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Soil organic amendments for climate-smart agriculture

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SUMMARY

The importance of organic matter in enhancing a soil's fertility is widely recognized. Organic matter contributes to the development of good soil structure and is an important source of nutrients for plants and soil-dwelling organisms. The application of organic waste to arable land as fresh biomass, compost, or derivative products has thus established itself as an ancient and traditional soil-improvement and waste-discarding strategy that is historically practiced in agricultural societies around the world. Nowadays, organic fertilizers play a less important role in our food production as fast-acting, easy-to-store, and simple-to-spread synthetic fertilizers have largely come to replace them.

In the current context of climate change and the need for climate-smart agriculture, however, organic amendments may come play an important role yet again. With their improvement of chemical and physical properties of agricultural soils, organic amendments can, for instance, increase the resilience of our crop production systems against climate extremes. Additionally, they are an effective means to sequester carbon and can thereby compensate for some of our greenhouse gas emissions. As a sustainable soil management practice, organic amendments can make our food production systems more resilient to the challenges of soil degradation and climate change, ultimately expediting our transition to climate-smart agriculture.

Whether organic amendments can meet expectations around soil improvement and carbon sequestration, however, depends on a multitude of factors. The diversity of organic amendments, the influence of many environmental factors on their decomposition, and the complexity of interactions with soil microorganisms make it difficult to determine how and through which mechanisms organic amendments impact soils. This uncertainty hinders the design of efficient and effective organic amendment application strategies and inhibits the utilization of readily available organic waste products as soil improvers.

This thesis aims to promote the effective and efficient use of organic residues by providing better insight into the complex relationships between the properties of organic amendments and changes in soil microbial communities and soil properties. In six chapters, I explore the relationship between the composition of organic amendments with changes in soil microbial communities and soil carbon dynamics (Chapter 2); present a soil model that can predict the effects of different organic amendments on soil carbon dynamics and so-called 'priming effects' - a change in the decomposition rate of soil-native carbon after applying organic amendments (Chapter 3); investigate the influence of organic amendments on the resistance and resilience of soil and soil microbial communities against extreme temperature changes (Chapter 4); and explore the influence of organic amendments on the development of soil physical properties within and between years after repeated application (Chapter 5). The

findings from these laboratory, field, and modelling experiments are then summarized in a final chapter (Chapter 6), where I additionally discuss their agricultural and social implications and set out a path forward for future research. The paragraphs below briefly outline in further detail the contents of each chapter.

In **Chapter 2**, I analyse correlations between twenty-two different characterizations of organic matter with changes in eleven microbial properties and processes and priming effects. Results from a 150-day laboratory experiment show that the concentration of hot water extractable carbon in organic amendments is a better predictor of priming effects than some of the existing popularly relied upon indexes of amendment quality such as those based on amendment stoichiometry. I also reveal that these priming effects correlate strongly with changes in microbial DNA concentrations, microbial biomass and metabolic quotients. The Chapter is concluded with a recommendation to integrate energetic principles into the modeling of microbial-driven carbon transformations and a reiteration that organic amendments with high concentrations of hot-water-soluble carbon can likely sequester soil carbon more efficiently per gram of amendment applied.

In **Chapter 3**, I utilize the data from the experiment described in Chapter 2 to develop MiPrime, the ‘**MI**crobially mediated **PR**iming effects model with **ME**asurable organic carbon pools’. MiPrime offers a framework for the mechanistic modelling of organic amendment impacts on microbially mediated transformation of organic carbon and allows for assessment of the priming effects of different organic amendments. Validation exercises demonstrate that the model is able to predict short-term carbon dynamics with good accuracy but that there is room for improvement in predicting changes in carbon fractions of the soil endogenous carbon pool. MiPrime demonstrates promise as a new tool for understanding amendment impacts and designing amendment application strategies.

In **Chapter 4**, I explore the potential of organic amendments to alter the sensitivity of microbial communities to rates of temperature change. The rate of temperature change is generally assumed not to impact soil microorganisms and is thereby disregarded as a mechanism in carbon models. However, different rates of temperature change may trigger different microbial stress responses, given the reliance of microbial defensive mechanisms on time-dependent signalling and activation processes. To explore those responses and the potential impacts of organic amendments thereupon, I monitored the changes in soil microbial properties and concentrations of different carbon and nitrogen fractions to temperature change treatments of 2.5 and 30 °C d⁻¹ after the application of three different organic amendments. The experiment demonstrates that the rate of temperature change affects bacterial and total microbial DNA concentrations, as well as dissolvable and insoluble carbon and nitrogen ratios regardless of the organic amendment treatment. Organic amendments influenced the effect of temperature on microbial respiration rates, priming rates and the concentration of soil hot water extractable carbon and nitrogen. This study further demonstrates how organic

amendments may be used to manipulate the impact of environmental stresses on soil processes.

In **Chapter 5**, I investigate the effects of organic amendments on physical soil properties and their development over time in an agricultural setting. The results show that organic amendments improve soil physical properties, but that these improvements varied greatly within a year, up to 10% for soil density, 100% for infiltration capacity, 45% for aggregate stability, and 70% for water retention, for a given amendment. The results did not reveal a consistent link to any single amendment property, but suggest that temporal differences are more closely related to differences in application quantity than application quality. Our findings highlight the importance of considering the potential intra-annual variability of amendment impacts when comparing different amendment studies and when designing amendment application strategies for the purpose of combating specific seasonal climatic challenges.

Finally, in **Chapter 6**, I summarize our findings and discuss the implications for the application of organic amendments in agriculture and for future research. As a rule of thumb, I postulate that applying amendments in higher *quantity* is generally more worthwhile than applying higher *quality* ones, especially for improvements in soil physical properties. I also recommend to look beyond carbon and nitrogen ratios in defining amendment quality, and, as one of many avenues for future research, suggest to further explore the potential importance of the hot-water extractable carbon fraction, given its close association with changes in a number of microbial properties. Finally, I discuss the opportunities of applying new techniques in data analysis made available with the advent of accessible artificial intelligence. Such tools may more easily get a grip on the overall complexity of the soil system and the vast amounts of studies published in this field on a daily basis.

Together, the findings from this research underscore the value of organic amendments to improving agricultural soils and thereby our food production systems. Although their precise effects on the range of different soil properties are difficult to predict, amendments demonstrate clear potential to improve soil structure and partially offset our CO₂ emissions. Providing further insight into relevant soil processes driving these effects, this thesis sheds additional light on the value of organic amendments for sustainable soil management and climate resilient agriculture.