil carbon (Brown and Cotton 2011; Kutos et al. 2023; Spaccini and Piccolo 2020). Ultimately, if choosing between different organic amendments, then our data shows that selecting those amendments with a high proportion of hot water extractable to total carbon concentration is likely to result in less priming and, therefore, more effective sequestration. Our compost product was characterized as such, and given also findings in other studies, compost appears generally safe and more effective than other amendments for sequestering soil carbon.

6.4.5 Amendment applications to improve soil hydro-physical properties

Improvements in soil hydro-physical properties following amendment applications can benefit crop growth and improve soil resilience to climate extremes. Of the amendments investigated, no single amendment outperformed all others in relation to each of the investigated soil properties. Greatest improvements in *bulk density* were observed for compost (-9.8% in summer); in *infiltration capacity* for the combined grasses and manure treatments (108% in summer); in *aggregate stability* for the combined grasses and manure treatments (46% to 60% across seasons); and in *water retention* for bokashi and manure treatments (33% to 78% across seasons) – though effects can vary depending on soil type and/or management practices. Regardless of soil type, the amount of organic matter applied was a stronger predictor for observed improvements than any single property, explaining 92% of variation observed in bulk density, 42% to 52% for infiltration capacity, 57% to 69% for aggregate, and 82% to 94% for water retention, depending on the season.

Therefore, efforts might initially focus on increasing the quantity of organic matter inputs rather than their quality for the purpose of improving soil hydro-physical properties.

6.4.6. Amendment applications to improve microbial biomass and diversity

Microorganisms mediate amendment impacts on soil chemical and hydro-physical properties, and due to this critical role, microbial community structure and diversity are proposed as indicators for soil quality (Sharma et al. 2011). Moreover, microorganisms offer agro-ecological benefits that are less explicit than soil chemical and physical properties. Through their impacts on microbial biomass and diversity, organic amendments might enable the development of a more robust ecosystem as a whole.

Experiments in this thesis demonstrate the greatest peaks in biomass (>300% on day 7, Appendix D) and the largest shifts in diversity (>400%, Appendix D) for the grasses amendment treatment (Chapter 2). The dissolvable to hot water extractable carbon ratio was the strongest predictor for peak biomass change, and the dissolvable carbon fraction for changes in microbial diversity (i.e. the fungal to bacteria ratio; though not statistically significant). While larger ecological implications were not investigated in this thesis, it may be deduced that frequent application of amendments with high dissolvable and low hot water extractable organic carbon fractions (e.g. grasses and likely other light, leafy green biomass) are greater stimuli for microbial growth in the short term. 150 days after amendment application, the effects of the grasses treatments had mostly diminished while impacts of the compost-amended soils grew more evident. Those soil managers looking to stimulate below-ground, microbial biomass growth and diversity could thus be recommended to frequently apply amendments with a high dissolvable to hot water extractable carbon ratio, such as the unprocessed grasses residues.

6.4.7. Raw application, composting or fermenting amendments

Because the chemical composition of amendments can, to a certain extent, affect their impacts, treatments that manipulate the chemical composition of amendments, such as composting and fermentation, might offer a means to upgrade amendments which may otherwise have potentially limited or non-required soil impacts. In the experiments underlying this thesis, we composted and fermented grasses and assessed changes in the stoichiometry and proximate fractions when compared to untreated grasses. A comparison of the properties for each showed unique shifts in chemical composition where *composting* lowered carbon and nitrogen concentrations (-31% and -23% on average), lowered C:N ratios (-11%), raised hot water extractable to total carbon ratios (63%), and lowered dissolvable to hot water extractable carbon ratios (-47%; Table 6.2); and *fermentation* did not affect total carbon concentrations but, contrastingly, raised C:N ratios (17%) and markedly lowered dissolvable and hot water extractable carbon concentrations (-58% and -44%; Table 6.2).

Table 6.2. Change in chemical properties of grasses after composting and bokashi fermentation. Raw data presented in Appendix H.

Chemical Property		**Composting**	**Bokashi Ferm.**
		Change rel. to parent material	Change rel. to parent material
C_x: N_x	**C_{TOT}: N_{TOT}**	-11% ± 8%	17% ± 7%
	C_{IS}:N_{IS}	24% ± 22%	51% ± 16%
	C_{AH}:N_{AH}	-61% ± 73%	-39% ± 48%
	C_{HW}: N_{HW}	6% ± 20%	-14% ± 11%
	C_{DO}: N_{DO}	10% ± 16%	23% ± 13%
N_x	**N_{TOT}**	-23% ± 6%	-14% ± 6%
	N_{IS}	-44% ± 20%	-35% ± 14%
	N_{AH}	70% ± 57%	79% ± 30%
	N_{HW}	21% ± 20%	-24% ± 8%
	N_{DO}	-46% ± 11%	-65% ± 12%
C_x	**C_{TOT}**	-31% ± 5%	1% ± 5%
	C_{IS}	-31% ± 9%	-1% ± 6%
	C_{AH}	-35% ± 46%	9% ± 37%
	C_{HW}	11% ± 11%	-44% ± 7%
	C_{DO}	-41% ± 10%	-58% ± 7%
C_x:C_{TOT}	**C_{IS}: C_{TOT}**	1% ± 11%	-2% ± 9%
	C_{AH}: C_{TOT}	-5% ± 46%	8% ± 37%
	C_{HW}: C_{TOT}	63% ± 11%	-44% ± 9%
	C_{DO}: C_{TOT}	-14% ± 11%	-58% ± 8%
C_{DO}:C_x	**C_{DO}: C_{IS}**	-15% ± 14%	-57% ± 10%
	C_{DO}: C_{AH}	-9% ± 47%	-61% ± 37%
	C_{DO}: C_{HW}	-47% ± 15%	-25% ± 11%

Compost and Bokashi products impacted soil properties differently despite being derived of the same parent material. Per gram of material applied, composted grasses resulted in lower priming effects, increased carbon use efficiencies, reduced fungal DNA concentrations, and reduced nitrogen and carbon mineralization rates. These findings suggest that composting grasses, and potentially similar substrates, may be an effective means to reduce an amendment's priming effects, fungal growth, and carbon and nitrogen mineralization rates. We applied a different (commercial) compost in our field experiments for assessing compost impacts on soil hydro-physical properties, but when compared to waterway residues and grasses, this compost demonstrated no substantial greater improvement in bulk density and aggregate stability, and actually had relatively lowered impacts on infiltration capacity and water retention – though dependent on the site and season. Compost might therefore have greater chemical impacts than soil hydro-physical ones, though differences in compost quality and parent material certainly also contribute to discrepancies in impact between the incubation (chemical) and field (hydro-physical) experiments. Of course, other reasons for composting also include prevention of weed propagation by seeds in the parent material and avoidance of pests (e.g. mice) that might otherwise be attracted to an amendment if applied to a soil untreated.

Bokashi fermentation resulted in mostly similar impacts as observed for the untreated grasses amendments, except that fermentation reduced fungal growth and reduced the amount of nitrogen mineralized. This suggests that bokashi fermentation might be an effective treatment to suppress fungal growth and nitrogen mineralization while retaining the benefits of high peaks in total biomass growth as observed for the untreated grasses amendment. For the field experiment, bokashi made from a mix of tree leaves was compared to waterway residues, thus again not sharing the same parent material as for the laboratory and field compost comparison. In the field experiment, bokashi showed lower impacts on infiltration rates but marked greater impacts on aggregate stability and water retention compared to untreated waterway residues. A comparative assessment for bulk density could not be made as waterway residues were not applied in the same year as the bulk density measurements (the final year of the experiment). Findings implicate that bokashi fermentation might be a method to enhance the aggregate binding potential and improve the water retention impact of an amendment, though more research is needed to establish whether this inference holds true for other amendments or whether the difference in parent material was the cause for this effect.

Despite these encouraging findings, it should be considered that the composting process itself also resulted in a 45% loss of the carbon concentration while fermentation resulted in a 20% loss (Chapter 2). This carbon was microbially respired during the treatment processes. For composts specifically, studies show that for every gram of compost applied, one needs approximately 1.12 to 1.46 grams of parent material simply due to this intermediate decomposition occurring during composting (11.5% to 31.4% loss in mass; Breitenbeck & Schellinger, 2013). If the amount of compost and bokashi applied in each experiment was reduced to reflect the amount of parent material lost over the composting process, then certainly their impacts will be reduced as well. Thus, if amendment supplies are limited, it may be more sensible to apply the amendment in raw form given that the experiments in this thesis have demonstrated the importance of quantity over quality, at least for improving soil hydro-physical properties.

Finally, although this study highlighted the potential of grasses and waterway residues as effective organic amendments in their raw form, further research is needed to evaluate the practicality of their application, variability in their chemical composition and quality, and their potential pathogenic properties and pollutant concentrations. Grasses, for instance, were difficult to integrate in the soil as they stuck to the tillage and harrow blades, thus potentially hindering their application at an agro-industrial scale unless shredded or otherwise processed - which may, in turn, affect their soil impacts. Other investigations have already expressed concerns around the application of waterway residues given the potential introduction of pathogens such as Ralstonia (Freark Beuckens et al. 2017) and have demonstrated the impact of grass maturity on its quality which may affect its impacts (Verbeke et al. 2013). Nevertheless, grasses recovered from public green areas demonstrated significant and favourable impacts on different soil properties, which merits further exploration of their potential use in agricultural settings.

6.4.8. Adoption of application practices by farmers

As different kinds of organic wastes and residues are generally readily available, their rejection or adoption for use in agriculture is largely determined by farmers. Implementing the use of amendments in agriculture therefore warrants a comprehensive understanding of farmer decision-making. Only then robust supply and demand chains can be established to form a sustainable network of organic residue producers and consumers.

Farmers’ experiences, norms and values, subjected to the influences of social, economic and legal contexts, are important variables affecting farmer decision-making (Happel et al. 2022). Studies have already identified a number of factors that result in the rejection of application practices, including: i) perceived economic infeasibility (Viaene et al. 2016); ii) expected high production costs (Aznar-Sánchez et al. 2020); iii) a lack of information and knowledge on application techniques (Bijttebier et al. 2015; Happel et al. 2022); iv) uncertainties around pathogens and weed propagation (Hijbeek et al. 2018); and v) a lack of access to appropriate machinery, storage or advisory services (Montanarella and Panagos 2021). Furthermore, cultural norms and legal and regulatory frameworks can also disqualify specific organic residues from agricultural use. For instance, the application of treated sewage sludge is often considered taboo, even when properly handled, sanitized and demonstrably safe. The ‘waste’ status of an organic residue may legally prohibit its application to soils or transportation from production to demand sites. Social, economic, cultural and legal drivers will thus in many cases be of greater importance than the differences in the hot-water extractable concentration in determining whether an amendment is utilized as a soil improver or not.

6.4.9. Other uses for organic residues

Organic wastes and residues are a diverse resource that can also be utilized for purposes other than as agricultural fertilizers and soil improvers. Depending on their characteristics, organic wastes can be used as biomass for bioenergy generation, as a resource for biobased products (e.g. paper) or as livestock fodder (Biomassa Alliantie 2017). The socially and economically optimal use of organic residues will depend, among other, on the local needs, the quantity and type of residues available and the proximity of sites of production to sites of demand. Case-by-case cost-benefit analyses should thus be made to determine whether organic residues are most effectively used as a soil fertilizer or otherwise.

Further consideration should also be given to the ecological implications of using organic residues from the maintenance of urban and rural greenspaces. The critical importance of green spaces such as verges, fringes, gardens and parks for biodiversity and ecological resilience is well established, serving as habitats and corridors for the movement of insects and larger wildlife (Beaugeard, Brischoux, and Angelier 2021; Lepczyk et al. 2017). However, in rural and urbanized environments these are often intensively managed and maintained for aesthetic and/or safety reasons. Instead of recovering organic material from these spaces, the biomass might sometimes better be left undisturbed, provided the potential benefits of limited intervention to the ecological value of a greenspace. In cases where nutrient concentrations exceed optimal levels for biodiversity, which is frequently the case for such green spaces, biomass should rather be removed to restore a natural nutrient balance. Ecological assessments per urban area or greenspace will help identify the optimal degree of intervention required, taking into consideration the local aesthetic, safety, agricultural, economic and ecological requirements and ambitions.

6.4.10 Global Outlook

Organic wastes make up about 46% of all solid wastes in the world (Chavan et al. 2022). As populations grow and urbanize, and the resource use per capita further intensifies, future organic waste streams will also continue to increase. The large volumes of organic wastes present an opportunity to reduce nutrient losses in the food chain by recycling organic residues. These efforts are further stimulated by onsetting climate change, whose effects are expected to worsen even in even the most optimistic IPCC scenarios (IPCC et al. 2021). One strategy to both mitigate and adapt to climate change, while contributing to food and water security, is to replace or at least supplement mineral fertilizers with organic wastes/fertilizers (IPCC et al. 2021). Thus, both demographic and climatic prospects encourage consideration of the opportunities that organic waste streams offer by reducing nutrient pollution, storing carbon, remediating soil depletion, building long-term soil fertility and enhancing the climate resilience of our agricultural production systems.

The benefits of organic amendment applications in agriculture can be reaped by both developed as well as developing economies, though the motivation and implementation speeds may vary between the two. In economically developed countries, established infrastructure and regulatory organisations may facilitate the establishment of supply-demand chain networks, thereby accelerating the adoption of amendment application practices. The emphasis of organic amendment applications in such economies will likely be predominantly on the circular economic development, carbon mitigation and soil remediation potential of organic wastes and residues. In economically developing countries, the utilization of organic amendments will uniquely benefit agricultural sites with limited access to synthetic fertilizers. Though potentially inhibited by limited infrastructure and machinery, the small-scale, local utilization of organic wastes offers a semi-effective substitute to synthetic fertilizers with the added benefit of building long-term soil fertility (improving soil physical properties, among other) at limited costs. In both economies, those regions that stand to benefit most are those areas where soils are degraded most or are of naturally low fertility. However, even at a national level, the perceived barriers and opportunities that farmers associate with organic amendment application practices vary strongly (Happel et al. 2022). At the global level, these differences may be even more pronounced. It is therefore difficult to determine precisely which social, logistical, cultural, legal and economic hurdles are to be overcome in normalizing organic amendment applications in agriculture globally as these will be highly regionally dependent. Nevertheless, once adopted, the regular application of organic amendments to soils can offer another small but effective contribution to the long-term productivity and sustainability of agriculture regardless of social and economic contexts.

6.5 CONCLUSION

To positively steer farmer sentiment in favour of organic amendment application practices, it is important that we are able to better predict the multifaceted responses that soils have to different organic substances. In this research, we revealed how the application of organic residues with a low proportion of hot water extractable to total carbon concentrations may reduce priming effects, potentially allowing for more efficient sequestration; that extreme rates of temperature change have limited impacts on soils but that amendments can affect this impact resulting in changes in soil carbon and nitrogen fractions; that amendment application quantity is likely to play a more important role in driving soil hydro-physical improvements than amendment quality; and that any soil impacts are temporally highly variable and that therefore not all organic residues are equally effective in combating specific seasonal challenges (i.e. droughts and floods). Our multicompartmental model, MiPrime, allows for the assessment of short-term carbon dynamics following the application of theoretically any kind of organic amendment. In contrast to existing models, MiPrime allows for such assessments (incl. priming effects) to be made based on changes in mostly measurable carbon pools and fractions through explicit microbially mediated processes. Together, these findings and tools add another piece to the puzzle of understanding organic matter quantity and quality influences on soil response, the role of microorganisms in this process, and the value of different amendments to improving soil functions for crop production and carbon sequestration purposes.

As both climate change risks and economic opportunity slowly drive policymakers and agronomists towards the re-adoption of organic amendment application practices in conventional agriculture, it is important that the scientific community continues its efforts to further unearth the complex processes and interactions *driving* amendment impacts. By developing this knowledge we may enable farmers to maximally exploit the potential that organic amendments have to offer in making our food production systems more sustainable and resilient to the challenges of soil degradation and climate change. Developing and implementing this knowledge will contribute to expediting our necessary transition into the era of climate-smart agriculture.