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DISSERTATION SUMMARY

The effect of soil management practices on the labile fraction of soil organic matter and related indicators.

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Dissertation summary

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Abstract

Soil serves as an indispensable resource for global agriculture, with soil health and fertility influenced by factors like soil organic matter. Organic matter can be categorized into living (roots and organisms) and non-living parts. The non-living part includes labile and stable fractions of soil organic matter, each with distinct properties. Labile fraction of soil organic matter, derived from plant parts and organisms, is more or less decomposable, has marginal cation-exchange capacity, provides substrate and food for soil microorganisms as well determines the soil fertility regime. In contrast, stable fraction of soil organic matter, comprising fulvic and humic acids, along with humins, exhibits high cation-exchange capacity, stability, and long-term carbon storage. This conceptualization enhances understanding of soil organic matter's role in assessing stable and labile fractions of organic matter quantity and quality. It also aids in studying soil organic matter build up, decomposition, turnover, and related monitoring indicators.

This thesis aimed to delve into the impacts of soil management practices on soil organic matter, placing a specific emphasis on the labile fraction of soil organic matter and associated indicators across different environments. Both short and long-term experiments were analyzed to assess the impact of land use and management practices on total, labile, and stable fractions of soil organic matter. The thesis also included meta-analyses and review to explore approaches in assessing soil organic matter dynamics for sustainable management, incorporating beneficial microorganisms such as entomopathogenic fungi and lactic acid bacteria in agriculture.

The findings demonstrated that while small changes in the total soil organic matter or carbon may be challenging to detect due to high background levels and natural soil variability, the sub-pools of soil organic matter or carbon prove to be more sensitive indicators of changes in the overall pool size. It has been observed that the labile fraction of soil organic matter is particularly responsive to management practices, although it also influences the formation of stable fractions and the overall total soil organic matter carbon.

The results also provided an overview of diverse approaches and methods for assessing soil organic matter dynamics, focusing on processes related to decomposition, lability, and stabilization. Various parameters, including oxidation kinetics, carbon management index, humification degree, and others, were evaluated for both quantitative and qualitative analyses of soil organic matter. The thesis emphasized the importance of developing soil organic matter models (analytical and simulation) and assessment techniques based on soil properties, environmental factors, and management practices for sustainable soil management.

Furthermore, the thesis introduced a modified method for organic matter fractionation into labile and stable fractions, demonstrating its efficiency in assessing the quality and quantity of primary soil organic matter and stable organic fractions. The new method exhibited sensitivity, speed, and ease of repeatability, making it a promising tool for practical soil organic matter evaluation.

The impact of land use and cover changes on soil organic matter dynamics was studied. The results demonstrated substantial variations in total soil organic matter carbon (TSOMC), carbon lability (CL), and carbon stability (CS) among different land use types. Forestland and organic farming

displayed significantly higher TSOMC, CL, and CS compared to fruit orchard lands, small-scale conventional farming, alternative fallow and conventional farming, large-scale conventional farming, and pastureland. Organic farming and forestland also exhibited elevated carbon management index (CMI) values, while pastures and forests showed higher stability ratios (SR) in comparison to other land use types. This underscores the crucial need to understand soil organic matter dynamics in the face of changing land use patterns, advocating for sustainable management practices and the use of the carbon management index and stability ratio as pivotal indicators in sustainable land management.

Finally, beneficial microorganisms were elucidated. The role of entomopathogenic fungi went beyond traditional pest management, as revealed by the thesis. These fungi positively influenced soil aggregation, organic matter, and nutrient recycling, contributing to overall soil health and plant growth. The thesis suggested that entomopathogenic fungi could play a vital role in nutrient recycling, soil health improvement, and acting as bodyguards for plant growth and productivity. Similarly, the thesis shed light on the less-explored relevance of lactic acid bacteria in soil-plant systems. Lactic acid bacteria, known for their probiotic nature, were identified as integral to promoting plant growth, improving soil health, serving as bio-fertilizers, biocontrol agents, and bio-stimulants. The thesis calls for increased acceptance of these microorganisms as sustainable and safe soil and plant health enhancers.

Overall, this thesis contributes valuable insights into soil organic matter dynamics, sustainable management practices, and the multifaceted roles of beneficial microorganisms in enhancing soil health and productivity. The findings emphasize the importance of holistic approaches to soil management for the sustainability of agricultural systems.

Keywords: soil organic matter dynamics, labile fraction of soil organic matter, stable fraction of soil organic matter, management practices, indicators of soil organic matter change.

Abstrakt

Půda je nepostradatelným zdrojem v globálním zemědělství, přičemž zdraví a úrodnost půdy ovlivňují faktory, jako je organická hmota v půdě. Organické látky lze rozdělit na živé (kořeny a organismy) a neživé části. Neživá část zahrnuje labilní a stabilní frakce půdní organické hmoty, z nichž každá má odlišné vlastnosti. Labilní frakce půdní organické hmoty, pocházející z rostlinných částí a organismů, je více či méně rozložitelná, nedisponuje kationtovou výměnnou kapacitou, ale slouží jako zdroj energie pro půdní mikroorganismy a tím ovlivňuje půdní úrodnost. Naproti tomu stabilní frakce půdní organické hmoty, obsahující fulvokyseliny, huminové kyseliny a huminy, vykazuje vysokou kationtovou výměnnou kapacitu, stabilitu a uhlík v půdě ukládá dlouhodobě. Tato konceptualizace zlepšuje porozumění úloze organické hmoty v půdě při hodnocení množství stabilních a labilních frakcí organické hmoty a jejich kvality. Pomáhá také při studiu přeměn půdní organické hmoty a souvisejících monitorovacích ukazatelů.

Tato práce si kladla za cíl prostudovat dopady hospodaření na půdní organickou hmotu se zvláštním důrazem na labilní frakci a související indikátory napříč různými prostředími. Byly realizovány krátkodobé i dlouhodobé experimenty, aby se posoudil dopad využívání půdy na celkové, labilní a stabilní podíly organické hmoty v půdě. Práce také zahrnovala metaanalýzy a přehledy k prozkoumání přístupů při hodnocení dynamiky půdní organické hmoty pro udržitelné hospodaření, zahrnující prospěšné mikroorganismy, jako jsou entomopatogenní houby a bakterie mléčného kvašení v zemědělství.

Výzkumy ukázaly, že zatímco malé změny v celkovém obsahu půdní organické hmoty nebo uhlíku mohou být obtížně detekovatelné kvůli přirozené variabilitě půdy, naopak dílčí frakce půdní organické hmoty nebo uhlíku se ukázaly být citlivějšími indikátory změn v zásobách organické hmoty v půdě. Bylo pozorováno, že labilní frakce půdní organické hmoty zvláště reagují na postupy hospodaření, ale také ovlivňují tvorbu stabilních frakcí a celkový uhlík půdní organické hmoty.

Výsledky také poskytly přehled různých přístupů a metod pro hodnocení dynamiky půdní organické hmoty se zaměřením na procesy související s rozkladem, labilitou a stabilizací. Při kvantitativní i kvalitativní analýze půdní organické hmoty byly hodnoceny různé parametry, včetně oxidační kinetiky, indexu hospodaření s uhlíkem, stupně humifikace a dalších. Práce zdůraznila význam vývoje modelů půdní organické hmoty (analytických a simulačních) a hodnotících technik založených na půdních vlastnostech, environmentálních faktorech a postupech hospodaření pro udržitelné hospodaření s půdou.

Dále byla v práci představena upravená metoda frakcionace organické hmoty na labilní a stabilní frakce, prokazující její účinnost při hodnocení kvality a množství primární půdní organické hmoty a stabilních organických frakcí. Nová metoda vykazovala citlivost, rychlost a snadnou opakovatelnost, což z ní činí slibný nástroj pro praktické hodnocení organické hmoty v půdě.

Byl studován dopad změn využívání půdy a pokryvu na dynamiku půdní organické hmoty. Výsledky ukázaly podstatné rozdíly v celkovém uhlíku v půdní organické hmotě (TSOMC), uhlíkové labilitě (CL) a uhlíkové stabilitě (CS) mezi různými typy využití půdy. Lesní půda a ekologické zemědělství vykazovaly výrazně vyšší TSOMC, CL a CS ve srovnání s ovocnými sady,

konvenčním zemědělstvím v malém i velkém měřítku, ladem ležící půdou a pastvinami. Ekologické zemědělství a lesní půda také vykazovaly zvýšené hodnoty indexu hospodaření s uhlíkem (CMI), zatímco pastviny a lesy vykazovaly vyšší poměr stability (SR) ve srovnání s jinými typy využití půdy. To podtrhuje zásadní potřebu porozumět dynamice půdní organické hmoty tváří v tvář měnícím se vzorcům využívání půdy, obhajovat udržitelné postupy hospodaření a používání indexu hospodaření s uhlíkem a poměru stability jako klíčových ukazatelů udržitelného hospodaření s půdou.

V neposlední řadě byly studovány prospěšné mikroorganismy. Role entomopatogenních hub přesahovala tradiční ochranu proti škůdcům, jak práce ukázala. Tyto houby pozitivně ovlivnily agregaci půdy, organickou hmotu a recyklaci živin, což přispělo k celkovému zdraví půdy a růstu rostlin. Práce naznačila, že entomopatogenní houby by mohly hrát zásadní roli v recyklaci živin, zlepšování zdraví půdy a působit jako stimulanty pro růst a produktivitu rostlin. Stejně tak práce osvětluje méně prozkoumaný význam bakterií mléčného kvašení v systémech půda-rostlina. Bakterie mléčného kvašení, známé pro svou probiotickou povahu, byly identifikovány jako nedílná součást podpory růstu rostlin, zlepšování zdraví půdy a sloužící jako bio-fertilizéry, biokontrolní činidla a biostimulanty. Práce vyzývá ke zvýšení akceptace těchto mikroorganismů jako udržitelných a bezpečných látek zlepšujících zdraví půdy a rostlin.

Tato práce jako celek rozšiřuje možnosti, jak nahlížet na dynamiku půdní organické hmoty, udržitelné postupy hospodaření a popisuje role prospěšných mikroorganismů při zlepšování zdraví půdy a produktivity. Zjištění zdůrazňují význam holistických přístupů při hospodaření s půdou pro udržitelnost zemědělských systémů.

Klíčová slova: dynamika půdní organické hmoty, labilní frakce půdní organické hmoty, stabilní frakce půdní organické hmoty, postupy hospodaření, indikátory změn půdní organické hmoty.

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List of abbreviations

SOM: Soil organic matter
PSOM: Primary soil organic matter
POM: Particulate organic matter
fLFOM: Free light fractions organic matter
oLFOM: Occluded light fractions organic matter
maom: Mineral associated soil organic matter
CEC: Cation-exchange capacity
pH: Potential of hydrogen
H_2SO_4: Sulfuric acid
$K_2Cr_2O_7$: Potassium dichromate
H_2O_2: Hydrogen peroxide
CO_2: Carbon dioxide
HCl: Hydrochloric acid
CuO: Copper (II) oxide
TMAH: Tetramethylammonium hydroxide
NaOH: Sodium hydroxide
$Na_4P_2O_7.10H_2O$: Sodium pyrophosphate decahydrate
LAB: Lactic acid bacteria
LOI: Loss on ignition
WB: Walkley-Black
NIR: Near-infrared reflectance
PyMS: Pyrolysis mass spectroscopy
NMR: Nuclear magnetic resonance
ESI-FTICR-MS: Electrospray ionization fourier transform ion cyclotron resonance mass spectrometry.
CPI: Carbon pool index
L: Lability
LI: Lability index
HI: Humification index.
HD: Humification degree
HR: Humification rate
TOC: Total organic carbon
TC: Total carbon
Ds: Soil bulk density

1. Introduction

Soil organic matter (SOM) plays a critical role in maintaining soil and ecosystem quality and functionality across different land use and management scenarios. Its multifunctional nature means that SOM loss from soil can impair various aspects of overall soil quality, including structural stability, water holding capacity, carbon sequestration, and nutrient status. However, confusion often arises between primary soil organic matter, humus, and soil organic matter concepts, leading to misunderstandings in research and practice. The loss of oxidizable carbon in soil is commonly mistaken as the loss of humus, although it primarily involves the loss of primary soil organic matter, which is the most labile fraction and easily decomposable due to increased micro-edaphon activity. This loss can actually lead to an increase in the content of actual humus, which is the stable fraction of soil organic matter. While the stable fraction of SOM determines long-term soil carbon storage, the labile primary SOM determines the nutrient regime of the soil. Hence, an increased content of easily decomposable components of SOM is considered a significant feature of potential soil productivity. Additionally, ongoing debate surrounds the stability of soil organic matter fractions, with some studies suggesting that the stable fraction is resistant to management practices, while others argue that it may be more affected than the labile portion.

Various techniques, including chemical, biological, and physical methods, have been proposed to study SOM and its fractions, providing valuable insights into SOM dynamics and its response to management practices. Understanding the effects of soil management on soil quality indicators and SOM is crucial for developing sustainable management practices, especially in intensively managed agricultural ecosystems where SOM depletion is a concern.

The thesis explores the intricate relationship between soil management practices and SOM dynamics, with a particular focus on the labile fraction of SOM. Through chemical fractionation, meta-analyses, and review, the effects of various management practices on SOM are investigated. Chemical fractionation involves analyzing soil samples from experimental fields to assess SOM composition, while meta-analyses and review chapters draw from existing research data. Despite potential variations in data due to methodological differences, these approaches provide valuable insights into SOM dynamics.

The emphasis on the labile fraction of SOM arises from its role as the most and primarily affected, leading to overall changes in total SOM. Contrary to the prevailing belief that the stable fraction is less susceptible to management-induced changes, conflicting findings suggest that it may be equally or more affected in certain scenarios. Field experiments conducted in the Czech Republic and Nepal, along with data from long-term experiments worldwide, contribute to understanding the diverse impacts of management practices on SOM across different regions. However, caution is warranted when generalizing results to areas with distinct properties.

The implications of the findings underscore the critical importance of SOM for soil quality, environmental health, and ecosystem functioning. Understanding the quantity, quality, stability, and lability of SOM pools is essential for nutrient cycling, soil health, and water storage. The study highlights the need for sustainable soil management practices to maintain or increase SOM levels, considering both the labile and stable fractions. Key indicators such as the Carbon Management Index (CMI), Lability (L), and Stability Ratio (SR) emerge as pivotal tools for assessing soil health and guiding management decisions.

Moreover, the thesis explores the role of beneficial microorganisms, such as lactic acid bacteria and entomopathogenic fungi, in influencing SOM dynamics. These microorganisms contribute to organic matter decomposition, acting as plant bodyguards, aiding in nutrient cycling, and improving soil health, offering sustainable alternatives to conventional management practices. Managing soil organic matter sustainably requires considering both natural and human-induced factors that affect its equilibrium. Natural elements such as climate, soil parent material, biota, and topography influence the input, output, and decomposition rates of organic matter. On the other hand, human activities like conventional tillage and overgrazing deplete soil organic matter, while regenerative practices such as cover cropping, agroforestry, and minimal soil disturbance can increase it. By adopting practices that reduce decomposition rates and increase organic matter input, we can conserve soil fertility, prevent degradation, and promote overall sustainability.

2. Objectives and hypotheses

2.1 Problem statement

Land use change and poor management practices pose significant threats, potentially leading to land degradation, desertification, climate change, and food insecurity (AbdelRahman, 2023). Globally, there is an ongoing shift from native land use/cover types, such as forests, grasslands, and shrub-lands, to human settlements and agricultural-lands dominated by conventional crop production practices (monoculture, intensive tillage, increased pesticide and synthetic fertilizer use, and falling short of embracing sustainable farming methods). This shift responds to the escalating global demand for food production to sustain the growing world population and human settlement. The far-reaching consequences of decades of such land use changes include deforestation, declining soil organic matter levels globally, unsustainable farming practices, over-exploitation of pastures, encroachment of agriculture into marginal lands, greenhouse gas emissions, and contributions to climate change (Gupta, 2019; Kopittke et al., 2019; Pozza and Field, 2020).

The soil quality is linked to both organic matter inputs, output and adopted management practices and even minor fluctuations in the soil organic matter pool can have significant repercussions on the global carbon cycle, hindering carbon sequestration potential and resulting in an uneven lateral distribution of soil organic carbon stocks that directly impact soil quality (Bot and Benites, 2005; Merante et al., 2017). It is imperative to gain a deeper understanding of the specific effects of land use changes and management practices on soil organic matter dynamics and related indicators within distinct areas for devising strategies to harness and mitigate the impacts, ensuring sustainable soil management practices in the face of evolving land use patterns and global agricultural demands.

2.2 Objectives

2.2.1 General objective

To assess the influence of changes in land use/cover and soil management practices on labile fraction of soil organic matter.

2.2.2 Specific objectives

1. To evaluate the change in total soil organic matter content across diverse land use types and management practices in various regions.
2. To examine the relative proportions of soil organic matter fractions that are more susceptible to alterations resulting from changes in land use and management practices.
3. To explore quantitative approaches for assessing soil organic matter dynamics in the context of sustainable management.
4. To Identify indicators serving as early warning signals for soil organic matter dynamics.
5. To Investigate the significant roles of lactic acid bacteria and entomopathogenic fungi in soil-plant systems.

2.3 Hypotheses

1. There is significant variation in soil organic matter across different land use types and management practices.
2. Certain soil organic matter fractions exhibit greater susceptibility to alterations in response to changes in land use and management practices.
3. Quantitative approaches for assessing soil organic matter dynamics demonstrate efficacy in promoting sustainable management practices.
4. There are specific indicators that can serve as early warning signals for changes in soil organic matter dynamics.
5. Lactic acid bacteria and entomopathogenic fungi play significant role in influencing soil-plant systems' productivity.

3. Methodology

This thesis presents the results of research activities as a comprehensive overview of publications. These scientific publications are published in journals (Q1- Q2) with impact factors and present the activities that led to the fulfillment of the objectives and verification of the established research hypotheses. This approach was chosen to better clarify the stated problem and the time sequence of the carried out scientific and research activities.

The publications were produced using three different methodologies, and each of them went through the peer review process. The first one was used for original research. A comprehensive investigation was conducted into assessing the quality and quantity of primary soil organic matter and stable organic fractions (Blair et al., 1995a; Kopecký et al., 2021a). Using the PRIMACS SLC TOC analyzer, the total organic carbon content was determined and separately analyzed for total carbon and inorganic carbon. The labile fraction of soil organic matter was assessed by studying the kinetics of the oxidation reaction, calculating reaction speed constants, and measuring oxidizable carbon levels. Additionally, the non-labile fraction of soil organic matter was investigated, and the Carbon Management Index, Lability Index, and Enrichment Ratio were developed to provide insights into soil carbon dynamics and management strategies.

The second methodology was a review. A systematic review process was meticulously followed to ensure the rigor and comprehensiveness of the research (Calderon-Martinez et al., 2023). Beginning with a clearly defined research question, a detailed protocol outlining the methods to be employed was developed. Subsequently, an exhaustive search strategy spanning various databases was constructed to identify pertinent studies. After systematically screening search results and extracting data from selected studies, the quality of each included study was meticulously assessed to gauge its relevance and reliability. Employing appropriate quantitative synthesis techniques, the findings were synthesized to offer a comprehensive understanding of soil organic matter dynamics and management strategies.

The third methodology was meta-analysis. Meta-analytical techniques were diligently employed, guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method (Shamseer et al., 2015). Starting with a clearly defined research question, a comprehensive protocol outlining the methods to be employed was developed, adhering closely to PRISMA guidelines. Through an extensive search strategy encompassing diverse databases, relevant studies for inclusion in the meta-analysis were meticulously identified. Systematic screening, data extraction, and rigorous quality assessment were conducted in accordance with PRISMA standards to ensure the robustness and reliability of the synthesized dataset. After subsequent analyses and leveraging meta-analytical approaches, the aggregated findings were quantitatively synthesized to derive meaningful insights and elucidate patterns across studies.

Through all publications, a scholarly contribution was made that advances understanding in soil-plant science and informs sustainable soil management practices.

4. Results and Findings

4.1 QUANTITATIVE APPROACHES IN ASSESSING SOIL ORGANIC MATTER DYNAMICS FOR SUSTAINABLE MANAGEMENT

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Soil organic matter affects the bio-physico- chemical properties of soil and plays a pivotal role in maintaining and enhancing soil health, fertility, and sustainability (Cardoso et al., 2013). Acknowledged as a cornerstone for sustainable agriculture, soil organic matter significantly contributes to soil productivity, agroecosystem functioning, and climate stability (Fageria, 2012). Higher levels of soil organic matter are associated with many benefits, including improved water management, soil aggregate stability, hydraulic conductivity, processing ease, rapid warming, nutrient retention, and increased productivity, among others, and the absence of these advantages underscores its indispensable role (Bot and Benites, 2005). In addition, the quantity of organic carbon in the soil directly influences carbon sequestration and, consequently, has implications for climate change (Lal, 2004). Therefore, the application and maintenance of organic fertilizers are recommended for enhancing soil organic matter, although their final effect depends on factors such as quantity, quality, and environmental conditions (Bot and Benites, 2005).

Although, the Soil organic matter provides all these benefits, the conflict between managing or increasing soil organic matter and the effects of different land-use practices necessitates further investigation. Different anthropogenic practices exert varying effects on soil organic matter dynamics. Conventional methods often accelerate decomposition, while practices like reduced tillage, crop rotations, cover crops, mulching, intercropping, and balanced fertilization enhance soil organic matter pools (Murindangabo et al., 2023a; Sainepo et al., 2018).

To explore and estimate the effects of anthropogenic and natural factors on organic matter dynamics, the development of accurate models and approaches (techniques and indicators) is essential to describe cause–effect relationships, assess impacts on the ecosystem, and propose potential remedial actions. This is crucial for sustainable soil and environmental management. By incorporating data on soil properties, climate, vegetation, and management practices, models analyze or simulate decomposition, mineralization, and stabilization of organic matter in the soil (Shibu et al., 2006) to give an idea about what measures should be taken. Advances in computer technology, modeling, and simulation have led to the development of diverse models with simple and complex designs. Various analytical and simulation models, including those developed by Stéphane Hénin and Hanna Parnas, have been instrumental in understanding soil organic matter decomposition and transformation (IRD France, 1993; Kwiatkowska-Malina, 2018; Parnas, 1975) Moreover, advanced physical, chemical, and biological approaches for quantitative and qualitative evaluation studies of soil organic matter have been developed. Various parameters, such as oxidation kinetics, lability, carbon management index, humification degree, humification index, and humification ratio, enable a detailed quantitative analysis of soil organic matter, providing valuable insights into its characteristics and transformation (Blair et al., 1995b; Sainepo et al., 2018). On the other hand, the qualitative assessment of soil organic matter involves techniques such as oxidizability, high-performance size-exclusion chromatography, electrospray ionization Fourier transform ion cyclotron resonance mass spectrometry, visual examination, olfaction, assessment of microorganism content, plant growth, cation exchange capacity, type of organic material, and decomposition (Kopecký et al., 2021b; Kwiatkowska-Malina, 2018). Combining both quantitative and qualitative methods is essential for a comprehensive analysis of soil organic matter, ensuring a nuanced understanding of its importance in maintaining soil health and sustainability (Murindangabo et al., 2023b)

Sustainable soil organic matter management and evaluation should consider different factors that can be categorized as natural and anthropogenic. Natural factors, such as climate, soil parent material, biota, and topography, regulate organic matter input, output, and decomposition rates. Anthropogenic practices influencing soil organic matter balance include those that reduce it, such as reduction in biomass production, organic matter input reduction, and increased rates of decomposition and mineralization. Practices that increase soil organic matter involve enhanced biomass production, increased organic matter input, and decreased decomposition rates (Bai et al., 2018; Bot and Benites, 2001; Murindangabo et al., 2023b).

This study identifies and review models, processes, approaches, and methods for the quantitative evaluation of soil organic matter dynamics in various land use/land cover scenarios. While previous studies have touched on these aspects, our comprehensive overview offers a current understanding of the field and proposes future research directions. Addressing these directions is crucial for advancing our understanding of soil organic matter dynamics, enhancing modeling accuracy, and contributing to the development of sustainable soil management strategies in the face of global environmental changes. Collaboration between diverse disciplines is pivotal in tackling the intricate challenges associated with soil organic matter modeling and informing policy and management decisions. Future research should prioritize areas such as model parameterization, multi-scale modeling, emerging technologies, climate change impacts, socioeconomic factors, and interdisciplinary collaborations to improve the accuracy and reliability of SOM models for sustainable land management.

4.2. FRACTIONATION OF SOIL ORGANIC MATTER INTO LABILE AND STABLE FRACTIONS

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The term soil organic matter has often been confounded, used generically, or interchangeably with its fractions, such as labile (primary soil organic matter) and stable (humus) ones. However, these fractions possess distinct properties. The labile fraction consists of actively decomposing elements (plant and animal parts, and microorganisms) that have not undergone the humification process. These elements exhibit varying stability to biodegradability, negligible cation exchange capacity, significant oxidation and hydrolysis, and play a crucial role in determining the soil nutrient regime (Kolář et al., 2011; Kopecký et al., 2021c).

On the other hand, the stable fraction is composed of recalcitrant elements undergoing the humification process and others that have already been humified. This fraction possesses high cation exchange capacity, stability to oxidation and hydrolysis, and influences the future carbon content of the soil (Kolář et al., 2009; Maroušek et al., 2020). While the loss of easily oxidizable carbon is sometimes considered a loss of the humus, it predominantly represents the loss of the labile fraction. This loss often leads to an increase in the stable fraction and other nutrients in the soil (Bashir et al., 2021). Thus, the two components of SOM should not be confused with each other and should be expressed separately.

This study illustrates a method for determining the total soil organic matter and emphasizes the importance of expressing the total amount of labile and stable fractions separately. The degree of lability or stability during hydrolysis or oxidation enables the accurate determination of each of these two fractions (Blair et al., 1995b; Sequeira et al., 2011).

The gradual oxidation of a soil sample in a solution of 0.4 mol/L $K_2Cr_2O_7$ in 12M H_2SO_4 along with the measurement of oxidation reaction kinetics of soil organic matter carbon loss, enables the determination of the rate constant 'k.' This rate constant is a measure of the quality of the labile fraction of soil organic matter. A higher k value indicates a less stable fraction, reflecting higher quality.

The amount of labile fraction of soil organic matter is calculated from the final state of such oxidation at a temperature of 90 °C for 30 minutes. In these conditions, the stable fraction of soil organic matter does not participate in the oxidation reaction. The quantity of stable fraction of organic matter is then determined as the difference between the total organic carbon amount in a soil sample, and the labile soil organic matter. Stable fraction quality is evaluated from a difference in the cation exchange capacity of the original soil sample and the sample whose organic matter was destroyed by H_2O_2 oxidation in the acetic acid medium, assuming that the cation exchange capacity of primary soil organic matter is practically zero.

4.3 COMPARATIVE ANALYSIS OF SOIL ORGANIC MATTER FRACTIONS, LABILITY, STABILITY RATIOS, AND CARBON MANAGEMENT INDEX IN VARIOUS LAND USE TYPES WITHIN BHARATPUR CATCHMENT, CHITWAN DISTRICT, NEPAL

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The advancement of human civilizations has heightened modifications in land use, driven by factors such as urbanization, agriculture, and development ventures. These changes have consequential effects on the delivery of various ecosystem services (Szabó et al., 2010). To address these consequences, adopting sustainable land and soil management practices has demonstrated efficacy by preserving soil organic matter, promoting carbon sequestration, and mitigating erosion and degradation processes (Kumar, 2017). Soil organic matter is recognized for its ability to enhance soil properties and environmental health, influencing aspects such as soil structure, nutrient supply, and providing a substrate for soil organisms (Bot and Benites, 2005). Consequently, soil organic matter content is widely regarded as a crucial attribute for assessing soil and environmental quality, acting as both a sink and source of carbon and other essential plant and microbial nutrients. Despite its often minor contribution to the total mass of mineral soils, it exerts a profound influence on soil physical, chemical, and biological functions (Nieder and Benbi, 2008). However, the impact of land use and land cover changes on ecosystems, particularly on soil quality and sustainability, has led to a lack of scientific consensus regarding the precise relationship between soil organic matter dynamics and such changes (Murindangabo et al., 2023a; Sainepo et al., 2018; Wang et al., 2023). The apparent lack of consensus on the relationship between soil organic matter dynamics and land use and land cover changes is indeed surprising given its generally accepted status as a key indicator. However, considering the multitude of pathways through which these changes can influence soil organic matter, and recognizing the variations in these impacts based on the prevailing environment, region, and adopted practices or technologies, makes this lack of consensus more understandable (Prout et al., 2021).

While recent concerns indicate that soil organic matter is declining even in European soils (Stolte et al., 2016), and proposals to maintain it above 3.5% (European commission, 2011) or increase it annually by 4‰ to safeguard the productive capacity of soils (Soussana et al., 2019) have been developed, it is well-established that organic matter decomposition rates in tropical soils are generally faster than in temperate soils due to the faster decay of the non-labile fraction (Ross, 1993). Consequently, tropical countries have recognized that the decline of soil organic matter can be remedied through proper land use and management practices (Bot and Benites, 2005). For example, the government of Nepal, often facing erosion and soil degradation issues, has set an ambitious target to increase soil organic matter from the current level to 4 percent by 2035 (Gairhe et al., 2021; The kathmandu post, 2024), and similar initiatives have been undertaken elsewhere in the tropics (Abdulkadir et al., 2021; European Commission, 2020; Stewart et al., 2020).

This study aimed to enhance our understanding of the effects of land use and land cover change on organic matter and related indicators in Nepal, examining the changes after more than three to five decades of land use transformation. The approach involved chemical fractionation based on organic matter carbon oxidizability, allowing the separation of soil organic matter into labile and stable fractions (Kopecký et al., 2021c; Murindangabo et al., 2023b). To improve the sensitivity of soil quality assessments across diverse land uses, the study incorporated refined indicators such as the carbon management index and stability ratio. Notably, studies utilizing these assessment tools are scarce in the study location. We investigated the dynamics of soil organic matter pools in various land use and land cover types within the Bharatpur Catchment, Chitwan District, Nepal, and developed a carbon management index for assessing soil quality in the region. Assessing the carbon management index and stability ratio provided a nuanced understanding of the stability and turnover dynamics of soil organic matter in the Bharatpur Catchment area, critical for soil health and carbon cycling processes. These parameters offered valuable information for evaluating soil quality and guiding sustainable land management practices.

4.4 PROMINENT USE OF LACTIC ACID BACTERIA IN SOIL-PLANT SYSTEMS

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In soil-plant systems, soil microorganisms exert multifaceted effects crucial for soil health, plant growth and ecosystem functioning (Avis et al., 2008; Chauhan et al., 2023). These microorganisms actively participate in the decomposition and transformation of organic matter, playing a pivotal role in carbon and nutrients cycling within soil systems (Manda et al., 2023). Nutrient cycling is facilitated as microorganisms break down organic matter, releasing nutrients for plant absorption through processes like mineralization, nitrification, and phosphorus solubilization (Jacoby et al., 2017).

Global food production has frequently depended on the use of chemical fertilizers and pesticides to enhance productivity, addressing the growing challenges posed by an increasing global population and rising food demand (Penuelas et al., 2023; Tudi et al., 2021). However, excessive use of these chemicals poses threats to ecological balance, food safety, and leads to land and water pollution. In response, sustainable agriculture, particularly organic farming, has gained global attention, emphasizing soil health and environmental preservation (Eyhorn et al., 2019). The symbiotic relationship between plants, soil, and microbes is pivotal in sustainable agriculture, promoting plant health and soil fertility. The application of microbial-based agricultural practices holds potential for ensuring food security, profitability, and global well-being. The interaction between plants and beneficial microorganisms, such as Rhizobium, Bacillus, lactic acid bacteria, Pseudomonas, and mycorrhizal fungi, fosters a symbiotic relationship, benefiting both species (Li et al., 2020; Todorov et al., 2012; Zhang et al., 2023). Despite the benefits, challenges such as pathogenic bacterial species, along with plant pathogens like insects, persist in sustainable agriculture. Developing innovative antimicrobial agents is crucial to increase yields and income for farmers (Van Esse et al., 2020).

Lactic acid bacteria (LAB), recognized as beneficial microorganisms, offer diverse advantages, including plant-growth-promotion, soil health, antimicrobial properties, and a crucial role in the food industry. LAB, such as Lactobacilli and cocci, produce various metabolites with applications in antibiotic development and preservation (Jaffar et al., 2023). Despite challenges, LAB serves as valuable biocontrol agents and contributes to bioremediation practices. Their versatile activities span antibacterial, antifungal, and pesticidal attributes, promoting sustainable agriculture. Their antibacterial prowess, involving the production of organic acids, hydrogen peroxide, and bacteriocins, defends against bacterial pathogens. LAB's antifungal properties, achieved through compounds like organic acids and peptides, effectively control fungal diseases in plants and soil. Certain LAB strains act as biopesticides, providing a natural alternative for pest management in agriculture (Desbois and Smith, 2010; Sadiq et al., 2019). Additionally, LAB functions as bio-stimulants, promoting plant growth by producing growth-promoting substances and enhancing nutrient uptake. Their role extends to biofertilizers, contributing to nutrient cycling through nitrogen fixation, phosphate solubilization, and improved nutrient availability for plants. Furthermore, LAB contributes to the improvement of soil carbon by facilitating the decomposition of organic matter, enhancing soil structure and fertility. LAB's involvement in soil bioremediation aids in pollution degradation, contributing to soil restoration (Raman et al., 2022). Finally, these bacteria play a crucial role in inducing plant defense mechanisms, activating the plant's ability to resist pathogens through the production of antimicrobial compounds and reinforcing immune responses. The multifaceted contributions of lactic acid bacteria underscore their significance in fostering sustainable and environmentally friendly practices (Lamont et al., 2017; Murindangabo et al., 2023d).

Nonetheless, there exists a gap in understanding the interplay among LAB, soil, and plant hosts. This study seeks to bridge this void by delving into the less-explored significance of LAB in soil-plant systems through a comprehensive review of literature and metadata, shedding light on the potential of LAB as sustainable and secure enhancers of soil and plant health. The initial segment scrutinizes the available metadata, laying the groundwork for a detailed exploration. Subsequently, the discussion segment predominantly centers on the findings derived from an extensive literature review.

4.5 RELEVANCE OF ENTOMOPATHOGENIC FUNGI IN SOIL-PLANT SYSTEMS PRODUCTIVITY

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Soil stands as an unparalleled reservoir, harboring more carbon than other terrestrial ecosystems combined. The intricate processes governing the formation and longevity of soil organic carbon pose a complex puzzle, complicating our comprehension of its potential responses to climatic shifts (Schmidt et al., 2011). Emerging as key actors in this intricate theatre of carbon dynamics, soil microorganisms have been proposed to wield significant influence over soil organic carbon, dictating its genesis, preservation, and, conversely, its susceptibility to depletion. In unraveling the mysteries of soil organic carbon dynamics, the role of these microbial communities takes center stage, emphasizing their pivotal contribution to the delicate balance within Earth's soil systems (Jackson et al., 2017).

Fungi, among others, play a vital role in soil ecosystems, acting as nature's decomposers and contributing significantly to nutrient balance. A thriving soil food web driven by fungi and other microbes, enhance nutrient and water absorption, enhanced soil structure, disease suppression, nutrient cycling and adsorption, increased water-holding capacity, fostering plant growth (Dara et al., 2017; Frąc et al., 2018). Fungi break down organic matter, releasing essential nutrients into plant-available forms, reducing the reliance on synthetic fertilizers (Rashid et al., 2016). Fungal hyphae and microbial secretions bind soil particles, creating stable aggregates that improve soil structure, water infiltration, and root penetration. Additionally, soil rich in organic matter and microbial activity has better water-holding capacity, preventing water runoff, reducing soil erosion, and improving drought tolerance. This, in turn, allows plants to access water and nutrients more efficiently (Marcacci et al., 2022; Miller and Jastrow, 2000). Disease suppression is achieved through outcompeting harmful pathogens or production of compounds inhibiting their growth (Dara, 2019).

The hypocrealean fungi *Beauveria bassiana, Hirsutella thompsonii, Isaria fumosorosea, Metarhizium anisopliae, M. brunneum and M. robertsii* are known as entomopathogens of a wide range of arthropod pests. Unlike some fungi that may have detrimental effects on crops, entomopathogenic fungi specialize in targeting and controlling insect pests. These fungi establish a unique relationship with insects, acting as natural biopesticides. Their mode of action involves infecting and ultimately killing the targeted pests, providing an environmentally friendly alternative to chemical pesticides (Bamisile et al., 2021). This targeted approach helps protect crops from insect damage while minimizing the ecological impact associated with traditional pest control methods. Therefore, the application of entomopathogenic fungi contributes to sustainable and eco-friendly agricultural practices (Sisay and Legese, 2020).

Entomopathogenic fungi are prevalent in soil and exhibit beneficial properties as rhizosphere colonizers, Soil-dwellers, and endophytes in agroecosystems. These fungi contribute to plant growth promotion, nutrient transfers, and the suppression of plant diseases and insect pests. They are adept root colonizers with diverse applications in agriculture, serving as bio-pesticides and bio-fertilizers. In the context of global agricultural challenges, the incorporation of plant-growth-promoting microbes, including entomopathogenic fungi can enhance plant survival and growth under stressful conditions. Secondary metabolites produced by these microbes, such as phenols, flavonoids, and indole acetic acid, play a key role in supporting crops during stress. Isoflavones, as phytoalexins, accumulate in plants to mitigate biotic or abiotic stress (Murindangabo et al., 2023c). Fungal entomopathogens, like Metarhizium anisopliae, known for controlling soil-dwelling insect pests, demonstrate potential as bioinoculants to alleviate abiotic stress, particularly salinity, and promote plant growth.

This study conducts a meta-analysis delving into the impact of entomopathogenic fungi on soil structure, nutrient uptake, plant growth, and defense mechanisms. Unveiling the intricacies of these fungi holds the key to optimizing their potential for fostering sustainable farming systems.

4.6 ENHANCING SOIL ORGANIC MATTER TRANSFORMATION THROUGH SUSTAINABLE FARMING PRACTICES: EVALUATING LABILE SOIL ORGANIC MATTER FRACTION DYNAMICS AND IDENTIFYING POTENTIAL EARLY INDICATORS.

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The escalating global population and heightened agricultural demands have led to widespread issues of soil organic matter depletion and degradation, particularly in regions like South Bohemia, Czech Republic, where conventional farming prevails. Soil organic matter is pivotal for soil health, crop productivity, and agricultural sustainability.

The study focuses on the impact of cultivated crops and management practices, particularly involving beneficial microorganisms, on soil organic matter pools, emphasizing their influence on soil fertility, nutrient cycling, and overall soil health. Legume crops, such as peas and lupins, in combination with microorganisms like *Trichoderma virens*, *Metarhizium brunneum*, and lactic acid bacteria, demonstrated positive effects on soil organic carbon levels. The labile fraction of soil organic matter was found to be particularly sensitive to management practices, with indicators like the lability index, carbon management index, carbon enrichment ratio, and organic matter oxidation rate constant serving as effective tools to assess changes in the organic matter pool. The findings underscore the importance of tailored crop selection, microbial inoculation, and sustainable soil management practices for enhancing soil carbon pools and promoting agricultural sustainability, especially in regions facing soil degradation due to conventional methods. The study recommends further exploration of various soil management practices, including diverse tillage methods, crop types, rotations, intercropping, and microorganism integration, to comprehensively understand and optimize sustainable agricultural practices.

4. General discussion

This thesis aimed to enhance the understanding of the impact of soil management practices on soil organic matter, focusing particularly on the labile fraction and associated indicators. It illuminates the underlying mechanisms steering soil organic matter dynamics and underscores the significance of adopting sustainable soil management practices. The thesis offers an inclusive overview of the approaches and methods employed to track changes in soil organic matter, encompassing the identification of pertinent processes to describe and estimate decomposition, lability, and humification for sustainable management. To achieve this goal, a comprehensive analysis of short-term and long-term experiments, along with reviews and meta-analyses, was conducted. To heighten the sensitivity of soil quality assessments across diverse land uses and management practices, refined indicators such as the carbon management index, soil organic matter oxidation speed constant, lability, and stability ratio were incorporated into the study. Notably, the utilization of these assessment tools in the specified study locations is limited. Within this chapter, the thesis findings are discussed across various dimensions: Evaluating the dynamics and fractionation of soil organic matter, the influence of beneficial microorganisms, the impact of land use and land cover change, Approaches for sustainable soil organic matter management, limitations of the study, and implications of the findings.

4.1 Evaluating the dynamics and fractionation of soil organic matter.

Soil organic matter Fractionation

Soil organic matter (SOM) can be physically, chemically, and biologically fractionated to help in better understanding its composition, properties, and functions in soil (Gregorich et al., 2006). Physical fractionation involves separating SOM based on its particle size, density and spatial distribution, where smaller particles usually have higher decomposition rates and contain more labile SOM fractions. One of the commonly used physical fractionation methods is density fractionation, which separates SOM into different fractions based on their densities using a heavy liquid (e.g., sodium polytungstate) (Golchin et al., 1994). Chemical fractionation separates SOM based on its chemical properties, where different fractions are at different degrees of decomposition and stability, solubility, hydrolizability, and chemical reactivity. The most common chemical fractionation method is the acid hydrolysis or oxidation method, which separates SOM into different fractions based on their oxidation or solubility levels in acid solutions of varying strengths (Blair et al., 1995c; Shirato and Yokozawa, 2006). Biological fractionation separates SOM based on its microbial accessibility and biomass, where different fractions have different microbial decomposability and utilization. One of the commonly used biological fractionation methods is the substrate-induced respiration (SIR) method, which measures the microbial respiration rate of SOM fractions incubated with a specific substrate (e.g., glucose). This method measures fungal, bacterial and total microbial contributions to glucose-induced respiration and the potentially active microbial biomass on decaying plant residues of differing composition (Bossuyt et al., 2005).

Quantitative techniques for SOM evaluation

Quantitative SOM measurement techniques can be broadly classified into two categories, dry combustion methods and wet oxidation methods (Apesteguia et al., 2018). Dry combustion methods include thermal exchange, loss on ignition (LOI), and Walkley-Black (WB) methods. These techniques rely on the complete combustion of soil samples to determine the organic carbon content. Thermal exchange involves heating a soil sample in a furnace under an inert atmosphere and measuring the evolved CO_2. The LOI method involves heating a soil sample to a high temperature to burn off organic matter and measuring the weight loss. The WB method involves adding a dichromate-sulfuric acid reagent to a soil sample, which oxidizes the organic matter and releases CO_2, which is then measured (De Vos et al., 2007; Shamrikova et al., 2022).

Wet oxidation methods involve the oxidation of dissolved organic material with dissolved oxygen at high temperatures. A strong oxidizing agent is used to release carbon dioxide or to change the absorbance properties of the soil sample. Wet oxidation methods include wet digestion and near-infrared reflectance (NIR) among others (Chang et al., 2001). Digestion methods breakdown soil samples using acid (such as hydrochloric acid and hydrogen peroxide) digestion to release SOM, while the NIR is a non-destructive method that uses the interaction of infrared light with organic matter to estimate the quantity and quality of organic matter by measuring using a spectrophotometer the reflectance or absorbance of near-infrared light by the soil sample (Roberts et al., 2004; Zornoza et al., 2008). The choice between dry and wet methods depends on accuracy and precision needed, time, resources, and all organic matter properties needing to be measured.

Qualitative techniques for SOM assessment

Qualitative techniques used to assess SOM are descriptive. They involve visual examination which is a technique entailing assessing physical properties of the soil such as color, texture, and structure (Gregorich et al., 1994). A positive correlation has been observed between soils with high organic matter content and darker color, crumbly texture, and granular structure. In addition to visual examination, the smell test can be employed to identify organic matter quality, as soils with high organic matter content often have a rich, earthy smell. Furthermore, the number of microorganisms, soil crumb structure test, infiltration rate, plant growth rate, organic matter color, cation exchange capacity, and crop residue decomposition rate can all serve also as qualitative indicators of SOM quality (Andriuzzi, 2015; Váchalová et al., 2014).

Other important qualitative techniques are using an infrared Spectroscopy where infrared radiation identifies and quantifies functional groups in SOM. It can provide information on the composition and structure of SOM. It measures the absorption and transmission of infrared light by SOM functional groups, providing information on SOM quality, quantity, and composition. Infra-red spectra can be collected from bulk soil samples, or from specific SOM fractions obtained by soil fractionation (Steffens et al., 2021); fluorescence Spectroscopy, this technique uses the fluorescence properties of SOM to characterize its composition and structure. It can provide information on the humification degree, aromaticity, and molecular weight of SOM. It measures the emission of light from SOM after excitation with ultraviolet or visible light. Fluorescence spectra are sensitive to SOM quality and can be used to assess changes in SOM quantity and quality due to management practices or environmental factors (Freitas et al., 2022); pyrolysis mass spectroscopy (PyMS), this technique uses high temperatures to decompose SOM into smaller fragments, which are then analyzed using mass spectrometry. It measures the mass and abundance of pyrolysis products generated from SOM upon heating to high temperatures in the absence of oxygen. PyMS provides information on SOM functional groups and the distribution of carbon and nitrogen within SOM molecules (Leinweber and Schulten, 1993); nuclear magnetic resonance (NMR), this technique uses magnetic fields to analyze the structure and composition of SOM. It can provide information on the molecular structure, functional groups, and chemical bonding of SOM. It measures the relaxation times of nuclei within SOM molecules in response to a magnetic field (Simpson and Simpson, 2009); high performance size exclusion chromatography, this technique separates SOM into fractions based on their size and chemical composition. It can provide information on the molecular weight, size distribution, and chemical composition of soil (Brezinski and Gorczyca, 2019); electrospray ionization fourier transform ion cyclotron resonance mass spectrometry (ESI-FTICR-MS), this technique measures the mass-to-charge ratios of SOM molecules. It combines electrospray ionization with fourier transform ion cyclotron resonance mass spectrometry. It informs about the molecular weight, elemental composition, and functional group composition of individual organic molecules which helps in processes that control the SOM dynamics (Bahureksa et al., 2021). Likewise, it should be noted that the use of both quantitative and qualitative methods is often advised for a more comprehensive assessment of soil health and organic matter dynamics.

Lability and stability of organic matter in soils.

Understanding the relationships between SOM fractions can express the relative degree of lability, stability and humification of overall SOM, hence carbon management index development. It should also be added that, variations in these sub-pools (fractions) can be used in developing and understanding SOM dynamics models (Parton et al., 2015). The constant supply of organic matter carbon depends on the available stock size and estimated turnover speed. Hence, quantitative assessment of SOM dynamics, its lability and stability could be early monitored using specific parameters such as carbon pool index (CPI), lability (L), lability index (LI), carbon management index (CMI) (Blair et al., 1995c); carbon stock (Sisti et al., 2004); humification index (HI), humification degree (HD) and humification rate (HR) (Kwiatkowska-Malina, 2018).

Modelling soil organic matter dynamics

SOM models are mathematical representations that describe the changes of organic matter in soils over time. These models can be used to analyze or simulate the effects of management practices, climate change, and other environmental factors on available SOM, turnover rates, and other related soil properties. SOM models are typically based on empirical or mechanistic approaches that help in predicting the future SOM trends (Lehmann and Kleber, 2015; Woolf and Lehmann, 2012). The development and advancement in SOM modelling from simple exponential decay functions, more complex functions with substrate concentration and time-dependent relative decomposition rate, simple regression equations, to more complex processes-based models have been a success in understanding and designing sustainable soils, SOM, crops, and climate management practices (Shibu et al., 2006). The progress in mathematical, computer and simulation skills has allowed the development of different SOM analytical and simulation models and as the measurement of the impact of a given management practice to SOM changes requires a long term or many short term data, it is the same for modelling data for reliable results (Powlson et al., 1996). SOM models can be either mono or multi-compartmental and the choice depends on the objectives of the study, the amount and quality of available data, and the complexity of the system being modeled. Mono-compartmental models assume that all organic matter in the soil is equivalent and represented by a single pool, with a single set of parameters describing its decomposition and turnover. Whereas multi-compartmental models recognize that organic matter in the soil is composed of different fractions (compartments), each with distinct properties and turnover rates. These models represent the different compartments, and their decomposition and turnover are modeled separately, with parameters that describe the properties of each fraction (Shibu et al., 2006).

Analytical models

SOM analytical models are based on mathematical equations and formulas (such as calculus or linear algebra) that describe the changes in SOM over time. These models use assumptions and simplifications to predict SOM dynamics based on a few input parameters. They can provide rapid and efficient estimates of SOM dynamics, but their accuracy can be limited by the simplifying assumptions made during model development. Analytical models predict the dynamics of a system in certain conditions and make accurate predictions if the underlying assumptions are met. Generally, they are also easier to use and interpret than simulation models (Parton et al., 2015). They include Hénin and Dupuis (1945), Kortleven (1963), Kolenbrander (1969), Godshalk (1977), ICBM, Andriulo et al. (1999), SOMM models, and others (Kwiatkowska-Malina, 2018; Shibu et al., 2006).

Simulation models

Simulation models (comprehensive and summary) are based on computer programs that simulate the behavior of the system being modeled. These models operate on realistic assumptions and are more complex than analytical models. They are able to deal with a wide range of conditions and handle large and complex data (Lawrence et al., 2009). They can provide more realistic and accurate predictions of SOM dynamics in response to different environmental conditions and management practices (Campbell and Paustian, 2015). They are based on a more detailed approaches and representation of soil ecosystems and use computer algorithms to simulate the biophysical and biochemical processes that control SOM dynamics, including microbial activity, plant residue decomposition, and soil structure formation to explain the flux and distribution of carbon over a given time and scale (Shibu et al., 2006). They include Pernas model (1975), Century model, RothC model, Van Veen and Paul model (1981), DNDC Model, DayCent Model, Yasso model, ANIMO model, CANDY model, Root Zone Water Quality Model, PAPRAN Model, NCSOIL Model, DAISY Model, SUNDIAL Model, ECOSYS Model, APSIM Model, NICCCE, EPIC Model, Verberne model, and others (Shibu et al., 2006).

4.2 The impact of land use and land cover change

This thesis underscores the profound impact of land use on soil organic carbon pools. It highlights the significance of understanding soil organic matter dynamics in the face of changing land use and recommends employing the Carbon Management Index (CMI) and Stability Ratio (SR) as crucial indicators for sustainable land management. Organic farming, forests, and fruit orchards demonstrate higher soil health, while conventional agricultural lands show lower levels, indicating the need for immediate conservation actions. The study emphasizes the pivotal role of CMI and SR in gauging soil degradation or improvement, urging proactive measures to enhance soil health and advance environmental sustainability in the region of the study. It contributes to comprehending underlying mechanisms and informing future land management decisions. For practical resource limitations, prioritizing CMI offers a comprehensive view of soil quality and response to land use, emphasizing sustainable practices like organic farming and afforestation. Balancing agriculture, forestry, and land use is essential for preserving soil health, biodiversity, and achieving overall environmental sustainability. The choice between CMI and SR testing depends on specific goals and resources, emphasizing a focus on sustainable land management for long-term soil fertility and environmental health.

4.3 The influence of beneficial microorganisms

In the realm of agricultural sustainability and pest management, both entomopathogenic fungi and lactic acid bacteria (LAB) have garnered considerable attention for their multifaceted roles. While traditionally recognized for their prowess in pest control and human health, recent studies delve into their broader impact on soil-plant systems, revealing promising insights into enhanced productivity and sustainable practices.

High microbial activity is one of the foundations of potential soil fertility (Kalantary and Kahani, 2019) and bacterial and fungal heterotrophs dominate microbial decomposer communities (Hieber and Gessner, 2002). However, these groups are phylogenetically distant and differ in their metabolic requirements and cellular capabilities (Mille-Lindblom et al., 2006). The typical filamentous structure of most fungi facilitates their penetration into particulate substrates, whereas bacteria are suspended in or attached to substrates (Baldy et al., 1995). Fungal decomposers have a lower metabolic nutrient demand (Danger et al., 2016) and wider enzymatic capabilities than bacteria, which allow them to mineralize even low-quality substrates like particulate leaf litter (Güsewell and Gessner, 2009), whereas, bacteria have a shorter turnover and higher metabolic activities (Attermeyer et al., 2013; Bardgett et al., 1999). Consequently, fungi and bacteria occupy different functional niches in primary organic matter decomposition: fungi act as primary degraders of particulate, predominately terrigenous carbon, and bacteria act as rapid recyclers of simply structured nutrient-rich organic matter compounds (Krauss et al., 2011; Kubicek and Druzhinina, 2007).

The relative abundance of fungi and bacteria varies among different primary organic pools (Findlay et al., 2002), which can have profound effects on ecosystem functioning (Rinnan and Bååth, 2009; Strickland et al., 2009) concerning their functional niche in the mineralization of terrigenous organic matter (de Graaff et al., 2010). However, studies simultaneously evaluating the different ecological roles of both fungi and bacteria are scarce (Rousk and Bååth, 2007; Schneider et al., 2012), the contribution of fungi and bacteria to organic matter degradation is not solely a function of their abundance but of their metabolic activity that varies with changes in primary organic matter quality (Brandstätter et al., 2013; Meidute et al., 2008).

Entomopathogenic fungi, recognized for their effectiveness in pest management, have traditionally been associated with insect control. Recent studies, however, unveil additional roles contributing to soil-plant systems' productivity. Through the literature review and metadata analysis demonstrated that these fungi positively impact soil aggregation by producing glomalin-like substances and contribute to organic matter and nutrient recycling. Furthermore, they promote plant growth, enhance overall soil health, and induce resistance in crop plants against herbivores, stress, and diseases. Despite some limitations reported in the literature, such as lengthy killing time and environmental specificity, these ubiquitous fungi show promise in nutrient recycling, soil health improvement, and acting as plant growth enhancers.

Lactic acid bacteria, versatile microorganisms commonly found in diverse environments, have also been extensively studied for their roles in food safety and human health. Beyond their traditional applications, empirical evidence suggests that LAB plays crucial roles in soil-plant systems. Through a comprehensive literature review and metadata analysis, this thesis highlighted LAB's less-explored relevance in soil-plant interactions. LAB demonstrates multifaceted roles, serving as biofertilizers, biocontrol agents, and biostimulants in plant production by producing bacteriocins, organic acids, and other compounds. The study emphasizes the potential of LAB as environmentally friendly and effective alternatives for managing pests and diseases, contributing to sustainable farming strategies. While some aspects remain unexplored, this reviewed the promising prospects of LAB in enhancing soil and plant health sustainably.

4.4. Approaches for sustainable soil organic matter management

For sustainable soil organic matter management, two categories of factors affecting the balance of soil organic matter, natural and anthropogenic, need to be considered. Natural factors, such as climate, soil parent material, biota, and topography, regulate the input, output, and rates of decomposition of organic matter (Aranda et al., 2011; Plante and Parton, 2007). While anthropogenic practices include those that reduce soil organic matter, such as reduction in biomass production, organic matter input, and increased rates of decomposition and mineralization. These practices include conventional tillage, overgrazing, crop residue removal, and burning practices. Practices that increase soil organic matter are those that increase biomass production and organic matter input, and decrease decomposition rates, such as balanced fertilization, cover crops, agroforestry, afforestation, regenerative agriculture, and pastoral practices (Bot and Benites, 2005). Contrary to certain practices like conventional farming, sustainable regenerative activities support and maintain soil biological processes, increase biomass production, and help build soil organic matter. It is important to focus on reducing the rate of organic matter decomposition and increasing the input of organic matter by managing crop residues, using animals and green manures, avoiding burning, and adopting minimal soil disturbance practices. By implementing practices that increase soil organic matter, we can help preserve soil fertility, prevent soil degradation, and promote sustainability (Hijbeek et al., 2018; Lal, 2022; Ramesh et al., 2019).

4.5. Limitations of the study

Analysis of effects of management practices on soil organic matter

In this thesis, the effects of management practices were assessed through the chemical fractionation of soil organic matter, meta-analyses, and review. The data for meta-analyses and review were sourced from existing research, while chemical fractionation relied on soil samples analyses conducted in experimental fields. Recognizing the potential for error or variation in data due to these methods was unavoidable when relying on published information.

Our focus in these studies centered on the labile fraction of soil organic matter. This emphasis stemmed from the prevailing notion that the stable fraction, with its recalcitrant nature and protection by sorption on fine particles, is less susceptible to changes induced by land use or management practices (Bayer et al., 2002). However, conflicting findings indicate that this stable fraction might be more affected than the labile portion in certain scenarios (Kopecký et al., 2021c).

Study area.

Study areas for different analyses varied. The meta-analyses and review chapters drew upon long-term experiments conducted in different countries and continents, selected based on data availability. Field experiments took place in the Czech Republic and Nepal. Given the diverse locations of these studies, caution is needed in generalizing results to areas without similar properties. It is established that organic matter decomposition rates are generally faster in tropical soils than in temperate soils, primarily due to the rapid decay of the non-labile fraction (Ross, 1993; Six et al., 2002). In tropical climates with stable temperature and humidity, organic matter input and output may achieve the equilibrium due to high litter biomass production and robust soil organism activity, creating a closed cycle of litter decomposition and nutrient mineralization (Davidson and Janssens, 2006; Kätterer et al., 1998). However, achieving this equilibrium is complicated by human intervention and the conducive environment for faster decomposition than input (Bot and Benites, 2005).

5. Conclusion

Soil organic matter is pivotal for soil quality and environmental health, acting as both a carbon source and sink. The findings in this thesis indicate that understanding the quantity, quality, stability, and lability of soil organic matter pools is crucial for nutrient cycling, soil and environmental health, and water storage. However, the conflict between maintaining or increasing soil organic matter and the impact of management practices on soil organic matter requires further investigation for sustainable soil management. Future research directions should involve enhanced model parameterization, multi-scale modeling, integration of emerging technologies, assessment of climate change impacts, incorporation of socioeconomic factors, and interdisciplinary collaborations. Optimizing soil organic matter levels and nutrient recycling through informed land management can enhance soil productivity and long-term health.

This thesis has shown a substantial impact of land use on soil organic carbon pools. It underscores the importance of comprehending soil organic matter dynamics amid changing land use patterns. The Carbon Management Index (CMI) and Stability Ratio (SR) emerge as pivotal indicators in sustainable land management, reflecting soil health, environmental sustainability, and resilience. Practices such as organic and conventional farming, forests, and fruit orchards exhibit sustainable practices, while conventional agricultural lands show lower levels due to less favorable practices. CMI analysis highlights severe degradation in conventional farming and pasture lands, emphasizing the need for immediate action. The thesis advocates for soil management strategies prioritizing both labile and stable organic matter fractions to enhance long-term soil fertility. Continuous monitoring and research are crucial for comprehending evolving trends and informing sustainable land management decisions. The choice between CMI, SR, and other indicators testing should depend on goals and resources, emphasizing balanced land use for soil health and overall environmental sustainability.

This study emphasizes the profound impact of sustainable management practices, including the application of microorganisms to cultivated crops, on organic matter dynamics. Results indicate that treating legume crops with entomopathogenic and mycoparasitic fungi, alongside lactic acid bacteria, influences soil organic matter pools, especially the labile fraction. Labile organic matter fluctuates significantly across all treatments, with indicators such as CMI, ER, LI, and k serving as early alerts to changes in SOM stocks. Lactic acid bacteria, Trichoderma virens, Metarhizium brunneum, and crop straw incorporation enhance organic matter status, decomposition, and nutrient mineralization, improving soil health and fertility. The study recommends further exploration of soil organic matter dynamics under diverse management practices.

In this thesis the on-farm benefits of beneficial microorganisms were explored. Despite their role in phytomicrobiomes and the food industry, lactic acid bacteria (LAB) among others remain underutilized in agriculture. LAB exhibits various benefits, including improved organic matter decomposition, fermentation, nutrient cycling, and soil remediation. They play a crucial role in alleviating stresses, acting as biocontrol against pathogens, and stimulating plant growth. While LAB has high metabolic activity, their application is hindered by factors like acidification and low buffering capacity. Future research should focus on efficient methodologies for LAB screening, development of commercial bioproducts, and refining application techniques for enhanced plant growth and environmental benefits.

Moreover, entomopathogenic fungi, traditionally recognized for pest management, have evolved into key contributors to nutrients cycling and plant growth, defense induction, stress tolerance, and soil structure improvement. Beyond pest control, these fungi offer environmentally friendly alternatives and play a crucial role in fostering a balance within soil–plant systems. However, challenges such as species identification and variability necessitate comprehensive investigation. The thesis calls for continued empirical scrutiny under real-world conditions to fully harness the potential of entomopathogenic fungi for sustainable agriculture.

To effectively manage soil organic matter sustainability, it's crucial to account for both natural and human-induced factors impacting SOM equilibrium. Natural elements like climate, soil parent material, biota, and topography play a role in regulating the input, output, and decomposition rates of organic matter. Conversely, anthropogenic activities such as conventional tillage and overgrazing diminish SOM, while regenerative approaches like cover cropping, agroforestry, and minimal soil disturbance enhance SOM levels. Adopting practices that decrease decomposition rates and boost organic matter input becomes instrumental in conserving soil fertility, averting degradation, and fostering overall sustainability.

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Curriculum vitae

YVES THEONESTE MURINDANGABO

Profile

A Research and Development Officer at the Institute of Soil Biology and Biogeochemistry, Biology Centre, Czech Academy of Sciences in České Budějovice, whose research focuses on understanding soil process interactions across different spatial and temporal scales to enhance soil health. My work investigates soil organic matter accumulation, composition, and turnover, examining how soil biota, plants, and the soil matrix interact within ecosystems. Understanding these interactions is key to discerning their role in ecosystem changes, particularly during succession and in response to disturbances, land use changes, and global environmental shifts.

Building on my doctoral studies at the University of South Bohemia in České Budějovice, I have a solid foundation in Agroecology and soil ecosystem complexities. My research interests include soil health, decomposition and buildup of soil organic matter, and the effects of anthropogenic activities on soil organic matter. I also explore interactions between soil, plants, and the environment.

I am trained in project management, global entrepreneurship, governance, and customer relations, which complements my expertise in Agro-ecology and soil science. My practical skills include sample collection and processing, soil organic matter fractionation, and data analysis. Additionally, I am experienced in publishing original research, reviews, and meta-analyses. With experience in teaching and interdisciplinary research, I have a strong interest in environmental health and sustainable food production. I am dedicated to finding environmental solutions through critical thinking and effective communication. I actively engage the public with scientific knowledge and present research compellingly. Committed to high-quality results and fostering collaborations, I aim to advance knowledge and promote sustainable practices for a resilient and secure future.

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Languages

- English
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Trainings

- Business Administration
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SERVICES

- Soil sampling and processing
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- Data analysis

PUBLICATIONS

Google Scholar Yves Theoneste Murindangabo

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Education

Ph.D. candidate, Agroecology

- University of South Bohemia in České Budějovice, Czech Republic 2020-2024

Master degree, Agriculture

- Kyungpook National University, Daegu, Korea Republic 2017-2019

Bachelor of science with honors, Agronomy

- University of Rwanda, Republic of Rwanda 2010-2014

Work Experience

Research and development officer at the Institute of Soil Biology and Biogeochemistry, Biology Centre of the Czech academy of sciences 2024-

- This role involves conducting research and development to solve basic research tasks in geographic information systems, ecosystem services, and pedology. Responsibilities include completing parts of the research plan, publishing results in peer-reviewed journals, and presenting at national and international scientific conferences. Additional duties include performing urgent tasks, business errands, and trips, ensuring health and safety compliance, creating databases, knowledge maps, and GIS applications, and extrapolating biophysical parameters of ecosystems in a GIS environment. The role also involves conducting meta-analyses, identifying factors determining ecosystem processes, presenting data in scientific and popular formats, substituting for colleagues during absences, and adhering to the labor code and internal regulations.

Director of Agriculture and natural resources Unit at Gicumbi District/Government of Rwanda 2015-2024

- Coordinating the planning, resources mobilization, implementation, monitoring and evaluation, reporting of the Unit and Sectors on matters related to Agriculture and Natural Resources and instill the practice of knowledge management;
- Coordinating the development and oversee the implementation of actionable strategies or plans meant to localize national policies and the District Council's decisions pertaining to agriculture, livestock, and natural resources;
- Coordinating campaigns meant to raise local population awareness on the use and importance of modem techniques of agriculture, livestock, and natural resource management;
- Coordinating the supervision of activities of animal and plants control diseases organized at the Sector level and facilitate access of local farmers' products to the market;
- Serves as a member of the District Technical Coordination Committee and advises the institution on matters pertaining to agriculture, livestock and natural resources management.

Adjunct Assistant Lecturer, University of Technology and Arts, Byumba/ Rwanda 2019-2020

- Undertake teaching and related activities
- Participating in continuous professional development

Enumerator, Laterite Rwanda LTD 2014-2015

- Questionnaire Designing and testing
- Data collection and cleaning

Farm manager, PROXIFRESH RWANDA Ltd 2014-2014

- Farm activities calendar and management of related tasks
- Labor recruitment
- Preparing payment
- Supervising farm activities
- Cleaning, sorting, and packing the produce