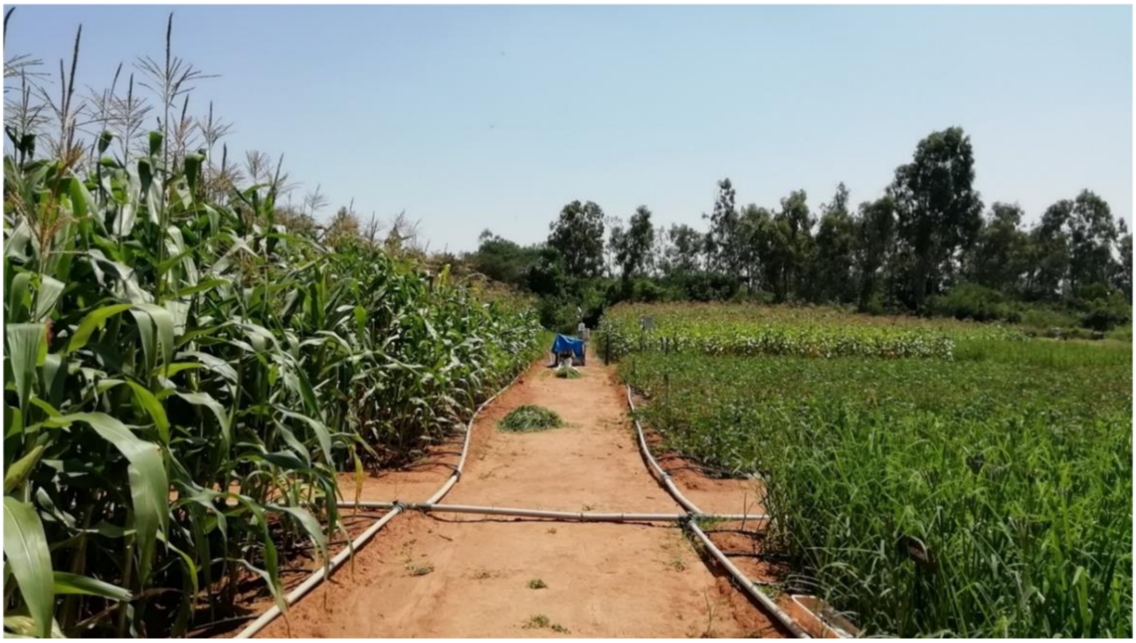
Management effects on soil microbial functions at a South-Indian rural-urban interface



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Management effects on soil microbial functions at a South-Indian rural-urban interface

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To Crixus, Chepe, my parents and sisters

To Bangalore

Preface

This document is intended as a dissertation to fulfill the requirements of a doctoral degree in the Faculty of Organic Agricultural Sciences of the University of Kassel. This dissertation is based on three papers as first author presented in chapters 2, 3, and 4. The three papers have been accepted in international peer-reviewed journals.

I could not be more grateful to culminate the work of the past years with this dissertation based on microbial communities of Bangalore, an amazing region, to which I hope this work helps and whose memories I deeply treasure.

The past years do not only include the past four years where most of my time was invested in this work. The past years started when I started my career as a biologist interested in animal ecology and conservation in the tropics. This brought me to Germany for my master's in Landscape Ecology and Nature Conservation thanks to a DAAD scholarship. From then, my view and understanding of nature, biology, and conservation changed, and I developed my current interest in biological research for sustainable agriculture. This project allowed me to do that kind of research. Therefore, I am thankful to my supervisors Dr. Christine Wachendorf and Prof. Jörgensen for the acceptance to this doctoral project and, for all the knowledge and advice that they have shared with me. They have contributed to building the researcher I am today.

Additionally, this path would not have been possible without the support and inspiration of many individuals who have contributed to shape my scientific career. Among them are school and college teachers; Dr. Helen Esser, Dr. Hermogenes Fernández, Prof. Andy Dobson, Prof. Stephen Pacala, Prof. Yves Basset, Prof. William Wcislo, and many other brilliant scientists I had the opportunity to meet with at STRI; Dr. Ema Flores, Dr. Javier Ibarra, Dr. Jorge Quezada (R.I.P.), and many other Latin-American brilliant biologists, and my parents Miguel Moran and Virna Rodas. To all of them, I am humbled and grateful.

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Abbreviations

AMF	arbuscular mycorrhizal fungi
ANOVA	analysis of variance
APB	aboveground-plant biomass
$BaCl_2$	Barium chloride
$BaCO_3$	Barium carbonate
C	carbon
C3	three-carbon fixation mechanism of plants
C4	four-carbon fixation mechanism of plants
$\delta^{13}C$	isotopic signature of carbon-13
$CaCl_2$	Calcium chloride
CaO	Calcium oxide
CO_2	Carbon dioxide
COVID-19	Coronavirus disease 2019
CUE	carbon use efficiency
CUE_{MB}	carbon use efficiency of microbial biomass
CV	mean coefficient of variation
DAP	diammonium phosphate
DM	dry matter
E_C	Extractable organic carbon
E_N	Extractable nitrogen
E_P	Extractable phosphorus
FYM	farmyard manure
FM	fresh matter
GalN	galactosamine
g	acceleration value of centrifuge or centrifuge force
GHG	Greenhouse gases
GlcN	Glucosamine
HH	Household
H_2O	water
HCl	Hydrochloric acid
HPLC	high-performance liquid chromatography
IUSS	International Union of Soil Sciences
NH_4F	Ammonium fluoride
K_2SO_4	Potassium sulfate

k_{EC}	microbial biomass fraction of extractable carbon
k_{EN}	microbial biomass fraction of extractable nitrogen
k_{EP}	microbial biomass fraction of extractable nitrogen
Max	Maximum value
MB	microbial biomass
MBC	microbial biomass carbon
MBN	microbial biomass nitrogen
MBP	microbial biomass phosphorus
Min	mineral fertilization/ minimum value
MRC	microbial residue C
MurN	Muramic acid
N	nitrogen / sample size
N_2	molecule of nitrogen gas
NaOH	Sodium hydroxide
N_2O	Nitrous oxide
NS	not significant
P	Phosphorus/ probability of significance of null hypothesis
PO_4	phosphate
pH	potential of hydrogen
PLFA	Phospholipid-derived fatty acids
POM	particulate organic matter
qCO_2	metabolic quotient
R^2	regression coefficient
r	Pearson coefficient
r_s	Spearman rank correlation coefficient
S	Sulphur
SSI	Survey Stratification Index
SOM	soil organic matter
SOC	Soil organic carbon
^{18}O	oxygen-18 isotope
SEM	standard error of means
Std. dev.	standard deviation
USDA	United States Department of Agriculture)
VPDB	Vienna Pee Dee Belemnnite
WHC	water holding capacity
WRB	World Reference Base for Soil Resources

Summary

Urbanization leads to effects on many aspects of ecosystems and societies. Among the affected are agricultural systems and, specifically, soils. One of the most evident pathways of urbanization effects on agricultural soils is through an increased demand for agricultural commodities requiring agricultural intensification, hence, changes in management practices that alter soils.

In this context, the purpose of this study was to understand how the main agricultural management practices taking place in urbanizing Bangalore affect soil microorganisms, and their functions of soil organic matter decomposition and carbon sequestration. Thus, the first aim of this research was to evaluate the effects of N fertilization level (low and high) and crop type (maize and finger millet) on a set of microbial indicators that characterize the state and functionality of the microbial communities. For this, a two-factorial split-plot design was used, at two fields (irrigated and rainfed) on typical soil types (Nitisol and Acrisol). This study found that more intensified irrigated systems (Nitisol) are more productive, which creates a greater buffer capacity against fertilization- or crop-type effects on soil microbes. In addition, the Nitisol system had larger soil organic C (SOC) levels, microbial biomass and necromass compared with acidic rainfed systems (Acrisol). Whereas microbial biomass remained similarly active in both systems.

Soil pH and the amount of particulate organic matter (POM), along with site-condition differences (clay content, irrigation), rather than N-fertilization level, were major drivers of microbial parameters. These results pointed out the need for improving SOC stocks and nutrient balances by providing fresh organic inputs to the fields, especially under rainfed agriculture and to the need of liming and evaluate liming impacts on SOC-associated microbial functions in Bangalore´s soils. Thus, the second aim of this research was to address the effect of liming on an integrative microbial indicator of

microbial C-cycling and C sequestration in soils: microbial carbon use efficiency (CUE). The effect of pH and liming were evaluated on total CUE (including microbial residues), CUE of microbial biomass (CUE_{MB}) and fungal biomass after maize-litter addition in a 6-week incubation experiment. Microbial measurements were addressed in both soils, on the acidic Acrisol (limed and unlimed) compared to the Nitisol (unlimed). Litter addition benefited fungal biomass, which was at the end greater in the limed Acrisol than the Nitisol and was positively associated to CUE_{MB}. An increased pH decreased CUE and promoted positive priming of SOC. According to these results is the low input of plant residues, and not reduced microbial efficiency, the most likely cause of lower SOC levels in the Acrisol.

The last aim of this research was to relate these field-scale and experimental findings to actual SOC dynamics taking place in Bangalore at the regional scale. This aim was split into two steps. The first step was to identify the medium- and long-term effect of relevant management practices on SOC levels, conducting a review of literature about effect of management practices on Indian soils (and Bangalore soils when available) followed by a local meta-analysis of N-fertilization effects in Bangalore. The second step was to understand how the socio-economic effects of rapid urbanization across Bangalore´s rural-urban interface could be leading to changes in such management practices. This was evaluated using interview data from farmers' households across an urbanity gradient in Bangalore.

Despite of the mild effect of increased N-fertilization on microbial parameters found in the current research, at the broader scale, N fertilization, in a recommended dose, positively influences SOC levels in Bangalore´s soils, especially when mineral and farmyard manure (FYM) fertilization are combined. However, this combination was less common than single mineral fertilization in Bangalore. Furthermore, conservation practices are necessary in Bangalore to improve current low SOC levels but less than 50%

of interviewed farmers apply conservation practices such as minimum/non-tillage and only 16% applied residue management such as mulching, crop-residue application or the use of cover crops. Residue management practices are significantly associated to market integration and to cultivation of specific irrigated (flowers, vegetables, fruits) and non-irrigated (pulses) crops. While urbanization reduces minimum-tillage application. When farmers rely more on agriculture, have the means and are better integrated to markets, it is more likely that they adopt intensification practices like irrigation. This practice is strongly associated with crop choice, i.e., adoption of irrigated crops like fruits, vegetables and fodder instead of traditionally non-irrigated crops like cereals.

Overall, our study points out that improved management of crop residues and cultivation of diverse crops, application of liming and increasing farmer economic opportunities (e.g., off-farm income, durable assets, market integration) would improve the current status of Bangalore´s soils.

Zusammenfassung

Die Urbanisierung hat Auswirkungen auf viele Aspekte und Komponenten von Ökosystemen und Gesellschaften. Zu den betroffenen Komponenten gehören auch landwirtschaftliche Systeme und insbesondere das Bodensystem. Einer der eindeutigsten Wege für die Auswirkungen der Verstädterung auf die landwirtschaftlichen Böden ist die erhöhte Nachfrage nach landwirtschaftlichen Erzeugnissen, die eine Intensivierung der Landwirtschaft und damit Änderungen der Bewirtschaftungsmethoden erfordert, die die Böden verändern.

Vor diesem Hintergrund sollte in dieser Studie untersucht werden, wie sich die wichtigsten landwirtschaftlichen Bewirtschaftungsmaßnahmen im urbanisierten Bangalore auf die Mikroorganismen im Boden und ihre Funktionen des Abbaus organischer Substanzen und der Kohlenstoffbindung auswirken. Das erste Ziel dieser Studie war es daher, die Auswirkungen der Stickstoffdüngung (niedrig und hoch) und der Pflanzenart (Mais und Fingerhirse) auf eine Reihe von mikrobiellen Indikatoren zu bewerten, um die Hauptfunktionen der mikrobiellen Gemeinschaft zu charakterisieren.

Zu diesem Zweck wurde ein zweifaktorielles Split-Plot-Design auf zwei Feldern (bewässert und beregnet) auf typischen Bodentypen (Nitisol und Acrisol) verwendet. Die Studie ergab, dass die höhere Produktivität unter der intensiven Bewirtschaftung mit Bewässerung des Nitisols, eine größere Pufferkapazität gegen Auswirkungen der Düngung oder der Kultur auf die Bodenmikroben bedingt. Darüber hinaus wies der bewässerte Nitisol im Vergleich zu sauren, regengespeisten Acrisol einen höheren SOC-Gehalt, eine größere mikrobielle Biomasse und eine höhere Nekromasse auf. Während die mikrobielle Biomasse in beiden Systemen ähnlich aktiv bleibt. Der pH-Wert des Bodens und die Menge an partikulärer organischer Substanz (POM) sowie Unterschiede in der Bodenart (Tongehalt, Bewässerung) waren die Hauptfaktoren für die mikrobiellen

Parameter und nicht die Höhe der N-Düngung. Diese Ergebnisse wiesen auf die Notwendigkeit hin, die SOC-Vorräte und die Nährstoffbilanzen durch die Zufuhr frischer organischer Stoffe auf den Feldern zu verbessern, insbesondere bei Regenfeldbau, sowie auf die Notwendigkeit der Kalkung und der Bewertung der Auswirkungen der Kalkung auf die SOC-assoziierten mikrobiellen Funktionen in den Böden von Bangalore. Das zweite Ziel dieser Untersuchung war daher die Untersuchung der Auswirkungen der Kalkung auf einen integrativen mikrobiellen Indikator für C-Kreislauf und C-Sequestrierung in Böden: die mikrobielle Kohlenstoffnutzungseffizienz (CUE). Die Auswirkungen von pH-Wert und Kalkung wurden auf den Gesamt-CUE (einschließlich mikrobieller Rückstände), den CUE der mikrobiellen Biomasse (CUE_{MB}) und die Pilzbiomasse nach der Zugabe von Maisstreu in einem 6-wöchigen Inkubationsversuch untersucht. Die mikrobiellen Messungen wurden in beiden Böden durchgeführt, auf dem sauren Acrisol (gekalkt und ungekalkt) im Vergleich zum Nitisol (ungekalkt). Die Zugabe von Streu kam der Pilzbiomasse zugute, die am Ende im gekalkten Acrisol größer war als im Nitisol und es mit der CUE_{MB} positiv verbunden war. Ein erhöhter pH-Wert verringerte die CUE und förderte die positive Grundierung des SOC. Nach diesen Ergebnissen ist der geringe Eintrag von Pflanzenrückständen und nicht die verringerte mikrobielle Effizienz die wahrscheinlichste Ursache für die niedrigeren SOC-Werte im Acrisol.

Das letzte Ziel dieser Forschungsarbeit bestand darin, diese Ergebnisse aus Feldversuchen und Experimenten mit der tatsächlichen SOC-Dynamik in Bangalore auf regionaler Ebene in Beziehung zu setzen. Dieses Ziel wurde in zwei Schritte unterteilt. Der erste Schritt bestand darin, die mittel- und langfristigen Auswirkungen einschlägiger Bewirtschaftungspraktiken auf den SOC-Gehalt zu ermitteln. Dazu wurde die Literatur über die Auswirkungen von Bewirtschaftungspraktiken auf indische Böden (und auf Böden in Bangalore, sofern verfügbar) ausgewertet, gefolgt von einer lokalen Meta-

Analyse der Auswirkungen der N-Düngung in Bangalore. In einem zweiten Schritt wurde untersucht, inwieweit die sozioökonomischen Auswirkungen der Urbanisierung im ländlich-städtischen Übergangsbereich der schnell wachsenden Megacity Bangalore zu Veränderungen bei den Bewirtschaftungspraktiken führen könnten. Dies wurde anhand von Umfragen in bäuerlichen Haushalten unterschiedlicher Urbanität in Bangalore untersucht.

Trotz der geringen Auswirkungen einer erhöhten N-Düngung auf mikrobielle Parameter, die in dieser Studie festgestellt wurden, hat die N-Düngung in der empfohlenen Dosierung einen positiven Einfluss auf den SOC-Gehalt der Böden in Bangalore, insbesondere wenn Mineral- und Stallmistdüngung kombiniert werden. Diese Kombination war jedoch in Bangalore weniger verbreitet als die alleinige Mineraldüngung. Darüber hinaus sind in Bangalore konservierende Praktiken notwendig, um die derzeit niedrigen SOC-Werte zu verbessern, aber weniger als 50 % der befragten Landwirte wenden konservierende Praktiken an, wie z. B. minimale bzw. keine Bodenbearbeitung, und nur 16 % wenden Rückstandsmanagement an, wie z. B. Mulchen, Ausbringen von Ernterückständen oder Verwendung von Zwischenfrüchten.

Die Verwendung von Ernterückständen stehen in signifikantem Zusammenhang mit der Marktintegration und mit dem Anbau bewässerter (Blumen, Gemüse, Obst) und unbewässerter (Hülsenfrüchte) Kulturen, während die Urbanisierung die Wahrscheinlichkeit der Anwendung von Minimalbodenbearbeitung reduziert. Die Wahrscheinlichkeit der Anwendung von Intensivierungspraktiken wie Bewässerung ist höher, wenn die Haushalte ihr hauptsächliches Einkommen aus der Landwirtschaft beziehen, über die nötigen Mittel verfügen und besser in die Märkte integriert sind. Diese Praxis steht in engem Zusammenhang mit der Wahl der Anbauprodukte, d. h. mit der Entscheidung für bewässerte Kulturen wie Obst, Gemüse und Futtermittel anstelle von traditionell unbewässerten Kulturen wie Getreide.

Insgesamt weist unsere Studie darauf hin, dass eine verbesserte Bewirtschaftung von Ernterückständen und Fruchtfolgen, Kalkung und verbesserte wirtschaftliche Möglichkeiten für die Landwirte (z.B. Off-farm Einkommen, dauerhafte Vermögenswerte, Marktintegration) den derzeitigen Zustand der Böden in Bangalore verbessern würden.

1 General introduction

1.1 Soil functions, ecosystem services and the role of soil microbes

Soil microbial communities allow the cycling of nutrients and sequestration of carbon in the soil, two indispensable ecosystem services in soils. This is possible through the microbial functions of organic matter decomposition, mineralization, immobilization of carbon and nutrients and nitrogen fixation, as a result of microbial processes such as growth (microbial biomass production), metabolic adjustments and the production of microbial residues such as extracellular enzymes and necromass.

1.1.1 Nutrient Cycling

Nutrient cycling is defined as the movement of nutrients within and between the various biotic or abiotic pools in which they occur. This includes their extraction from their mineral or atmospheric sources and their conversion from organic forms to ionic forms, enabling uptake and ultimately returning them to the atmosphere or soil (recycling) (Millennium Ecosystem Assessment 2005).

In the Anthropocene, in general, an improved cycling of nutrients refers to reduced emissions of soil GHG, improved nutrient response efficiency by plants, improved cation exchange capacity, reduced nutrient saturation, reduced nutrient leaching, synchronization of mineralization of plant available nutrients and plant demand, improved N_2 fixation or increased recycling of nutrients through litter decomposition.

1.1.2 Soil organic matter decomposition

SOM is composed of several pools that include fresh litter inputs, particulate organic matter (size-fractionated plant residues), microbial, and animal residues.

SOM decomposition is controlled by the microbial demand for C and nutrients (Sinsabaugh et al. 2009; Manzoni et al. 2010; Stone et al. 2013; Vidal et al. 2021).

Microbial biomass in fact is a strong predictor of decomposition rates at both local and global scales (Bradford et al. 2017). Microbial stoichiometry (element ratios) displays the requirements of the soil microbial biomass for maintenance and growth (Sinsabaugh et al. 2009; Manzoni et al. 2010; Buchkowski et al. 2015; Schleuss et al. 2021). Therefore, the analysis of microbial biomass stoichiometry and soil limiting elements (i.e. soil stoichiometry) is important for predicting SOM decomposition and cycling of elements (Sinsabaugh et al. 2009; Manzoni et al. 2010; Buchkowski et al. 2015). Environmental drivers that shape decomposition and determine its rate are in consequence those that alter the microbial processes, and include water availability, temperature, soil properties and substrate quality (e.g., nutrient stoichiometry and lignin content) and, their interactions (Palm et al. 2001; Bradford et al. 2017). Substrate stoichiometry affects which microorganisms dominate the decomposition process and the extent to which elements limit microbial growth (Zechmeister-Boltenstern et al. 2015).

1.1.3 Soil fertility and carbon sequestration

SOM is an indispensable factor for soil fertility (Tiessen et al. 1994). Besides, it relates to other services such as the provision of habitat for soil organisms, the promotion of biodiversity and C sequestration (Oldfield et al. 2019). Although SOM is composed by many elements, it directly relates to its SOC concentration that constitute at least 50% of it (Pribyl 2010). Therefore, SOC is used as a proxy for SOM and, thus, as a broad indicator of soil functionality.

The amount of C sequestered in soil is larger than the atmospheric C pool (Lal 2008a). However, C sequestration depends not necessarily just on a higher C input, but also on how soil microbial communities process and assimilate or mineralize C according to their demands (Sinsabaugh et al. 2009; Manzoni et al. 2010; Stone et al. 2013; Vidal et al. 2021). Soil carbon is known as the main limitation for microbial growth and activity (Heuck et al. 2015; Sanaullah et al. 2016). However, the sequestration process will also depend on the recalcitrance of the C source. Recalcitrant components like humus have a longer residence time in soils.

1.2 Soil microbial indicators of microbial functions

1.2.1 microbial biomass and microbial residues

Both microbial biomass and necromass production are indicators of microbial anabolism. In addition, the microbial biomass contribution to SOC or MBC (%SOC), provides a more sensitive indicator to C changes than the total SOC (Sparling 1992) and reflects the soil (substrate) quality for microbial biomass production (Joergensen et al. 2019).

Microbial residues are an important, or probably the main source of C sequestered and stabilized in SOM (Cotrufo et al. 2013; Kallenbach et al. 2016; Liang et al. 2017; Liang et al. 2019). According to this, the use of amino sugars as indicators of microbial residues can be a useful indicator of C sequestration. Furthermore, specific amino sugars can indicate specific portions of this microbial-residues pool. For example, Muramine is considered an indicator of bacterial residues and Galactosamine an indicator of microbial extracellular polymeric substances (Joergensen 2018).

1.2.2 microbial growth, activity and carbon use efficiency

Microbial SOC stabilization can only be determined when both microbial processes C mineralization (catabolism or CO_2 production) and sequestration (anabolism, microbial biomass and necromass production) are considered (Liang et al. 2017).

The metabolic quotient (qCO_2), which is the ratio of basal respiration to microbial biomass C (MBC), is an important index of SOM utilization to satisfy the microbial demand for maintenance energy (Anderson and Domsch 1993, 2010; Hartman and Richardson 2013), indicating microbial catabolism.

Microbial carbon use efficiency (CUE) is defined as the relation between the amount of C used for anabolic and catabolic processes in the microbial community (Jones et al. 2018, 2019; Horn et al. 2021). As such it is a relevant global regulator of SOC cycling (Allison et al. 2010; Li et al. 2019; Wang et al. 2021). Some studies have found correlations between CUE and SOC contents (Oliver et al. 2021; Wang et al. 2021). Nevertheless, different approaches are used for calculating CUE, yielding different results. The most frequent is CUE of microbial biomass (CUE_{MB}) (Manzoni et al. 2012; Sinsabaugh et al. 2013; Spohn et al. 2016b). It, however, excludes microbial residues and is usually based on specific easy-to-assimilate substrates. An additional approach that do not require substrate to calculate CUE_{MB} because is focused on SOC consumption directly consist on ^{18}O labelling from water (Spohn et al. 2016a). Yet, this method still excludes microbial residues. Using an approach that considers necromass production increases CUE from 3 up to 5-fold, compared to CUE_{MB} (Börger et al. 2022; Schroeder et al. 2020); This more inclusive total CUE is referred simply as CUE hereafter.

1.2.3 community composition, structure and diversity

Shifts in the microbial community structure play a role in C dynamics, due to differences in resource use especially between fungi and bacteria (Rousk and Bååth 2011; Scott et al. 2012; Kallenbach et al. 2016; Malik et al. 2016). There are findings that point out fungi as more efficient organisms than bacteria, inferring that fungal dominated communities should favor SOC stabilization (Six et al. 2006; Kallenbach et al. 2016; Malik et al. 2016). However, in microbial communities where bacterial growth has been promoted over fungal growth by improved pH, CUE has also increased (Silva-Sanchez et al. 2019); showing that both bacteria and fungi can be more efficient under certain conditions. In any case, it is suggested that community changes (composition, structure, diversity) are drivers of CUE and of priming (Domeignoz-Horta et al. 2020; Kallenbach et al. 2016; Nottingham et al. 2009).

To date, however, there are still limitations among the methods available to quantify the relative contribution of the different groups. Amino sugars are a broadly used technique to characterize fungal and bacterial portions of microbial biomass and obtain fungal:bacterial ratios. Molecular techniques offer the possibility to characterize the community with larger resolution providing information on the different groups of bacteria and fungi (diversity) with more classification-accuracy than other methods such as PLFA´s. However, molecular methods are still unable to provide accurate group-partitioning or absolute abundances, due to the impossible assignation of quantified genes to specific units of microorganisms. Saprotrophic fungi and biotrophic arbuscular mycorrhizal fungi (AMF) are known to contribute differently to SOM cycling, due to their trophic differences (Verbruggen et al. 2017; Zhang and Elser 2017). In this case the ergosterol/fungal GlcN ratio provide a reliable indicator of shifts between saprotrophic fungi and AMF (Faust et al. 2017).

1.3 Management effects on soil microbial functions

Intensified N fertilization and irrigation increase plant primary production and the input of plant residues to the soil (Yue et al. 2016; Oldfield et al. 2019; Araya et al. 2021). N additions interact with microbial C and N limitation (Stone et al. 2013, Drake et al. 2013); and with other soil factors such as pH. These effects may lead to short term increases and long-term decreases in microbial biomass (Hartman and Richardson 2013; Wallenstein et al. 2006; Treseder 2008; Heitkamp et al. 2009). Increased respiration rates can also occur with high N fertilization in cropland soils (Li et al. 2018) but also positive effects on amount of SOC (Tian et al. 2012). Nevertheless, potential increased N_2O emissions that may outweigh environmental benefits (Tian et al. 2012). Organic fertilizers such as plant byproducts, biochar, compost, and FYM contribute to SOC sequestration (Anand et al. 2015; Powlson et al. 2011; Paustian et al. 2016; Palm et al. 2001). Although their potential to provide N is more limited (Palm et al. 2001).

One of the most important soil parameters for microbial communities, including its CUE and C sequestration mechanisms is pH but its effect can vary according to acidity thresholds and changes in the microbial community (Canini et al. 2019; Malik et al. 2018; Wang et al. 2019; Rousk et al. 2009; Oliver et al. 2021; Jones et al. 2019; Silva-Sánchez et al. 2019; Horn et al. 2021; Xiao et al. 2021; Pei et al. 2021). In addition, the effect of liming to improve soil pH can vary according to the quality and origin of the lime (Bailey et al. 1991), or to soil factors such as nutrient availability, buffering capacity, aluminum saturation and others (Islam et al. 2004; Nelson and Su 2010; Olego et al. 2014).

An additional management factor that affects SOC stocks is the removal of crop residues, especially in tropical soils (Lal 2004). This is caused by higher demands for crop residues for alternative uses, such as livestock feeding, fuel, and fiber (Fujisaki et al. 2018).

In systems where aboveground crop residues are not retained, roots are an important C supply to soil. Hence, in such systems, crop choice may alter soil dynamics via differential root traits and root inputs (Bardgett et al. 2014; Manjaiah et al. 2000; Moran-Rodas et al. 2022; Palm et al. 2001; Srinivasarao et al. 2014). Particulate organic matter (POM) is strongly correlated with annual root productivity (Ontl et al. 2015; de Freitas Iwata et al. 2021). The positive effects of crop-residue retention and mulch include improve soil's structure, water holding capacity, soil moisture, protection against erosion, and increase C and nutrient inputs, reduce nutrient exports, and soil quality in general (Liu et al. 2017; Chaudhary et al. 2018; Fujisaki et al. 2018; Yadvinder-Singh et al. 2005;

Powlson et al. 2011). Despite of these necessary measures, especially in rainfed systems, its use is not frequent in India (Lal 2008a).

Differences in quality between the type of residues also plays a role on microbial indexes related to SOM decomposition and C sequestration such as their activity and production of microbial residues (Yadvinder-Singh et al. 2005; Fontaine et al. 2007; Moran-Rodas et al. 2022; Liang et al. 2017). Thus, e.g. the greater leaf-quality, the faster leaf-litter decomposition rate (Joly et al. 2023). Besides, due to their different chemistry there are differences. Root-litter decomposes slower than leaf litter, due to the chemical differences of their composition (Sun et al. 2018). Crop selection of N_2-fixing plants can contribute to some extent as a substitution of mineral N fertilizer.

Intensive tillage practices alter soil structure in a way that represents a factor of SOC losses (Lal 2004; Oelbermann et al. 2004; Powlson et al. 2011; Paustian et al. 2016). To counteract these effects, conservation-, reduced- or even non-tillage systems are recommended and proven to improve SOC concentrations (Pandey et al. 2010; Kushwa et al. 2016; Kumar et al. 2018).

Zooming out on the ecosystem scale of soil functions, precipitation regimes are one of the main global and regional drivers of decomposition patterns (Bradford et al. 2017). This is because at the microbial scale of soil functionality, soil moisture affects a number of microbial processes, for example microbial growth and community dynamics like differential growth between bacteria and fungi (Frey et al., 1999). Hence, microbial residues can be affected by precipitation/drought patterns (Amelung et al. 1999). Hence, besides increasing plant productivity, irrigation is an essential aspect to evaluate soil dynamics. It can on the one hand increase SOC inputs through increased plant productivity, but on the other hand will accelerate decomposition rates likely making C sequestration mechanisms inefficient or ineffective (Fujisaki et al. 2018). Furthermore, there are other potential negative effects from irrigation, such as increased erosion rates and nutrient losses (Sojka et al. 2007); that may, however, interact with plant productivity.

1.4 Effects of urbanization on agricultural management and soil

Urbanization leads to an increased demand for natural resources globally and thus, to agricultural intensification. Farmer´s vulnerability to global change can also increase at the rural-urban interface of fast-growing cities mainly because it reduces fertile cropland areas for the expansion of urban infrastructure, which brings further consequences to the farmers (Seto and Ramankutty 2016). In this context, it is likely that farmers pursue alternative work outside agriculture (Kurgat et al. 2018) and may change their agricultural management practices (Lee 2005).

1.4.1 The case of Bangalore's rural-urban interface

Bangalore exemplifies many key characteristics of urbanization and related agricultural transformations (Rao et al. 2007; Narayana 2011; Kraas and Mertins 2014), including its negative environmental effects (Sudhira and Nagendra 2013; Ramachandra et al. 2019).

In Bangalore, rural-urban dynamics have led to the introduction of irrigation in originally rainfed agriculture, depletion of groundwater sources, increased fertilization, especially with nitrogen, and crop-choice changes (Prasad et al. 2016; Prasad et al. 2019; Patil et al. 2019). Increasing urban demand is promoting crop-choice changes from traditional rainfed cereal crops to more intensively managed irrigated vegetables in the vicinity of city markets (Patil et al. 2019). Nevertheless, cereals and pulses continue to be the main crop choice for farmers, especially finger millet and maize (Patil et al. 2019).

A continuous practice is the removal of above-ground biomass for energy and fodder production, without animal manure returns because this product is also used as fuel, or disposed in the city by urban cattle, reducing the return of C inputs to the soil and increasing water pollution (Prasad et al. 2016; Prasad et al. 2019).

As a consequence, increasingly low SOC levels are common in Indian agricultural soils, with no exception for Bangalore (Lal 2004; Sathish et al. 2016). Although some conservation practices have also been identified in Bangalore.

Fertilization practices in Bangalore include mineral fertilizer, FYM, organic fertilizers, compost, a combination of mineral and FYM, or a combination of mineral and organic fertilization.

Considering the potential influence of the different management practices on soil microorganism and agricultural soils in Bangalore, this research addresses the following objectives:

1.5 objectives

- To characterize the effect of intensified N fertilization level and crop type modified by irrigation on microbial-, fungal-, and bacteria biomass, microbial stoichiometry, microbial activity and production of microbial residues, as functional indicators of SOC dynamics and soil quality at the field scale in two typical soil types in Bangalore's rural-urban interface.
- To understand the feedback mechanisms between soil-, vegetation- and microbial-function indicators, and therefore, the pathways by which microbial functions are altered in the two soils representative of Bangalore's rural-urban interface.
- To test the effect of pH and liming on CUE, CUE_{MB} and fungal biomass of an acidic Acrisol compared to a nearby Nitisol with optimal pH, after maize litter addition in Bangalore's rural-urban interface.

- To provide an overview, based on literature review and farmer-interview data, of how current management practices relate to urbanization and alter SOC levels in Bangalore's soils.

2 Microbial response of distinct soil types to land-use intensification at a South-Indian rural-urban interface

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Abstract

Aims Rural-urban dynamics are leading to agricultural intensification practices, which affect microbial ecosystem functions in a soil-specific way. This study aimed to investigate what effects agricultural intensification has on soil microbial communities.

Methods The effects of N fertilization level (low and high) and crop type (maize and finger millet) on microbial communities were investigated, using a two-factorial split-plot design, at two fields (irrigated and rainfed) on typical soil types (Nitisol and Acrisol) mimicking an intensification gradient in the rural-urban interface of the Indian Megacity Bangalore.

Results The Nitisol had higher pH and clay content than the Acrisol. In combination with irrigation, this led to higher aboveground plant biomass (APB), soil organic carbon (SOC), microbial biomass (MB), fungal ergosterol and microbial necromass. High APB resulted in low total P content, due to P export in APB and high soil C/P and MB-C/P ratios in the Nitisol. Crop type and N fertilization level did not affect microbial parameters in the irrigated Nitisol, whereas crop type affected ergosterol and MBP and N fertilization level affected basal respiration in the rainfed Acrisol. Particulate organic matter (POM) was a major explanatory factor for most microbial parameters in both soils. In the Acrisol, drought reduced metabolic demand, which counteracted negative effects of low pH and clay on the MB. This was indicated by similar metabolic quotients and MBC/SOC ratios in both soils.

Conclusions These results indicate the current need for water and high-quality fresh plant inputs to improve the microbial contribution to soil fertility at Bangalore.

Key words: Nitrogen fertilization, Carbon cycling, Tropical agriculture, Metabolic quotient, $\delta^{13}C$ of particulate organic matter, Irrigation.

2.1 Introduction

Urbanization of rural areas leads to a higher resource demand and agricultural intensification, altering soil microbial dynamics globally, especially in the tropics (Elmqvist et al. 2013; Steinhübel and von Cramon-Taubadel 2021). In Bangalore (India), in particular, rural-urban dynamics have led to the introduction of irrigation in originally rainfed agriculture, depletion of groundwater sources, intensified fertilization, especially with N, and changes in crop selection (Prasad et al. 2016; Patil et al. 2019; Prasad et al. 2019). In addition, aboveground biomass from crops is removed from the fields for energy or fodder production, and even the resulting manure is used as fuel for domestic activities elsewhere, reducing the C return to the soil (Prasad et al. 2016; Prasad et al. 2019).

Intensified N fertilization and irrigation increase plant primary production and the input of plant residues to the soil (Giardina et al. 2003; Compton et al. 2004; Asner et al. 2011; Yue et al. 2016). In systems where aboveground crop residues are not retained, roots are an important C supply to soil, which illustrates the importance of crops with a higher root/shoot ratio as a C input in such soils, as in the case of finger millet (Goron et al. 2015). Particulate organic matter (POM) is an indicator of the labile soil C fraction mainly composed of recent plant residues (Fontaine et al. 2007; Kauer et al. 2021). POM is strongly affected by management and highly correlated with annual root productivity (Ontl et al. 2015; de Freitas Iwata et al. 2021). However, a higher C input may not promote C storage per se. It is the soil microbial activity and demand for C and nutrients that drives soil organic matter (SOM) decomposition or stabilization (Sinsabaugh et al. 2009; Manzoni et al. 2010; Stone et al. 2013; Vidal et al. 2021). This highlights the importance of microbial stoichiometry (element ratios) and limitations in the soil, which determine the requirements of the soil microbial biomass for maintenance and growth (Sinsabaugh et al. 2009; Manzoni et al. 2010; Buchkowski et al. 2015; Schleuss et al. 2021). In general, N and P are considered the most limiting nutrients in temperate and tropical soils, respectively (Elser et al. 2007; Vitousek et al. 2010). In terms of soil microbial community structure, growth and activity, there is evidence to suggest contrasting N addition effects (Compton et al. 2004; Wallenstein et al. 2006; Treseder 2008; Heitkamp et al. 2009). In this context, the metabolic quotient (qCO_2), which is the ratio of basal respiration to microbial biomass C (MBC), is an important index of SOM utilization to satisfy the microbial demand for maintenance energy (Anderson and Domsch 1993, 2010; Hartman and Richardson 2013).

Shifts in the microbial community structure play a role in C dynamics, due to reported differences in resource use of fungi and bacteria and potentially different contributions to SOM (Rousk and Bååth 2011; Scott et al. 2012; Kallenbach et al. 2016; Malik et al. 2016). This highlights the importance of the fungal to bacterial ratio as an indicator for SOM dynamics. This ratio can be estimated on the basis of amino sugars in soil, which are present in the cell wall residues of fungi and bacterial cells (Joergensen 2018; Liang et al. 2019). Muramic acid (MurN) is specific for bacterial necromass, and glucosamine (GlcN) can be corrected to be used as an indicator for fungal necromass (Joergensen 2018). Saprotrophic fungi and biotrophic arbuscular mycorrhizal fungi (AMF) also contribute differently to SOM, due to their trophic differences (Verbruggen et al. 2017; Zhang and Elser 2017). Saprotrophic fungi decompose SOM, while biotrophic AMF receive organic compounds from plants in exchange for nutrients taken up from the soil. In arable soils, saprotrophic fungi contain exclusively ergosterol, which is not present in the cell-membranes of AMF (Olsson et al. 2003). In this way, the ergosterol/fungal GlcN ratio has served as a reliable indicator of shifts between saprotrophic fungi and AMF (Faust et al. 2017).

Management intensification affects microbial SOM stabilization, but the pathways and variation across agroecosystems are difficult to predict, due to the many factors involved, which is especially true for dynamic tropical agroecosystems (Joergensen 2010; Banger et al. 2015; Srivastava et al. 2020). Consequently, this study addresses important knowledge gaps in microbial ecology and stoichiometry in relation to urbanization-driven intensification in the tropics, caused by N fertilization level and crop type modified by soil type and irrigation. We investigated the following hypotheses: (1) High N fertilization leads to higher plant biomass, increasing MBC and MB-C/P ratios. (2) POM is an indicator of recent plant residue input, and positively correlates with microbial indices. (3) Unfavorable conditions like low pH or nutrient limitation lead to a higher qCO_2. (4) A more efficient SOM utilization by microbial biomass is positively correlated to indicators of fungal biomass (ergosterol, fungal C/bacterial C, ergosterol/MBC, and ergosterol/fungal GlcN ratios).

2.2 Materials and Methods

2.2.1 Experimental design

The experimental fields were located at the GKVK campus, University of Agricultural Sciences, Bangalore (°58′20.79″N, 77°34′50.31″E) at an altitude of 920 m above sea level. The mean annual temperature is 29.2 °C (Prasad et al. 2016) and the mean annual rainfall is 902 mm, with a total rainfall of approximately 500 mm during the monsoon season from July to October (Murugan et al. 2019). The study was conducted on a drip-irrigated (4 mm depth) Nitisol and a rainfed Acrisol (IUSS Working Group WRB 2015). Both soil types were developed from granitic bedrock of the Precambrian shields and were assigned as Alfisols in the USDA (United States Department of Agriculture) classification system (Vineela et al. 2008; Prasad et al. 2016; Sathish et al. 2016).

Both fields were cultivated with lablab (*Lablab purpureus* (L.) Sweet), maize (*Zea mays* L.), and finger millet (*Eleusine coracana* Gaertn.) as main crops (Table 1) during the rainy season, and only the irrigated Nitisol was used for vegetable cultivation of cabbage (*Brassica oleracea* cv.), eggplant (*Solanum melongena* L.), and tomato (*Solanum lycopersicum* L.), respectively, during the dry season (Dayananda et al. 2019). Both field experiments, established in 2016, had the same factorial randomized split-plot design, consisting of crop type and N fertilization level as factors. Maize and finger millet were randomly assigned to the plots, in which subplots for low and high N levels were established, with four replicates per treatment (Figure 2.1). The high N level treatments received 100% of the recommended urea rate, split into two halves, i.e., at the time of sowing and 4 weeks after sowing (Dayananda et al. 2019). The low N level plots received no N fertilizer input in the sampling year (Table 1). In addition, single super phosphate and potassium were applied to low and high N treatments equally during sowing, but the amounts were adapted to expected yields for crops at each field.

2.2.2 Soil sampling, soil characteristics and plant yields

In October 2018, soil samples were collected before harvest. In each treatment replicate, three soil cores (diameter: 4.2 cm) were randomly taken at 0-10 cm depth and mixed to a composite sample. The soil bulk density was 1.65 and 1.72 g cm_3^{-1} at 15 cm depth for the irrigated Nitisol and rainfed Acrisol, respectively (Stephan Peth, personal communication).

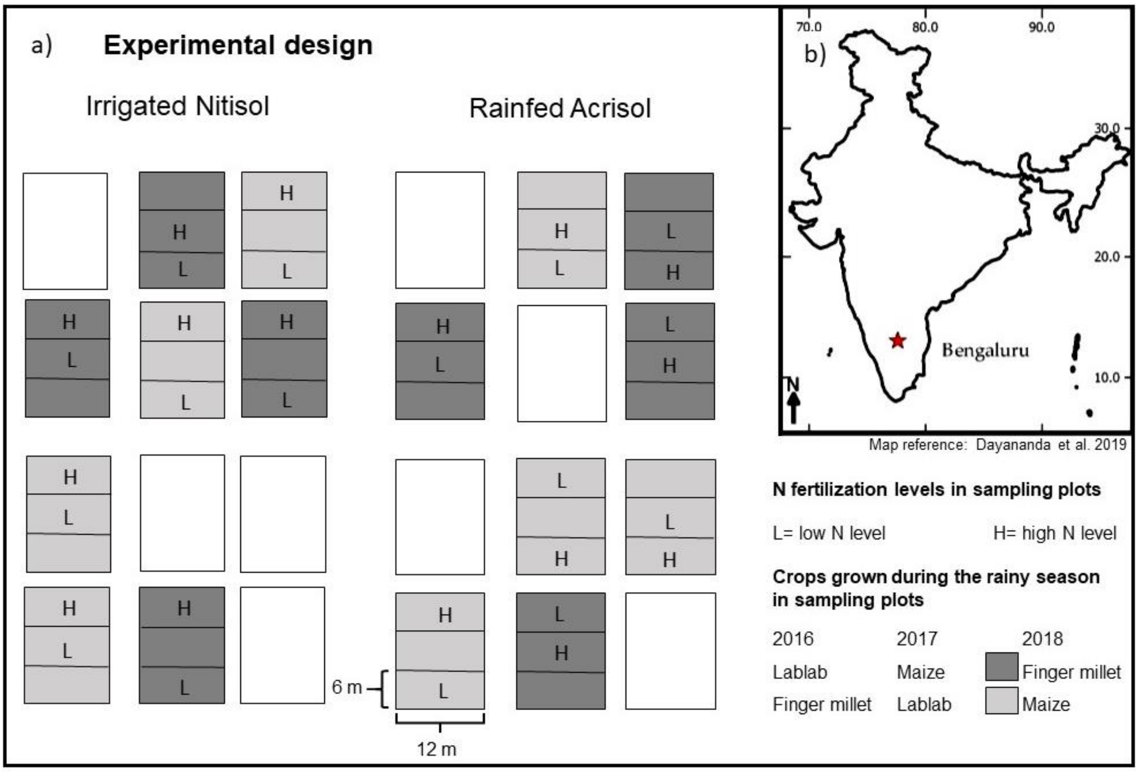

Figure 2.1 a) Description of the field experiments with a randomized split-plot design for crop type and N fertilization level treatments at the irrigated Nitisol and rainfed Acrisol. Finger millet and Maize plots are indicated in different colors, and subplots with low and high N fertilization level are indicated with L and H letters, respectively. b) Location of Bangalore within India is indicated with a star

Soil samples were sieved to 2 mm and divided into two portions, one fresh portion (approx. 11% and 5% water content after sieving for the irrigated and rainfed soils, respectively) was stored frozen at -18 °C for biological analysis, the other was oven-dried at 105 °C and ground for chemical analysis. Soil pH was measured in water at a ratio of 1:2.5. Total C and total N were determined by gas chromatography, using a Vario MAX (Elementar, Hanau, Germany) elemental analyzer. Total C was considered equivalent to SOC, after verifying the absence of carbonate C. Total P and Total S were determined by

HNO_3/microwave digestion, followed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) at 213.618 nm wavelength (Vista-Pro radial, Palo Alto, USA).

Table 2.1 Mineral fertilization and corresponding rotation crops since the establishment of the field experiments in 2016 for the plots I and II with high and low N fertilization, sampled in 2018 under maize and finger millet at an irrigated Nitisol and a rainfed Acrisol (modified from Dayananda et al. 2019)

Plot	Year	Crop	Low N	High N	P	K
			(kg ha^{-1})			
Irrigated Nitisol						
I	2016	Finger millet	50	100	17.5	41.5
I	2017	Lablab	0	25	21.8	20.8
I	2018	Maize	0	150	32.7	41.5
II	2016	Lablab	10	25	4.4	8.3
II	2017	Maize	0	150	32.7	33.2
II	2018	Finger millet	0	50	21.8	41.5
Rainfed Acrisol						
I	2016	Finger millet	25	50	21.8	31.1
I	2017	Lablab	0	25	21.8	20.8
I	2018	Maize	0	150	21.8	31.1
II	2016	Lablab	10	25	4.4	8.3
II	2017	Maize	0	100	21.8	20.8
II	2018	Finger millet	0	50	17.5	31.1

For soil texture, the sand fraction was determined by wet sieving after destruction of the organic matter with hydrogen peroxide, and dispersion with sodium metaphosphate. Clay fraction was quantified by the pipette method. Silt fraction was calculated as the difference of the sum of sand and clay to 100% (Stephan Peth, personal communication).

Sampling of aboveground plant biomass (APB) and data of the specific treatments were performed and provided by Dayananda et al. (2019).

2.2.3 Microbial biomass indices

Microbial biomass C (MBC), N (MBN), and P (MBP) were determined by chloroform fumigation extraction, using soil samples adjusted to 50% of their water holding capacity after thawing for 5 d at 4 °C. For MBC (Vance et al. 1987) and MBN (Brookes et al. 1985), fumigated and non-fumigated samples were extracted from 5 g moist soil with 20 ml 0.5 M K_2SO_4, followed by measuring organic C and total N in the extracts with a multi C/N 2100S automatic analyzer (Analytik Jena, Germany). MBC was calculated as E_C/k_{EC}, where E_C = (organic C extracted from fumigated soil) − (organic C extracted from non-fumigated soil) and k_{EC} = 0.45 (Wu et al. 1990). MBN was calculated as E_N/k_{EN}, where E_N = (total N extracted from fumigated soil) − (total N extracted from non-fumigated soil) and k_{EN} = 0.54 (Brookes et al. 1985).

MBP was extracted from 2 g soil (on an oven dry basis) with 40 ml Bray I solution (0.025 M HCl + 0.03 M NH_4F) at pH 2.6 (Khan and Joergensen 2012). Phosphate was analyzed by a modified ammonium molybdate-ascorbic acid method (Olsen and Sommers 1982). MBP was calculated as E_P/k_{EP}/recovery, were E_P = (PO_4-P from fumigated soil) – (PO_4-P from non-fumigated soil) and k_{EP} = 0.40 (Brookes et al. 1982).

The fungal-cell membrane component ergosterol was extracted from 2 g moist soil with 100 ml ethanol by 30 min oscillating shaking at 250 rev. min^{-1} (Djajakirana et al. 1996), followed by reversed-phase high-performance liquid chromatography (HPLC) with 100% methanol as the mobile phase and detection at 282 nm.

Basal respiration was measured for one incubation week at 22°C, after adjusting the water holding capacity of the soil to 40% and pre-incubating the soil for one week. The CO_2 was trapped with NaOH solution and then precipitated with 5 ml of a saturated $BaCl_2$

solution. The NaOH not consumed was back titrated with 0.25 M HCl, using a TITRONIC 500 (Xylem Analytics, Weilheim, Germany) system to the transition point of phenolphthalein at a pH of 8.3.

2.2.4 Amino sugars

Glucosamine (GlcN), galactosamine (GalN) and muramic acid (MurN) were measured after hydrolyzing 0.5 dry soil samples with 10 ml 6 M HCl for 6 h at 105 °C (Appuhn et al. 2004) as described by Indorf et al. (2011). Amino sugars were measured, using ortho-phthalaldehyde derivatization, by HPLC in a Dionex (Germering, Germany) Ultimate 3000 pump, a Dionex Ultimate WPS-3000TSL analytical autosampler with in-line split-loop injection and thermostat and an Ultimate 3000 fluorescence detector set at 445 nm emission and 330 nm excitation wavelength. Fungal GlcN was calculated by subtracting bacterial GlcN from total GlcN as an index for fungal residues, assuming that MurN and GlcN occur at a 1 to 2 molar ratio in bacteria, with the formula: fungal GlcN (mg g^{-1}soil) = (mmol GlcN − 2 × mmol MurN) × 179.17 mg $mmol^{-1}$, where GlcN is the total GlcN and 179.17 is the molecular weight of GlcN (Engelking et al. 2007; Joergensen 2018). Fungal C and bacterial C for calculating the ratio of fungal to bacterial necromass were obtained by multiplying the contents of fungal GlcN and bacterial MurN by their conversion factors 9 and 45, respectively (Appuhn and Joergensen 2006).

2.2.5 Particulate organic matter

Particulate organic matter (POM) was obtained from 400 g of air-dried soil by wet sieving and flotation-decantation (Magid and Kjærgaard 2001; Muhammad et al. 2006) for the 400-2000 µm size-fraction. POM was dried at 40 °C for 48 h, weighed, ground, and analyzed for total C and N contents. The $^{13}C/^{12}C$ ratio of SOC and POM-C was measured by elemental analyser – isotope ratio mass spectrometry (Finnigan MAT, Bremen, Germany) and is expressed in δ-notation relative to the Vienna Pee Dee Belemnnite

(VPDB). To obtain estimates of the C contribution of C3 and C4 plants (%) to POM, $\delta^{13}C$ natural labelling was used in a two pooled-mixing model (Balesdent and Mariotti 1996), with the following equation:

$$C_{c4}(\%) = \frac{\delta^{13}\,C_{POM} - \delta^{13}\,C_{control}}{\delta^{13}\,C_{c4} - \delta^{13}\,C_{control}}$$

where $\delta^{13}C_{POM}$ represents the average signature of POM from all maize and millet plots in the irrigated Nitisol (-23.6±0.7‰) and the rainfed Acrisol (-21.6±0.7‰); $\delta^{13}C_{c4}$ is the average signature of pure maize and millet litter (-12.8±0.4 ‰ and 12.6±0.6 ‰ in irrigated and rainfed fields, respectively); $\delta^{13}C_{control}$ is a representative signature for tropical C3 plants (-27.6±0.8 ‰) obtained by averaging the value provided by Diels et al. (2004) from a C3 plant and the average value from Swap et al. (2004) for C3 plants under an annual precipitation range between 650 and 970 mm.

2.2.6 Statistical analysis

Results were presented as arithmetic means on a soil dry mass basis. Variance homogeneity and normal distribution of the residuals were tested with the Levene test and Shapiro-Wilk test, respectively. The effect of treatments and their interactions on soil and microbial parameters were evaluated with a two-way analysis of variance employing the 'aov'-function in the 'stats' R package v. 3.5.3 in the R environment (R Core Team 2019), except for MBP at the irrigated Nitisol, the residuals of which were not normal and were tested with the non-parametric Kruskall-Wallis test ('kruskal.test'-function, 'stats' R package v. 3.5.3, R environment, R Core Team 2019). Multiple linear regression models were calculated for relevant microbial parameters as dependent variables and selected soil properties as independent factors, using the 'lm'-function in the 'stats' R package v. 3.5.3 in the R environment (R Core Team 2019). ANOVA and regression model simplification were applied in sequential steps to remove non-significant interactions and/or factors until the minimal adequate model was obtained. To test the relationship between MBC and ergosterol in the irrigated Nitisol and the relationship between the MB-C/N and ergosterol (%MBC) in the rainfed Acrisol, Pearson correlation was used. Pearson correlation was also used to test collinearity between soil properties prior to their selection for regression analysis.

2.3 Results

Soil properties of both soils differed, with higher pH and clay, SOC, total N, total S and POM-C contents of the irrigated Nitisol, but total P content 50% below that of the Acrisol (Table 2). The APB of the irrigated Nitisol exceeded that of the rainfed Acrisol by more than three times. In both fields, higher N levels significantly increased APB. Maize yield was higher than millet yield at the irrigated Nitisol. In both fields, soil pH and total P were higher in plots cropped with finger millet, regardless of the N fertilization level.

The irrigated Nitisol contained between 20% (MurN) and 80% (MBC, MBN, fungal GlcN, and GalN) more of the microbial biomass and necromass markers than the rainfed Acrisol (Table 3). MBP varied in a large range around a similar mean of 6.6 µg g^{-1} soil in both fields. N fertilization level did not affect any soil biological property at the irrigated Nitisol and increased only basal respiration at the rainfed Acrisol. MBP and ergosterol were the two soil biological properties that showed a significant positive response to millet cropping, but only at the rainfed Acrisol.

Table 2.2 Soil physical and chemical properties on a soil dry mass basis as well as APB (aboveground plant biomass) at 0-10 cm soil depths at an irrigated Nitisol and a rainfed Acrisol, cropped with maize and finger millet under low and high N fertilization rates; probability values for the two-way ANOVA, using crop and N level as factors

Crop	N level	Clay[a]	Soil pH	SOC	Total N	Total P	Total S	POM-C	POM-C/N	APB[b]
		(%)	(H_2O)	($mg\ g^{-1}$ soil)		($\mu g\ g^{-1}$ soil)				(kg FM m^{-2})
Irrigated Nitisol										
Maize	Low	28	7.0	9.1	0.81	180	100	324	18.3	2.9
Maize	High	30	7.0	9.8	0.89	170	107	345	20.0	4.1
Millet	Low	32	7.3	9.5	0.85	220	111	375	19.5	1.6
Millet	High	28	7.2	9.3	0.84	190	100	349	20.0	3.4
Probability values										
Crop		NS	0.02	NS	NS	0.01	NS	NS	NS	0.04
N level		NS	NS	NS	NS	0.06	NS	NS	NS	0.004
SEM		2	0.1	0.4	0.04	10	10	31	1.0	0.43
Rainfed Acrisol										
Maize	Low	18	5.0	4.5	0.43	320	85	205	20.8	1.0
Maize	High	18	4.9	4.4	0.43	320	85	202	20.5	1.3
Millet	Low	18	5.5	5.3	0.50	410	86	260	21.5	0.4
Millet	High	17	5.2	4.8	0.46	380	87	276	21.8	1.1
Probability values										
Crop		NS	0.01	NS	NS	0.01	NS	NS	NS	0.07
N level		NS	NS	NS	NS	NS	NS	NS	NS	0.03
SEM		1.0	0.2	0.4	0.03	30	3	43	0.9	0.20

SEM = standard error of means for the crop and N fertilization treatments; NS = not significant; all interactions were not significant; [a] data from 0-5 cm depth (Stephan Peth, personal communication); [b] Fresh matter (FM) aboveground plant biomass from Dayananda et al. (2019)

Table 2.3 Mean of the microbial indices MBC MBN, MBP (microbial biomass C, N, P), ergosterol, MurN (muramic acid), fungal GlcN (glucosamine), GalN (galactosamine), and the CO_2-C (basal respiration rate) on a soil dry mass basis at an irrigated Nitisol and a rainfed Acrisol, cropped with maize and finger millet under low and high N fertilization rates; probability values for the two-way ANOVA, using crop type and N level as factors

Crop	N level	MBC	MBN	MBP	Ergosterol	MurN	Fungal GlcN	GalN	CO_2-C
		($\mu g\ g^{-1}$ soil)							($\mu g\ g^{-1}$ soil d^{-1})
Irrigated Nitisol									
Maize	Low	165	29	5.1	0.49	44	750	237	7.19
Maize	High	179	29	8.0	0.56	49	694	272	6.75
Millet	Low	166	28	9.7	0.59	49	772	293	6.61
Millet	High	180	31	4.7	0.55	50	782	266	7.00
Probability values									
Crop		NS	NS	NS	NS	NS	NS	NS	NS
N level		NS	NS	NS	NS	NS	NS	NS	NS
SEM		11	2	3.4	0.05	5	52	20	0.33
Rainfed Acrisol									
Maize	Low	80	13	5.2	0.21	35	363	126	3.99
Maize	High	95	14	5.1	0.15	40	423	143	5.21
Millet	Low	102	17	8.4	0.31	42	425	170	4.23
Millet	High	107	17	7.1	0.28	44	480	164	4.97
Probability values									
Crop		NS	NS	0.03	0.02	NS	NS	NS	NS
N level		NS	NS	NS	NS	NS	NS	NS	0.01
SEM		12	2	0.9	0.04	4	47	16	0.14

SEM = standard error of means for the crop and nitrogen treatments; NS = not significant; all interactions were not significant

Soil C/N and MB-C/N ratios varied around 10.5 and 6.5, respectively, at both fields, whereas soil C/P and MB-C/P ratios were four and three times larger, respectively, at the irrigated than at the rainfed field (Table 4). The MBC/SOC ratio varied around 1.8% at both fields and was not affected by any treatments, although there was a tendency that high N fertilization level increased this ratio at the rainfed Acrisol (Figure 2.2).

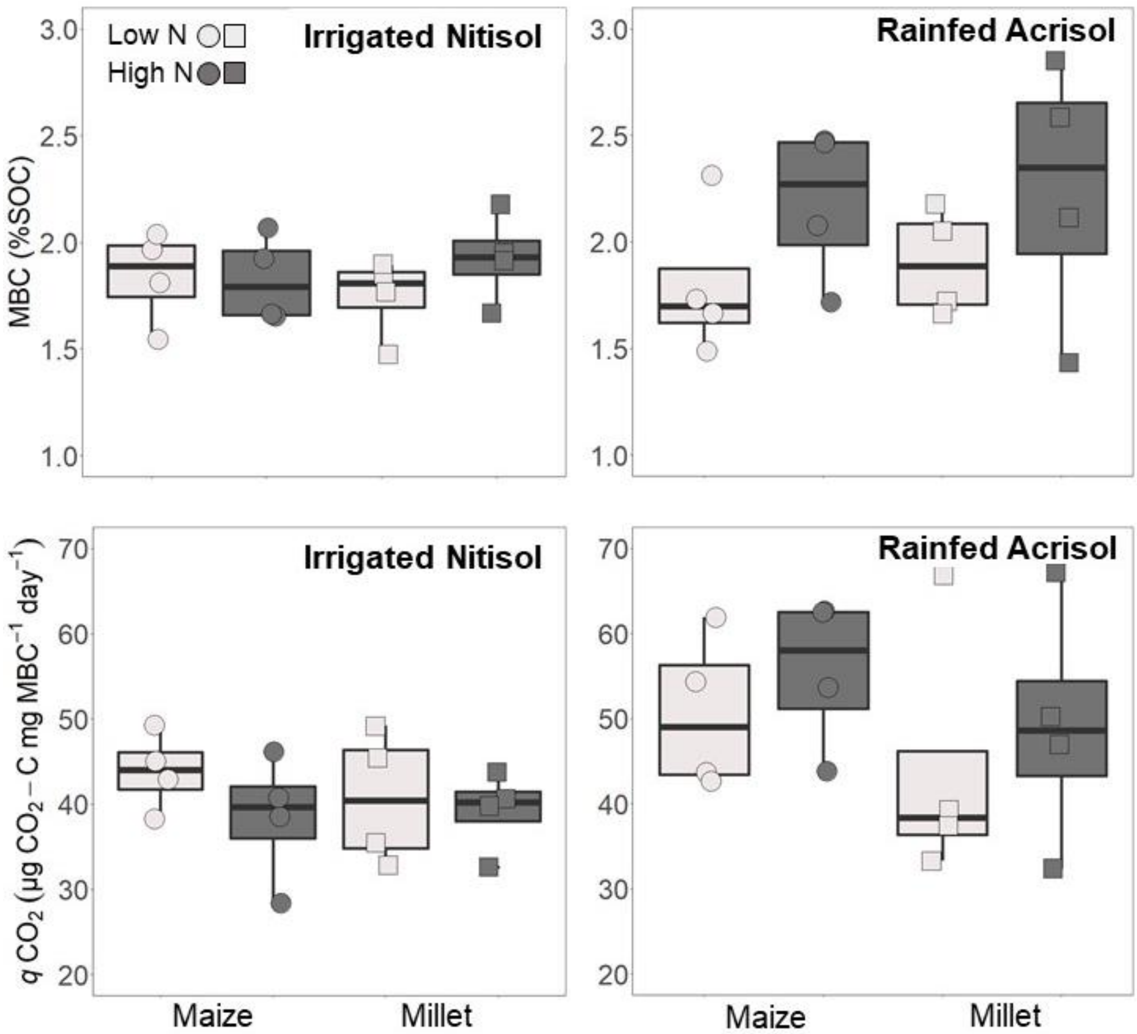

Figure 2.2 Boxplots of the microbial biomass C (MBC)/SOC ratio and metabolic quotient $q\mathrm{CO_2}$ at an irrigated Nitisol and a rainfed Acrisol, cropped with maize and finger millet under low and high N fertilization rates (P>0.05); dots indicate the data of all replicates per treatment. Crop type is indicated by different shape, and N level is indicated by different color

The metabolic quotient $q\mathrm{CO_2}$ varied around 43 µg $\mathrm{CO_2}$-C $\mathrm{mg^{-1}}$ MBC $\mathrm{d^{-1}}$ in both fields, with a tendency that millet cropping reduced the $q\mathrm{CO_2}$ values at the rainfed Acrisol

(Figure 2.2). The ergosterol/MBC and ergosterol/fungal GlcN ratios varied around 0.29% and 0.75 mg g^{-1}, respectively, at both fields, exhibiting a considerably larger variation at the rainfed Acrisol (Figure 2.3). The fungal C/bacterial C ratio varied around 3.3 at the irrigated Nitisol and around 2.4 at the rainfed Acrisol, without treatment effects (Figure 2.3).

Table 2.4 Stoichiometry of soil and microbial biomass (MB) at an irrigated Nitisol and rainfed Acrisol, cropped with maize and finger millet under low and high N fertilization rates; probability values for the two-way ANOVA, using crop type and N level as factors

Crop	N level	Soil C/N	Soil C/P	Soil C/S	MB-C/N	MB-C/P
Irrigated Nitisol						
Maize	Low	11.2	51	91	5.6	40
Maize	High	11.0	56	92	6.1	45
Millet	Low	11.2	43	87	5.8	21
Millet	High	11.1	49	94	5.8	40
Probability values						
Crop		NS	<0.01	NS	NS	NS
N level		NS	<0.01	NS	NS	NS
SEM		0.2	2	4	0.2	11
Rainfed Acrisol						
Maize	Low	10.3	14	53	6.4	19
Maize	High	10.1	14	51	7.1	19
Millet	Low	10.7	13	62	6.1	13
Millet	High	10.4	13	55	6.6	15
Probability values						
Crop		NS	NS	0.04	NS	NS
N level		NS	NS	NS	NS	NS
SEM		0.2	1	3	0.5	4

SEM = standard error of means for the crop and nitrogen treatments; NS = not significant; all interactions were not significant

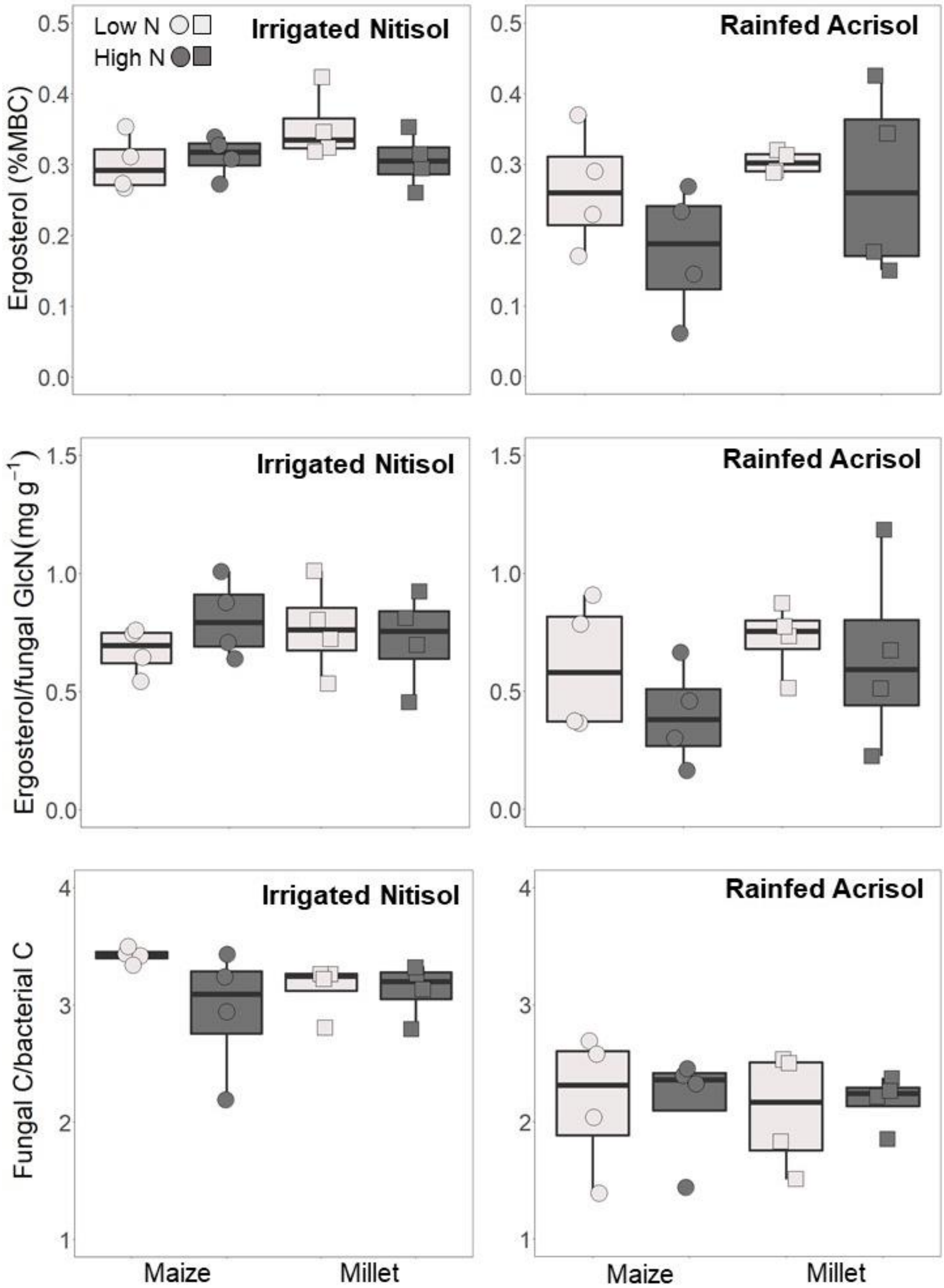

Figure 2.3 Boxplots of the ergosterol/microbial biomass C (MBC) ratio, the ergosterol/fungal glucosamine (GlcN) ratio, and the fungal C/bacterial C ratio at an irrigated Nitisol and a rainfed Acrisol, cropped with maize and finger millet under low and high N fertilization rates ($P>0.05$); dots indicate the data of all replicates per treatment. Crop type is indicated by different shape, and N level is indicated by different color

At the irrigated Nitisol, MBC was mainly explained by the soil C/N ratio but also by the soil C/S ratio (Table 5). Ergosterol as well as the ergosterol/MBC and ergosterol/fungal GlcN ratios were all positively affected by POM-C, whereas the necromass markers fungal GlcN and bacterial MurN were both negatively affected by the POM-C/N ratio. At the rainfed Acrisol (Table 5), MBC was mainly explained by the clay content and POM-C, and ergosterol and the ergosterol/fungal GlcN ratio revealed a strong positive influence of POM-C. In contrast, soil C/N was the only predictor found for the fungal C/bacterial C ratio. APB was negatively related to the ergosterol/fungal GlcN and to GalN, while the ergosterol/MBC ratio was positively influenced by pH and showed a negative relationship to the MB-C/N ratio (Figure 2.4). The MB-C/P ratio was influenced by clay content and the MB-C/N ratio by soil pH (Table 5).

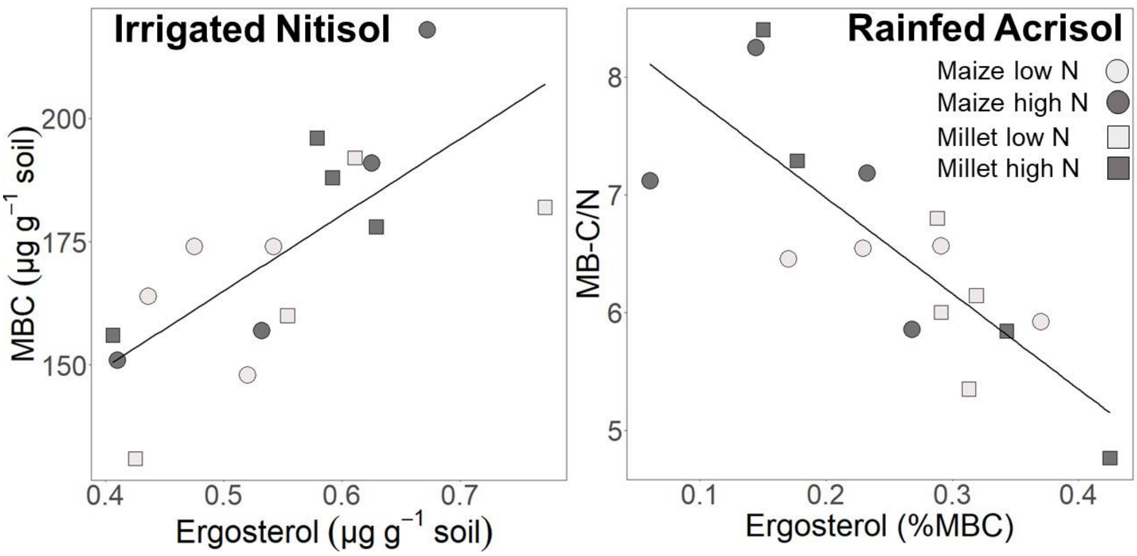

Figure 2.4 Relationships between microbial biomass C (MBC) and ergosterol at the irrigated Nitisol ($y = 154.1 \times x + 87.9$, $R^2 = 0.52$, $P < 0.01$) and between the microbial biomass C/N ratio (MB-C/N) and ergosterol/MBC ratio at the rainfed Acrisol ($y = -8.11 \times x + 8.59$, $R^2 = 0.63$, $P < 0.001$), cropped with maize and finger millet under low and high N fertilization rates. Crop type is indicated by different shape, and N level is indicated by different color

Table 2.5 Simple linear and multiple linear regressions between soil microbial indices as the dependent variable and soil physical and chemical properties and aboveground plant biomass as independent variables at two field experiments cropped with maize and finger millet under low and high N fertilization rates

Dependent variable	Intercept	Coefficient	Independent variables	R^2
Irrigated Nitisol				
MBC	666	-32.7	Soil-C/N	0.60**
		-1.4	Soil-C/S	
Ergosterol	0.06	0.001	POM-C	0.64***
Ergosterol (%MBC)	0.37	-0.003	Soil C/P	0.55**
		0.0003	POM-C	
Ergosterol/fungal GlcN	-0.47	0.002	POM-C	0.56**
		0.035	POM-C/N	
Fungal GlcN	1275.5	-27.04	POM-C/N	0.26*
MurN	94.56	-2.39	POM-C/N	0.25*
Rainfed Acrisol				
MBC	-45.19	6.19	Clay	0.55**
		0.13	POM-C	
MB-C/N	15.02	-1.65	Soil pH	0.42**
MB-C/P	-22.57	2.19	Clay	0.31*
Ergosterol	0.04	0.0008	POM-C	0.53**
Ergosterol (%MBC)	-0.47	0.14	Soil pH	0.32*
Ergosterol/fungal GlcN	0.45	0.002	POM-C	0.53**
		-0.3	APB	
Fungal C/bacterial C	7.05	-0.47	Soil C/N	0.31*
GalN	221.5	-44.19	APB	0.42**

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$; MBC = microbial biomass C, MB-C/N = microbial biomass C/N ratio; MB-C/P = microbial biomass C/P ratio; POM = particulate organic matter; SOC = soil organic C; APB = aboveground plant biomass; MurN = muramic acid; GlcN = glucosamine; GalN = galactosamine

The mean soil $\delta^{13}C$ values varied around -21.9‰ and -19.3‰ at the irrigated and rainfed field, respectively (Table 6). These mean values were 2.0‰ lower in the POM-C recovered at both fields. The C contribution from maize and millet residues to POM-C was on average only 27% in the irrigated Nitisol and 40% in the rainfed Acrisol, thus the contribution of former C3 plant material represented the larger contribution in the POM fraction.

Table 2.6 Isotopic $\delta\ ^{13}C$ signature of SOC (soil organic C), POM (particulate organic matter) and APB (aboveground plant biomass) at an irrigated Nitisol and a rainfed Acrisol, cropped with maize and finger millet under low and high N fertilization rates; probability values for the two-way ANOVA, using crop and N level as factors

Crop	N level	SOC-$\delta\ ^{13}C$ (‰)	POM-$\delta^{13}C$ (‰)	APB-$\delta^{13}C$ (‰)
Irrigated Nitisol				
Maize	Low	-21.7	-23.7	-12.3
Maize	High	-22.1	-24.5	-12.5
Millet	Low	-21.8	-23.3	-13.1
Millet	High	-21.8	-22.9	-13.1
Probability values				
Crop		NS	0.02	NA
N level		NS	NS	NA
SEM		0.22	0.36	NA
Rainfed Acrisol				
Maize	Low	-19.3	-21.7	-12.1
Maize	High	-19.1	-22.1	-12.1
Millet	Low	-19.5	-22.1	-13.4
Millet	High	-19.1	-20.6	-12.6
Probability values				
Crop		NS	NS	NA
N level		NS	NS	NA
SEM		0.18	0.61	NA

SEM = standard error of means for the crop and nitrogen treatments; NS = not significant; NA = not applicable, partly due to an insufficient number of replicates; all interactions were not significant

2.4 Discussion

2.4.1 Soil and treatment effects on general microbial properties

Soil type and water management effects considerably exceeded the experimental treatment effects on soil microorganisms. Nevertheless, the MBC and SOC contents and the pH of the rainfed Acrisol were in line with those obtained previously on Nitisols and Acrisols under rainfed conditions in or around Bangalore, summarized as Alfisols (Vineela et al. 2008; Prasad et al. 2016; Sathish et al. 2016). At the irrigated, more fertile Nitisol, none of the microbial properties responded to the crop type or N fertilization level. In this soil, the negative effect of the soil C/N and soil C/S ratios on MBC indicate nutrient limitation. However, the fact that this effect was not reflected by an increased MB-C/N ratio suggests an additional limitation of C inputs, which were reduced under lower N availability. Effects of N fertilization level and crop type were observed in the acidic rainfed Acrisol. The higher total P content in millet plots was reflected by higher MBP. Similar amounts of P fertilizer applied in millet and maize plots but lower millet yields resulted in higher P uptake in microbial biomass under millet. In the rainfed Acrisol, microorganisms responded more sensitively to basic properties, i.e., variations in clay content and soil pH.

It was a striking feature of the current results that lower clay content and lower soil pH of the rainfed Acrisol did not result in much higher qCO_2 values and lower MBC/SOC ratios in comparison with the irrigated Nitisol. This contrasts other studies, in which a lower pH (Anderson and Domsch 1993, 2010; Hartman and Richardson 2013) or lower clay content (Müller and Höper 2004) significantly increased the qCO_2, due to an increased demand for maintenance energy and reduced protection of SOM, respectively. However, such effects may have been counteracted by a drought-reduced microbial turnover in this study.

The irrigated Nitisol was characterized by extremely low total P contents, but the total P contents of the rainfed Acrisol were also low in comparison with other soils from India (Paul et al. 2018). The reason for the three times lower total P content of the irrigated Nitisol in comparison with the rainfed Acrisol could not be fully explained by the current study. Most likely, a similar P fertilization, but considerably lower yield resulted in less P uptake by crops and finally in a higher total P content of the rainfed Acrisol. This view is supported by the observation that the lower yield of millet cropping generally increased total P content and soil pH in comparison with maize, with a positive correlation between soil C/P and APB (r = 0.64) in the irrigated Nitisol. This indicates a rapid soil response to changes in the crop cultivated.

It should be considered that millet cultivation followed maize after lablab. Maize received more N from the preceding legume crop and from the higher urea fertilization than millet, which led to a small but significant decrease in soil pH at both fields. Consequently, the observed crop effects on soil properties were larger than those of the N fertilization level. This was especially true at the rainfed Acrisol, where millet cropping increased the contents of saprotrophic fungi by approximately 50% in comparison with maize, suggesting a larger C input by millet roots. On the basis of the current APB results and the calculated root/shoot ratios of 0.57 for millet (Goron et al. 2015) and of 0.16 for maize (Amos and Walters 2006), the resulting belowground root biomass at maturity was higher ($P < 0.05$) for millet (1.4 kg and 0.4 kg m^{-2} at the irrigated and rainfed field, respectively) compared to maize (0.6 kg and 0.2 kg m^{-2} at the irrigated and rainfed field, respectively). Although the rhizodeposits of the two crop species may be very similar, acid phosphatase and dehydrogenase activities are higher in finger millet than in maize cropping systems (Dotaniya et al. 2014). Acid phosphatases are also excreted by fungi (Dotaniya et al. 2019), which may additionally support the observed interactions between roots, the increase in saprotrophic fungi, and MBP under millet plots.

2.4.2 Specific effects on microbial stoichiometry

The strong P deficiency of the irrigated Nitisol led to wide MB-C/P ratios in comparison with other tropical soils (Joergensen 2010; Tischer et al. 2014). Large MB-C/P ratios were often observed in situations of low P availability in combination with relatively high C availability (Anderson and Domsch 1980; Kapoor and Haider 1982; He et al. 1997). The higher yield level at the current irrigated Nitisol aggravated P deficiency. In contrast to other studies (Heuck et al. 2015), high MB-C/P ratios were not related to high MB-C/N ratios, probably due to the combination of sufficient N fertilization and N_2 fixing lablab in the crop rotation.

At the rainfed Acrisol, clay positively affected the MB-C/P ratio, probably due to an increase in MBC, although no correlation was found between MB-C/P and MBC, both positively benefitting from higher clay content. With increasing soil pH, the MB-C/N ratio decreased but the ergosterol/MBC ratio increased, indicating an increasing contribution of saprotrophic fungi to the microbial community. The MB-C/N ratio reflected the complex interaction with SOC, total N and P and not the ratio of fungi to bacteria suggested by Khan et al. (2016).

2.4.3 Specific soil and treatments effects on fungi

Irrigation led to a strong increase in crop yield, and most likely also in root input in comparison with the rainfed Acrisol. This increased MBC and MBN, but especially the ergosterol content, an indicator of saprotrophic fungi in arable soils (Joergensen and Wichern 2008). The positive relationship of ergosterol with POM-C was in line with the observation that fungal biomass is strongly dependent upon POM in soils with low carbon contents (Wachendorf et al. 2014).

At the irrigated Nitisol, the ergosterol/MBC ratio was negatively affected by the soil C/P ratio, suggesting that P availability specifically controls saprotrophic fungi. The current ergosterol/MBC ratios were generally in the range of other tropical arable soils (Joergensen and Castillo 2001; Joergensen 2010; Murugan and Kumar 2013). However, the strong differences between the two fields in clay content and in soil pH had only minor effects on the ergosterol/MBC ratio in comparison with the results of others (Joergensen and Castillo 2001; Rousk et al. 2009; Wentzel et al. 2015).

The ergosterol/fungal GlcN ratio was relatively consistent in all treatments of the two fields, which supports the view that there is a strong relationship between fungal biomass and fungal necromass (Khan et al. 2016). In contrast, the fungal C/bacterial C ratio was markedly higher at the irrigated Nitisol, in line with the lack of response of bacterial biomass but positive response of fungi to soil moisture (Frey et al. 1999). Under rainfed conditions, GalN and fungal GlcN were more than 43% lower than in the irrigated Nitisol, whereas MurN only decreased by 25%. Drought apparently promoted the specific accumulation of bacterial residues. For this reason, Amelung et al. (1999) observed a relative increase in MurN in comparison with GlcN with decreasing mean annual precipitation. The markedly higher fungal C/bacterial C ratio at the neutral Nitisol in comparison with the acidic Acrisol contrasted other studies from India (Murugan and Kumar 2013) and many other regions (Rousk et al. 2011; Khan et al. 2016), suggesting that drought effects override pH effects.

2.4.4 Relevance of particulate organic matter at the two fields

Drought also promoted the accumulation of POM-C, which contributed 3.7% to SOC at the irrigated Nitisol and 5.0% at the rainfed Acrisol. POM contained only 27-40% C4 plant material, indicating that maize and millet were not main contributors to POM. Therefore, there was a lack of correlation between POM-C and APB. This result is surprising, considering that the C4 plants were the actual main crops for the study year in maize plots and for two consecutive years in millet plots, neglecting the small root input of vegetables during the dry period at the irrigated Nitisol. Hence, POM mainly consisted of plant residues not decomposed for several years. This contrasts the view that POM-C is always a very labile and readily bio-available pool, derived from less decomposed plant material of the previous crop (Benbi and Richter 2002; Wang et al. 2004; Heitkamp et al. 2009). The current results are even more surprising, considering the observation that POM-C generally had dominating positive effects on saprotrophic soil fungi, which were apparently unable to decompose these plant residues under the environmental conditions of the two fields. However, it is important to highlight that the crop yield in 2018 was particularly low compared to the previous year (Dayananda et al. 2019). This probably reduced the contribution of the current crop residues to POM and the correlation between the two variables, thus reducing the influence of APB on microbial indices.

The generally positive effects of POM-C on the ergosterol/fungal GlcN ratio indicate that this C-fraction promoted especially fungal biomass in comparison with fungal necromass. The negative effects of the POM-C/N ratio at the irrigated Nitisol on fungal GlcN and bacterial MurN suggest that not the amount but the quality of plant residues controls microbial necromass accumulation. APB at the rainfed Acrisol had negative effects on the accumulation of GalN, an indicator of microbial extracellular polymeric substances (Joergensen 2018). This suggests that microorganisms have to invest more energy in this fraction under drought conditions with a lower input of root and harvest residues.

2.5 Conclusions

Microorganisms in typical soil types at Bangalore are C and nutrient limited under major cereal cropping systems. The microbial response to intensification varied depending on soil pH and water availability. More favorable abiotic soil conditions and higher SOM of the irrigated Nitisol resulted in higher APB and MB in comparison with the rainfed

Acrisol. N fertilization generally led to higher APB but had only minor effects on microbial biomass in both soil types. Crop effects were probably strengthened by indirect effects of higher N-fertilization of maize than millet, inducing a decrease of soil pH under maize. A low percentage of particulate organic matter from recent plant material indicates the additional importance of crop residues from previous rotations for soil microorganisms under tropical conditions. Fungal biomass and necromass was reduced in the rainfed Acrisol in comparison with the irrigated Nitisol. However, it was not possible to differentiate irrigation effects from land use history and soil effects, i.e., irrigation and rainfed treatments should be carried out on both soil types. To address the entire rural-urban dynamics taking place in the soils at Bangalore, additional crops should be studied. In particular, the effects of vegetables, fruits and non-food crops, which are being increasingly cultivated due to increasing urban demand, have been largely unexplored.

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3 Does liming improve microbial carbon use efficiency after maize litter addition in a tropical acidic soil?

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Abstract

Soil pH is one of the main drivers of soil microbial functions, including carbon use efficiency (CUE), the efficiency of microorganisms in converting substrate C into biomass, a key parameter for C sequestration. We evaluated liming effects after maize-litter addition on total CUE (including microbial residues), CUE of microbial biomass (CUE_{MB}) and fungal biomass on an acidic Acrisol with a low C. We established a 6-week incubation experiment to compare limed and unlimed Acrisol treatments and a reference soil, a neighboring Nitisol with optimal pH. Fungal biomass (ergosterol) increased ~10 times after litter addition compared with soils without litter, and the final amount was greater in the limed Acrisol than the Nitisol. Litter addition induced a positive priming effect that increased with increasing pH. The increases in soil pH also led to increases in litter-derived CO_2C and decreases in particulate organic matter (POM)C. Thus, in spite of increasing microbial biomass C, CUE decreased with increasing pH and CUE_{MB} was similar across the three soils. CUE_{MB} was positively associated with saprotrophic fungi, implying that fungi are more efficient in incorporating litter-derived C into microbial, especially fungal biomass after 42 days. By including undecomposed maize litter and microbial residues, CUE provided a more comprehensive interpretation of pH and liming

effects than CUE_{MB}. Nevertheless, longer-term studies may provide further information on substrate-C turnover and, the persistence of liming and pH effects.

Keywords: Priming effect, Soil pH, Carbon sequestration, Soil organic carbon, Fungal ergosterol, Acrisol, Nitisol

3.1 Introduction

Soil functions, soil microbial communities and their activity, are largely controlled by soil reaction (Canini et al. 2019; Malik et al. 2018; Wang et al. 2019). A low pH reduces microbial indicators of soil quality such as fungal, bacterial, and microbial biomass, and, to a lesser extent, microbial activity (Rousk et al. 2009), without affecting the metabolic quotient (Moran-Rodas et al. 2022). On the other hand, a pH increase above 6.2 in low-pH soils of intensified systems can create a shift towards alkalinity, reducing soil organic carbon (SOC) sequestration through increased decomposition, following alleviation of acid retardation of microbial growth (Malik et al. 2018).

The most representative indicator of the role of microbial communities on SOC sequestration is microbial C use efficiency (CUE), which is usually defined as the relation between the amount of C used for anabolic and catabolic processes in the microbial community (Horn et al. 2021; Jones et al. 2018, 2019). CUE is a major regulator of SOC cycling at the local and global scale (Allison et al. 2010; Li et al. 2019; Wang et al. 2021). However, many soil factors such as nutrient availability, initial SOC levels and pH can affect SOC sequestration directly and additionally alter CUE, generating co-varying or interactive effects on soil C-sequestration potential (Malik et al. 2018; Oliver et al. 2021). Some studies have found correlations between CUE and SOC contents (Oliver et al. 2021; Wang et al. 2021).

Soil pH is one of the most important variables to affect CUE, with increasing CUE up to a threshold of ~6.2 pH (Horn et al. 2021; Jones et al. 2019; Malik et al. 2018; Oliver et al. 2021; Pei et al. 2021; Silva-Sánchez et al. 2019; Xiao et al. 2021). The most common way to assess pH effects on CUE has been through existent geographical pH gradients, while a few studies have used the same soils, manipulating the pH through liming, which reduces the variability from other factors (Horn et al. 2021; Silva-Sánchez et al. 2019). Microbial anabolic and catabolic processes are important for predicting microbial stabilization of SOC (Liang et al. 2017), and CUE aims to represent both. However, its measurement is still ambiguous and different methods are used, with each of them influenced by different factors (Geyer et al. 2016). To assess the role of CUE in SOC dynamics, the CUE approach frequently used is the CUE of microbial biomass (CUE_{MB}) (Manzoni et al. 2012; Sinsabaugh et al. 2013; Spohn et al. 2016). However, CUE_{MB} has the disadvantage of excluding the role of microbial residues, non-biomass microbial metabolites, which are not mineralized during the incubation period. This fraction has been recognized for its relevant contribution to organic matter accumulation (Cotrufo et al. 2015; Geyer et al. 2020; Kallenbach et al. 2016; Liang et al. 2019; Miltner et al. 2012). Therefore, microbial residues add up to the C-fractions of microbial biomass and CO_2 that are produced during metabolization of added substrate. If this is taken into consideration, CUE is increased 3 to 5-fold, compared with CUE_{MB} deduced from microbial biomass growth and CO_2C evolution alone (Börger et al. 2022; Schroeder et al. 2020). An additional difference between these CUE approaches is the fact that experimental studies on CUE_{MB} from incubation experiments have been performed using low-molecular-weight substrates easy to assimilate, such as sugars, amino- and organic acids (Jones et al. 2018), making it difficult to translate to field conditions, where the ultimate substrate is plant residues.

Increasingly low SOC levels and acidic conditions are common in Indian agricultural soils (Lal 2004; Sathish et al. 2016). This study addresses an Acrisol with low pH and low SOC levels; in comparison with a Nitisol in South India (Moran-Rodas et al. 2022). The Acrisol had lower levels of microbial soil-quality indicators, such as microbial biomass, fungal biomass, and microbial residues, compared with irrigated conditions under improved pH (Moran-Rodas et al. 2022). However, other studies have shown different results on fungi, where acidic conditions (above a threshold of pH 4.5) favored their growth compared with bacteria (Rousk et al. 2009); or where bacterial growth and CUE_{MB} were promoted by liming, while fungi remained unaffected (Silva-Sanchez et al. 2019).

To evaluate the effect of lime on both CUE and fungal biomass of an Acrisol, we performed an incubation experiment using limed and unlimed treatments of the Acrisol and a neighboring soil with an optimal pH (Nitisol) and applied both CUE methods. We hypothesize that 1) the constraints related to pH for the microbial community of the Acrisol are alleviated by liming, improving its CUE; thus 2) the CUE is positively associated with pH, and 3) fungal biomass increases with litter addition but not with liming and it positively affects CUE.

3.2 Materials and Methods

3.2.1 Experimental design

The soils studied were a drip-irrigated (4 mm depth) Nitisol and a rainfed Acrisol (IUSS Working Group WRB 2015) from two experimental fields located at the GKVK campus, University of Agricultural Sciences, Bangalore (12°58′20.79″N, 77°34′50.31″E) at an altitude of 920 m above sea level. Mean annual temperature is 29.2°C (Prasad et al. 2016) and mean annual rainfall is 902 mm (Murugan et al. 2019).

Four replicate plots under maize cultivation were located in each field. The plots contained subplots with high and low N fertilization levels. From each subplot, three soil cores were randomly collected from the topsoil (0-10 cm depth, diameter: 4.2 cm) and combined to a composite sample just before the harvest period in October 2018. These soil samples were sieved (< 2 mm) and stored frozen (−18°C) until analysis. The incubation experiment took place in November and December 2020 in Witzenhausen, Germany. Samples were thawed and corresponding low and high N level replicates were combined to four general samples per soil type. This was done to optimize the use of the soil as there were no relevant differences between low and high N level in terms of microbial and SOC related parameters in either of the two fields, except for microbial respiration, which was a little higher under high N level in the Acrisol (Moran-Rodas et al. 2022).

The Nitisol had a higher soil pH and more clay, SOC, total N and S, while the Acrisol contained more total P (Moran-Rodas et al. 2022). The Nitisol had a pH-$CaCl_2$ of 6.32 and the Acrisol of 4.39. To evaluate the effects of improved pH conditions and liming in the Acrisol, each of its four replicates were divided into four sub-replicates for a two-factorial experiment with the factors lime (limed and unlimed treatments) and maize litter addition (with and without treatments), resulting in four replicates per treatment and 16 in total. Additionally, the Nitisol remained unlimed with a neutral pH, but was subject to the litter treatment (with and without).

The maize litter used as substrate from the corresponding fields had a $\delta^{13}C$ of -12.38 ± 0.1‰, a CN ratio of 47± 5.6 and a total C of 426.5 ±5.2 mg g^{-1} DM at the Nitisol; and -12.15 ± 0.1‰, a CN ratio of 64 ±7.5, and 443.6 ±7 mg C g^{-1} DM at the Acrisol. The litter was applied to soil samples corresponding to each field.

3.2.2 Soil pH-adjustment experiment

To achieve an optimal pH in limed soil replicates, we tested previous soil samples (from 2016) from the Acrisol with different amounts of lime as commercially available CaO, using three replicates per treatment. The pH changes after application were monitored to obtain the stabilization period required before litter addition. The pH was stabilized after 8 days of lime application. We used the final values to draw a regression model of required lime amounts to achieve a specific pH. The resulting equation for the regression model was $y = 518.303-167.43x + 13.97x^2$, where y= mg CaO in 50 g soil, and x = target pH. For a pH of 6-7 similar to that of the Nitisol, this resulted in 0.62 mg CaO g^{-1}soil equivalent to 0.44 mg Ca g^{-1}soil or 1.066 t ha^{-1}.

Having determined the lime concentration, the next step of the pre-experiment was to find out whether the CO_2 emissions and $\delta^{13}C$ signature of CO_2C of limed and unlimed soils differed without adding litter. It was assumed that the lime in contact with the soil CO_2 trapped from the air and H_2O would generate direct CO_2 emissions with a slightly different $\delta^{13}C$ signature than that of microbial respiration derived from SOC decomposition. $\delta^{13}C$ was measured after the first week and resulted in a slight difference between the $\delta^{13}C$ of limed and unlimed soil (-19.8 and -20.73 $\delta^{13}C$, respectively), however the CO_2 emissions were only different after the first three days, and this difference disappeared over time, with no difference by the end of the first week, this trend completely disappearing in the second week. We assumed that the $\delta^{13}C$ difference between limed and unlimed soils would also completely disappear from the second week onwards. Thus, we established a pre-incubation period of two weeks for the main experiment, after which pH and CO_2 emissions of limed and unlimed soils were stabilized before substrate addition. We also adjusted the soil WHC to 50%. After lime addition (0.44 mg Ca g^{-1}soil) and the subsequent two pre-incubation weeks, we measured the new pH in the limed samples before dividing them into the two subsamples for substrate addition (with and without litter) and incubation was started.

3.2.3 Incubation and CO_2 analysis

Each treatment replicate consisted of 150 g of fresh soil in 200 ml glass beakers. For the substrate addition replicates, the soil was mixed with maize litter (5 mm cuttings), corresponding to 2 mg C g^{-1} soil. The beakers were placed into Mason jars, equipped with sealing rings, together with plastic containers with 0.5 M NaOH solution to trap the CO_2 evolved during the incubation period. The vials were incubated at 25°C for tropical soils. CO_2 evolution was measured after 3 and 7 days and then on a weekly basis for six weeks. Water content was monitored gravimetrically every two weeks, but no adjustments were necessary over the six weeks.

We removed the initial CO_2 in the jars with compressed oxygen to have a CO_2-free atmosphere at the beginning of incubation. This compressed oxygen-ventilation procedure was repeated every time that isotopic analysis of CO_2 samples was done. During week 3 and 5, compressed air was used instead of oxygen. To measure the respired CO_2 trapped in the NaOH solution, we used precipitation with 5 ml of saturated $BaCl_2$ solution, followed by back titration with 0.5 M HCl using a TITRONIC 500 (Xylem Analytics, Weilheim, Germany) system to the transition point of phenolphthalein at a pH of 8.3. The titration precipitates were centrifuged (3000 *g* for 10 min at 20°C), rinsed with H_2O to remove excess ions and freeze-dried for isotopic analysis to obtain the amount of litter-derived CO_2C. This was done after 3, 7, 14, 28 and 42 days. The results from the third and fifth weeks were calculated by linear interpolation. At the end of the incubation period we measured the final pH for all treatments.

3.2.4 Total microbial and fungal biomass

Total microbial biomass C (MBC) was determined by chloroform fumigation extraction (Vance et al. 1987), using soil samples adjusted to 50% of their water holding capacity after thawing for 5 d at 4°C. Fumigated and non-fumigated samples were extracted from 5 g moist soil with 20 ml 0.5 M K_2SO_4, followed by measuring organic C in the extracts with a multi C/N 2100S automatic analyzer (Analytik Jena, Germany). MBC was calculated as E_C/k_{EC}, where E_C = (organic C extracted from fumigated soil) − (organic C extracted from non-fumigated soil) and k_{EC} = 0.45 (Wu et al. 1990).

The fungal-cell membrane component ergosterol was extracted from 2 g moist soil with 100 ml ethanol by 30 min oscillating shaking at 250 rev. min^{-1}, followed by reversed-phase high-performance liquid chromatography (HPLC) with 100% methanol as the mobile phase and detection at 282 nm (Djajakirana et al. 1996).

3.2.5 Particulate organic matter (POM)

Particulate organic matter (POM) was obtained at the end of the incubation experiment from 100g of fresh soil by wet sieving and flotation-decantation (Magid and Kjærgaard 2001; Muhammad et al. 2006); using a 400-µm sieve. POM was dried at 40°C until constant weight, weighed, and ground, for the analysis of total C and $\delta^{13}C$. The recovery rates of this method at day 0 were 95% and more (Börger et al. 2022, Schroeder et al. 2020).

3.2.6 Analysis of maize litter-derived C

The presence of litter-derived C through isotopic analysis of $\delta^{13}C$ was measured on MBC, CO_2C and POMC. The $\delta^{13}C$ in K_2SO_4 extracts (for MBC) as well as $\delta^{13}C$ of $BaCO_3$ (for CO_2C) were analyzed in freeze-dried samples, while POM was analyzed on milled-dry samples. Isotope values were measured by elemental analyzer–isotope ratio mass spectrometry. The fraction of litter-derived C in the K_2SO_4 extracts of fumigated and non-fumigated samples, in CO_2C as well as in POM-C in each treatment replicate was calculated from the $\delta^{13}C$ data according to a two pool-mixing model (Balesdent and Mariotti 1996) using the following equation:

$$C_{maize}(\%) = \frac{(\delta^{13}\,\mathrm{C}_{sample} - \delta^{13}\,\mathrm{C}_{control})}{(\delta^{13}\,\mathrm{C}_{maize} - \delta^{13}\,\mathrm{C}_{control})}$$

where $\delta^{13}C_{sample}$ represents the samples with litter-amended treatments, $\delta^{13}C_{control}$ the treatments without litter at six incubation weeks and $\delta^{13}C_{maize}$ is the average signature of the substrate, i.e., pure maize litter.

The litter-induced priming effect was calculated as the difference between native soil-derived CO_2C of the litter-amended soils and that of soils without litter for each corresponding soil and lime treatment.

3.2.7 CUE and CUE_{MB} calculations

CUE values of maize litter calculated according to Joergensen and Wichern (2018) considering all microbial metabolites, i.e., litter-derived microbial residue C (MRC_{maize}):

$$CUE = (MBC_{maize} + MRC_{maize}) / (100 - POMC_{maize})$$

$$MRC_{maize} = 100 - POMC_{maize} - CO_2C_{maize} - MBC_{maize}$$

where litter-derived C is considered as a percentage of the added substrate in MBC, POMC, and CO_2C, abbreviated as MBC_{maize}, $POMC_{maize}$, and CO_2C_{maize}. CUE was additionally calculated in the classical way that considers the incorporation of litter-derived C into the MBC but not that into MRC (Manzoni et al. 2012; Sinsabaugh et al. 2013; Spohn et al. 2016), and is therefore abbreviated in this study as CUE_{MB}:

$$CUE_{MB} = MBC_{maize} / (CO_2C_{maize} + MBC_{maize})$$

3.2.8 Statistical Analysis

All statistical analyses were performed in the R environment (R Core Team 2019). Results are presented as arithmetic means on a soil dry mass basis. Variance homogeneity and normal distribution of the residuals were tested with the Levene test and Shapiro-Wilk test, respectively. One-way ANOVA was performed to test differences between Nitisol, limed and unlimed Acrisol treatments in litter-amended soils and in soils without litter separately, followed by Tukey test. To generate regression model equations for the relationships between pH ~ CaO (pH-adjustment experiment), priming effect ~ pH, CUE ~ pH, CUE_{MB} ~ fungal biomass, the 'lm' function in the 'stats' R package v. 3.5.3 was used, after testing for their significant relationships using Pearson correlation (for normally distributed data) and Spearman rank correlation (for non-normally distributed data).

3.3 Results

Initially, the pH of the limed Acrisol was in the desired range of the reference Nitisol (Table 3.1), but this pH dropped compared with that of the Nitisol during the 6 incubation weeks. However, when comparing individual treatments, no significant changes occurred from initial to final pH.

Ergosterol showed an approximate 10-fold increase in litter-amended soils compared with soils without litter (Table 3.1), whereas that of total MBC (MBC_{maize} + MBC_{soc}, Tables 3.2 and 3.3, respectively) was just a three-fold increase. The change in fungal biomass due to litter addition was more drastic in the Acrisol treatments than in the Nitisol. Liming had no significant effect on ergosterol content in the Acrisol, but the ergosterol content of the limed Acrisol surpassed that of the Nitisol.

Table 3.1 Soil pH at the beginning and at the end of the 6 incubation weeks and ergosterol content at the end of the incubation period of the Nitisol and the limed and unlimed treatments of the Acrisol with ("Maize") and without ("No maize") maize-litter amendment

Soil	Lime	Initial pH-$CaCl_2$	Final pH-$CaCl_2$		Ergosterol (µg g^{-1} soil)	
			No maize	Maize	No maize	Maize
Nitisol	Unlimed	6.32 a	6.81 a	6.86 a	0.37	1.83 b
Acrisol	Limed	6.59 a	6.04 b	5.82 b	0.23	2.95 a
Acrisol	Unlimed	4.39 b	4.36 c	4.70 c	0.21	2.20 ab
CV (± %)		4.3	4.7	5.7	30	18

CV = mean coefficient of variation between replicates (n = 4); different letters within a column indicate a significant difference ($P < 0.05$; Tukey test); the absence of letters indicates absence of difference between the treatments

Maize litter decomposition decreased with decreasing pH (Table 3.2, Figure 3.1) according to the positive correlation between CO_2C_{maize} and soil pH ($r_s = 0.85$, $P < 0.05$). This was confirmed by the negative correlation between recovered $POMC_{maize}$ and soil pH ($r_s = -0.70$, $P < 0.05$). Total CO_2C ($CO_2C_{maize} + CO_2C_{soc}$) in litter-amended soils were 6 to 8-fold larger compared with soils without litter. In the soils without litter, soil respiration generally remained low (Supplementary figure S3.1). However, soil-derived CO_2C_{soc} in litter-amended soils were doubled compared with soils without litter addition (Table 3.3), indicating a positive priming effect. CO_2C_{soc} decreased in the order Nitisol > limed Acrisol > unlimed Acrisol, i.e., soil pH positively affected priming (Figure 3.3A). In spite of greater SOC mineralization in litter-amended treatments, a greater amount of soil-derived $POMC_{soc}$ was recovered by the end of the incubation compared with the total POMC recovered in their corresponding soils without litter (Table 3.2).

Table 3.2 Maize-derived cumulative ΣCO_2C, MBC, and POMC in an unlimed Nitisol as well as a limed and unlimed Acrisol after 6 weeks of incubation at 25°C

Soil	Lime	ΣCO_2C_{maize} ($\mu g\ g^{-1}$ soil 42 d^{-1})	MBC_{maize} ($\mu g\ g^{-1}$ soil)	$POMC_{maize}$
Nitisol	Unlimed	672 a	127	292 b
Acrisol	Limed	520 b	141	363 b
Acrisol	Unlimed	425 b	92	557 a
CV (± %)		7.7	22	27

CV = mean coefficient of variation between replicates (n = 4); different letters within a column indicate a significant difference ($P < 0.05$; Tukey test); the absence of letters indicates absence of difference between the treatments

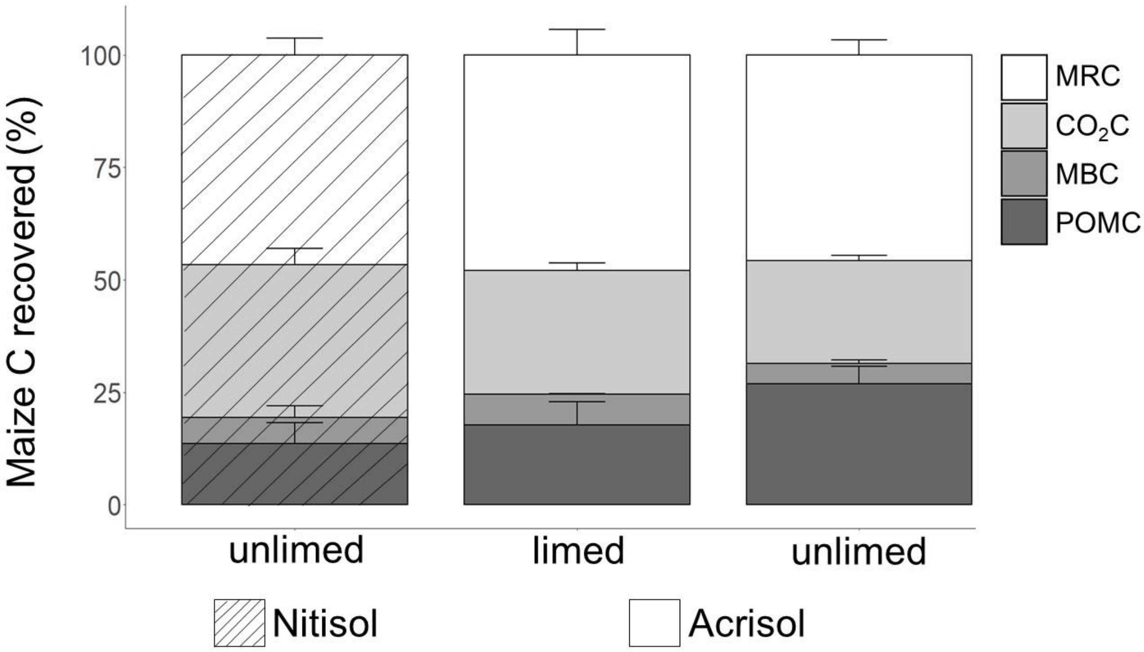

Figure 3.1 Recovery in percent of maize-derived CO_2C, MBC, POMC and MRC in an unlimed Nitisol as well as a limed and unlimed Acrisol after 6 weeks of incubation at 25°C; error bars show one standard deviation

Table 3.3 Soil organic C-derived cumulative ΣCO_2C, MBC and POMC in an unlimed Nitisol as well as a limed and unlimed Acrisol with ("Maize") and without ("No maize") maize-litter amendment after 6 weeks of incubation at 25°C

Soil	Lime	ΣCO_2C_{SOC} (μg g^{-1} soil 42 d^{-1})		MBC_{SOC} (μg g^{-1} soil)		$POMC_{SOC}$ (μg g^{-1} soil)	
		No maize	Maize	No maize	Maize	No maize	Maize
Nitisol	Unlimed	168 a	397 a	76 a	139	181	241
Acrisol	Limed	115 b	300 b	47 b	13	129	263
Acrisol	Unlimed	83 c	227 c	48 b	35	138	288
CV (± %)		11	10	23	96	26	24

CV = mean coefficient of variation between replicates (n = 4); different letters within a column indicate a significant difference ($P < 0.05$; Tukey test); the absence of letters indicates absence of difference between the treatments

CUE was much greater than CUE_{MB} and was greater in the limed and unlimed treatments compared with the Nitisol (Figure 3.2A), due to greater values in terms of remaining POMC and smaller values in accumulated CO_2C (Figure 3.1). CUE was negatively affected by pH (Figure 3.3B). The positive effect of fungi was only evident on CUE_{MB} (Figure 3.3C). The distributions of litter-derived C in some fractions differed among soils; however, they resulted in similar CUE_{MB} values (Figure 3.2A).

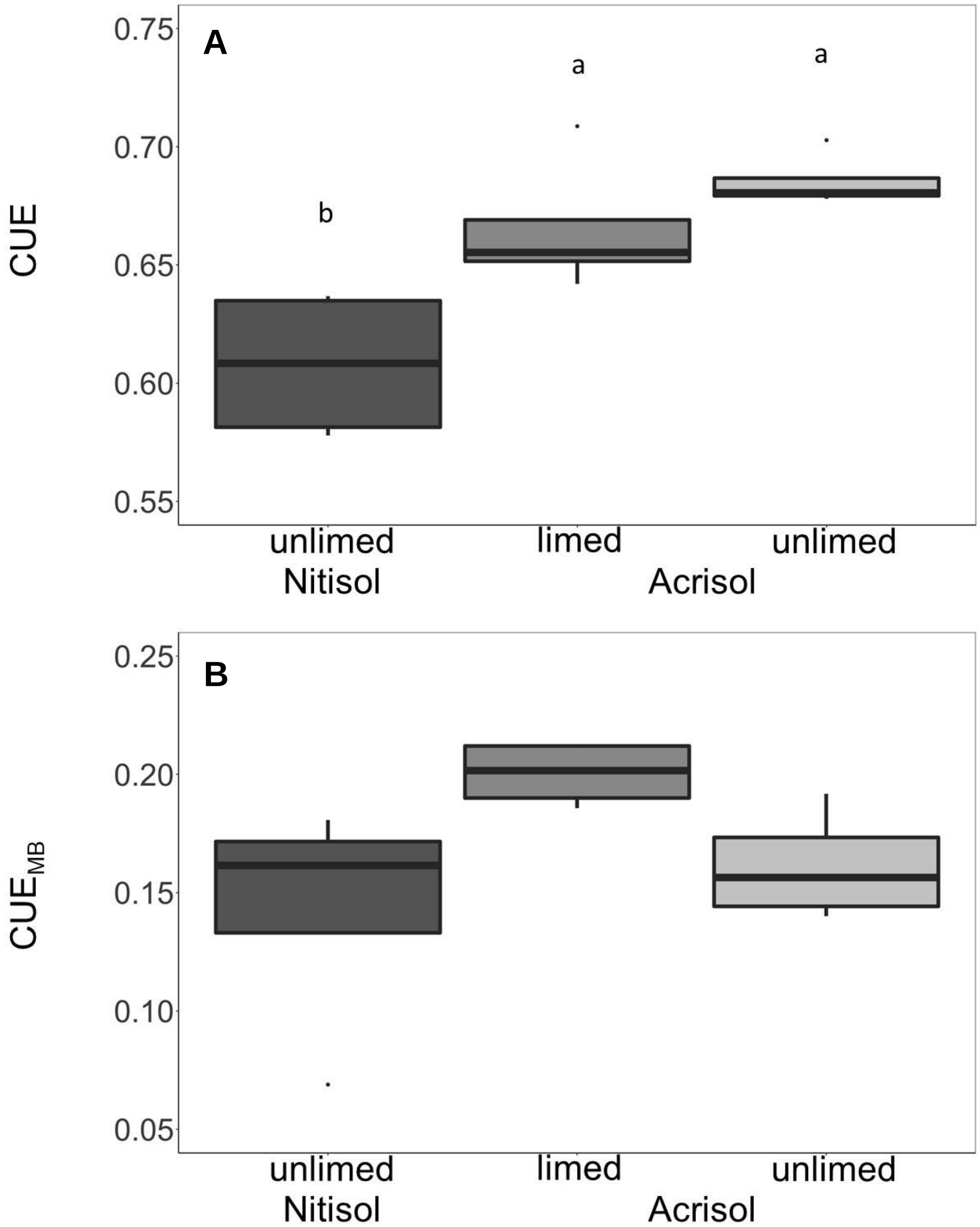

Figure 3.2 Boxplots of (A) CUE including microbial residues and (B) CUE_{MB} in an unlimed Nitisol as well as a limed and unlimed Acrisol after 6 weeks of incubation at 25°C, letters on top of the boxplots indicate a significant difference ($P < 0.05$; Tukey test)

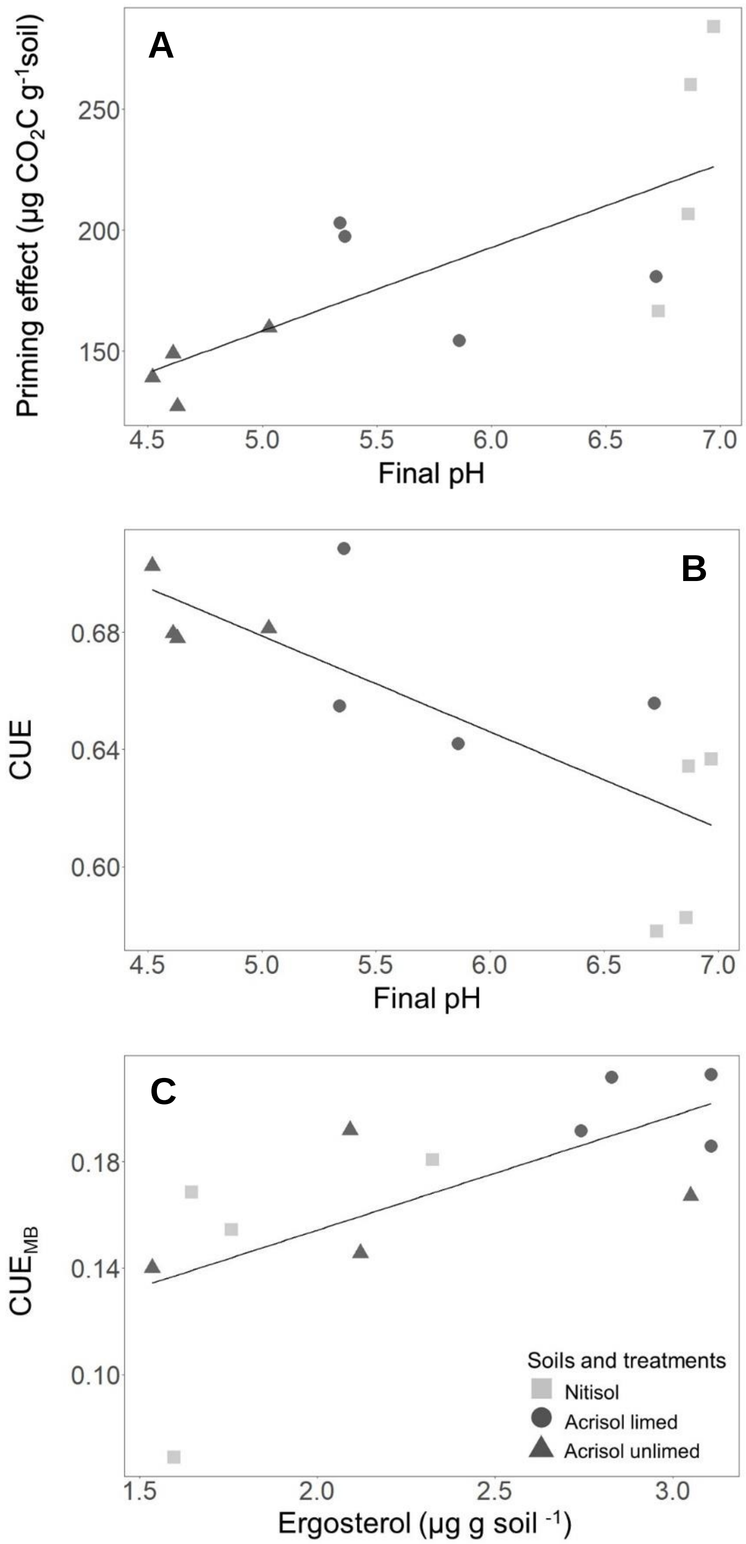

Figure 3.3 Linear relationships between (A) the priming effect of litter decomposition and final soil pH-$CaCl_2$ (y = – 14 + 34.49x, R^2 = 0.51, $P < 0.01$), (B) CUE and final soil pH-$CaCl_2$ (y = 0.84 – 0.03x, R^2 = 0.6, $P < 0.01$) as well as (C) CUE_{MB} and ergosterol (y = 0.07 + 0.04x, R^2 = 0.5, $P = 0.02$) in an unlimed Nitisol as well as a limed and unlimed Acrisol after 6 weeks of incubation at 25°C

3.4 Discussion

3.4.1 Liming effect on pH and its general implications

The model prediction to achieve a desired initial pH using CaO was very accurate, despite the potential risk of model-prediction effects associated with quality and origin of the lime (Bailey et al. 1991) or with varying soil factors such as nutrient availability, buffering capacity, aluminum saturation and others (Islam et al. 2004; Nelson and Su 2010; Olego et al. 2014). The drop in pH of the limed Acrisol treatment compared with the Nitisol after the 6 incubation weeks was probably due to the buffer capacity of the soils. Stabilizing soil properties such SOC or clay content were both higher in the Nitisol and positively associated with its buffer capacity (Aitken et al. 1990). Furthermore, substrate addition per se can differentially influence the liming effect on pH in different soils across time (Bramble et al. 2021).

3.4.2 Priming effect of litter addition on SOC

The current priming effect increased with increasing soil pH. Therefore, we do not discount the possibility that SOC priming is caused by the energy-induced synthesis of SOM-degrading exoenzymes. This was probably combined with accelerated turnover of the microbial biomass and a correlation between priming and mineralization of the added substrate (Mason-Jones et al. 2018), as indicated by the correlation between CO_2C_{maize} and CO_2C_{soc} ($r = 0.7$, $P < 0.01$). An increase in pH may cause the increases in extracellular enzyme production and enzyme activity, because the optimal pH value of the enzyme is reached. This may generally promote microbial activity and microbial biomass formation, followed by increased mineralization and priming. This is particularly true when growth of less efficient groups is promoted, suggested by the negative relationship between the contribution of fungal ergosterol to MBC and priming ($r = -0.6$, $P<0.05$). The negative association between more efficient microorganisms and priming is consistent with previous research that has found negative relationships between CUE and priming after straw addition (Mo et al. 2021). The apparently lower $POMC_{soc}$ mineralization in litter-amended soils compared with soils without litter may be explained by humified SOC particles adhering to litter-derived POM, altering the sample's $\delta^{13}C$ and confounding the results of apparently recovered $POMC_{soc}$, with $POMC_{maize}$ containing humified SOC.

3.4.3 The role of pH and liming in CUE

Low soil pH in the Acrisol resulted in less MBC_{SOC} and MBC_{maize} as well as less CO_2C_{maize} but more $POMC_{maize}$, indicating general negative effects on the decomposition of fresh plant residues. Liming already alleviated some of this stress (Jones et al. 2019; Liu et al. 2018; Malik et al. 2018). However, at the same time, liming promoted microbial turnover and increased substrate mineralization, resulting in a similar CUE for limed and unlimed treatments. Thus, the increase in CUE with decreasing soil pH implies the accumulation of SOM, due to acidity constraints of microbial growth and activity (Malik et al. 2018; Zhang et al. 2020). On the other hand, and in agreement with previous studies, the trend observed on CUE_{MB} in this study shows that liming may be a positive contributor to CUE of microbial biomass (CUE_{MB}), as compared with substrate quality (i.e., litter C/N ratio). No difference in CUE_{MB} was found in a study that compared two soils differing in POM-C/N ratios (Schroeder et al. 2020), which corresponds to our results, as the limed Acrisol and Nitisol did not differ, despite distinct litter C/N ratios.

3.4.4 The role of fungi in CUE

Fungi remained unaffected by liming or pH in our study, in agreement with others (Silva-Sanchez et al. 2019). This suggests that the pH is not a direct limiting factor for saprotrophic fungi in the current study, as similarly observed by Rousk et al. (2009) for pH-H_2O < 4.5. In this case, the pH effects previously identified by Moran-Rodas et al. (2022) may rather indicate the indirect effects of lower plant productivity, lower fresh-C inputs, and competitive interactions with bacteria in the long term. The increases in fungal biomass promoted by litter addition were related to a higher CUE_{MB}. Furthermore, the less MBC_{soc}, the higher CUE_{MB}. Apparently, fungi that preferentially utilize fresh substrate inputs, incorporate the litter-derived

C into MBC, making the community more efficient. This greater capability of fungi to incorporate litter-derived C into their biomass has already been observed (Wei et al. 2022). Other groups that preferentially feed on original SOC may be the main reason for the increases in priming and the decrease in CUE. The competitive interaction between these distinct groups that form microbial biomass is reflected by a negative correlation between fungal biomass and MBC_{soc}. These findings are in agreement with studies that suggest community characteristics (composition, diversity) as major drivers of CUE (Domeignoz-Horta et al. 2020; Kallenbach et al. 2016) and/or priming (Nottingham et al. 2009).

3.4.5 Carbon use efficiency measurements and their implications

The similar CUE_{MB} values between the soils are the result of quite different combinations in the proportions of C_{maize} recovered in the different pools. In the Nitisol, microbial communities assimilated more litter-derived C, but also respired more, resulting in a larger CO_2C_{maize} fraction, whereas in the unlimed Acrisol microbial communities assimilated less C_{maize} and respired less. Hence, more C_{maize} was recovered in the POM pool of the latter. Thus, the results of the CUE indicate that, from a broader perspective, the Acrisol is more efficient, as it produces a similar number of microbial residues (~47%) while consuming less POMC, compared with the reference Nitisol. The proportion of microbial residues found is consistent with recent findings within a similar timeframe (Geyer et al. 2020).

Our CUE_{MB} values lay in the range of 15-20%, which is similar to those of Schroeder et al. (2020) of ~15% and of Börger et al. (2022) of ~17%, using the same approach as that applied in this study. CUE values were greater than CUE_{MB} values in this study. This was very much in line with results found by Geyer et al. (2020), who used the concept of carbon stabilization efficiency "CSE" to compare it with CUE_{MB} from several studies. Even if CUE_{MB} values were obtained by short-term incubations with glucose addition in their case, their ranges of CSE and CUE_{MB} resemble ours. This highlights the importance of the fractions included for the calculation of CUE values and their interpretation. Most studies evaluating CUE used CUE_{MB} approaches based on short incubation periods and labile substrates. Our CUE can provide an insight into additional pools such as microbial residues for an intermediate period, as well as intermediate trends on SOC pathways.

3.5 Conclusions

Our 42-day incubation study revealed decreases in CUE, increases in litter mineralization and increases in priming of SOC as a function of soil pH, refuting our first and second hypotheses. The higher CUE in the Acrisol compared with the Nitisol was mainly due to lower maize-derived CO_2C production from reduced litter decomposition by the microbial community under lower pH. The fungal biomass was not affected by pH but was associated with a more efficient microbial community, confirming our third hypothesis. Saprotrophic fungi were responsible for increases in CUE_{MB} by the incorporation of maize litter into microbial biomass. These results suggest that the low SOC content in the Acrisol is due to a low input of plant residues in the field and not to a lower CUE, while liming only moderately increased SOC mineralization and litter consumption. Furthermore, our CUE-CUE_{MB} comparison confirms that not accounting for undecomposed maize and microbial residues underestimates CUE of litter-amended soils. Longer-term studies may provide further information on substrate-C turnover and the persistence of the observed effects on CUE and priming.

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Conflict of interest

The authors declare no competing interests.

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4 Agricultural management practices and decision making in view of soil organic matter in the urbanizing region of Bangalore

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Abstract

Rapid urbanization and agricultural intensification are currently impacting the soils of many tropical countries. Bangalore is a growing megacity experiencing both issues and their derived ecological and socio-economic effects. This paper seeks to understand how the socio-economic effects of urbanization are affecting soil organic carbon (SOC) in Bangalore's rural–urban interface. We first compiled information on how management practices affect SOC dynamics and specifically evaluated the effects of fertilization practices on SOC levels in major cropping systems. We then used interview data from farmers' households across an urbanity gradient in Bangalore to test the association between urbanization as well as related socio-economic drivers and farming practices. We found that fertilization increases SOC concentrations, especially when mineral fertilizer is combined with additional farmyard manure. Single mineral fertilizer and a combination of mineral fertilizer and farmyard manure are commonly applied in Bangalore. Conservation practices, such as reduced tillage and mulching, are applied by 48% and 16% of households, respectively. Farm and household characteristics, including market

integration, are the most important determinants of management decisions that affect SOC. Our study shows that improving farm and household conditions and opportunities, independently of the degree of urbanity, is necessary for implementing agricultural practices that can benefit SOC in Bangalore.

Keywords: rurality; mineral fertilization; irrigation; mulching; tillage; crop choice; rural-urban index; farmers' welfare; SOM; SOC

4.1 Introduction

Cultivation has led to a decline of soil organic matter (SOM), especially in most weathered tropical soils. Reductions in SOM constitute a negative feedback loop, altering the provision of soil functions, such as C sequestration, habitat for soil organisms, bio-diversity, and plant productivity (Oldfield et al. 2019). Consequently, a low SOM content makes farmers more vulnerable to global change conditions, e.g., climate change and urbanization, which is particularly pronounced in regions of quickly growing megacities (Seto and Ramankutty 2016). Urban expansion implies a loss of fertile cropland to con-structed areas, environmental degradation, competition for natural resources, and it might even result in the displacement of farmers into marginal lands (Seto and Ramankutty 2016). Generally, farmers in urbanizing areas might have a higher adaptive capacity to changing framework conditions like climate change than remote rural farmers, due to better access to certain infrastructures (Gbetibouo et al. 2010; Bouroncle et al. 2017; Parker et al. 2019). However, farmer communities from the city periphery may be more vulnerable to climate change than at least a portion of the urban population in the city center, where the economy is more active and physical and social infrastructures are more developed (Kumar et al. 2016), although such urban facilities may only benefit wealthier urban inhabitants (Satterthwaite et al. 2010).

In India, the soil organic carbon (SOC) concentration in most cultivated soils is less than 5 mg g^{-1}, compared with 15 to 20 g mg g^{-1} in uncultivated soils (Lal 2004). A low SOC concentration is attributed to frequent tillage, the removal of crop residues, and the mining of soil fertility (Lal 2004). In recent years, there has been an increased need for and interest in how SOC accumulation can be achieved through agricultural management practices, with reviews on best practices and their impacts on SOC (Oelbermann et al. 2004; Paustian et al. 2016; Fujisaki et al. 2018). Studies suggested that the retention of crop residues mitigates nutrient exports from soils and effectively preserves or even accumulates SOC (Fujisaki et al. 2018). Therefore, retaining crop residues on site is an important measure to maintain the chemical, physical, and biological properties of soils (Yadvinder-Singh et al. 2005; Powlson et al. 2011), thus mitigating negative climate change impacts on crop yield (Liu et al. 2017).

Management practices altering SOC dynamics interact considerably with social-ecological factors that may be changing in the context of rural–urban transformation. For example, crop-choice changes in cultivated soils are increasingly being promoted by urban demand, inducing a switch from traditional rainfed cereal crops to more intensively managed irrigated vegetables in the vicinity of city markets (Patil et al. 2019). Furthermore, farm households in urban areas may pursue alternative work outside agriculture, providing an additional income and enabling landowners to invest in innovative agricultural technologies (Kurgat et al. 2018). However, off-farm work may reduce the time and motivation spent on agriculture by directly increasing agriculture's opportunity cost (Steinhübel and von Cramon-Taubadel 2021). Potentially, this might promote the selection of less management-intensive agricultural practices that may only be beneficial in the short term instead of labor-intensive practices often required in sustainable agriculture (Lee 2005). The main management factors that affect SOM dynamics are the selection of crop species, the retention of crop residues by using mulching, the application of mineral and organic fertilizer, water management, and tillage. Different combinations of these management practices can counteract SOM accumulation, and the practices' effects may differ between agricultural systems, soils, and climate regimes.

This paper aimed at providing an overview of how current management practices are affecting the SOC dynamics and SOC accumulation in soils in an urbanizing setting in India. To achieve this objective, we first reviewed the literature on the effects of the abovementioned management factors in relevant tropical systems, performing a more in-depth statistical analysis of fertilization-type effects on SOC concentrations with a focus on agriculture in the surrounding areas of the South Indian megacity of Bangalore. Since socio-economic factors that are dynamically changing during urbanization are expected to affect SOC-related management factors, the second aim of this study was to disentangle and analyze the relationship between socio-economic characteristics of farm households in Bangalore's urbanizing area and the use of agricultural management practices that affect SOC. We hypothesized that (1) conservation practices, such as mulching, minimum tillage, and FYM addition, improve SOC levels in the context of Indian agriculture; (2) decisions for crop choices are driven by the vicinity of city markets and affect management practices, such as fertilization and irrigation; and (3) decisions for adopting soil conservation practices are more likely for traditional rainfed cereal crops, and these crops are more frequently cultivated in rural areas. To test Hypothesis 1, data from the literature were evaluated. To test Hypotheses 2 and 3, we used survey data from 362 farm households located in the rural–urban interface of Bangalore to examine farmers' crop choices, the adoption of irrigation, as well as the adoption of mulching practices, farmyard manure, and minimum or no tillage. We used Bangalore as a case study as it exemplifies many key characteristics of urbanization and related agricultural transformations (Rao et al. 2007; Narayana 2011; Kraas and Mertins 2014). Urbanization in Bangalore negatively affects the local environment, ecosystems, and biodiversity (Sudhira and Nagendra 2013; Ramachandra et al. 2019). We addressed these issues in terms of SOC in our study since SOC is a holistic indicator of soil degradation (Obalum et al. 2017).

4.2. Literature review of management practices and their effects on SOC dynamics during rural–urban transformations

4.2.1. Crop Choice and Diversification

Crop diversity is a critical factor in food security because having a variety of crops means that at least some crops will yield despite harsh climate conditions, insect out-breaks, and other natural disasters (Leff et al. 2004). Patil et al. (2019) reported 82 distinct crops in Bangalore. Among the different categories, cereals and pulses are the main crop choice for farmers in Bangalore, finger millet and maize being the major crops. Commercial crops, such as fruits, vegetables, fodder, and horticultural crops, complement the range (Patil et al. 2019). Market proximity supports the production of high-value crops (Drechsel and Zimmermann 2005). Proximity to Bangalore city increases the likelihood of farmers choosing vegetables, suggesting that the primary market is a main decision factor (Patil et al. 2019). Crop type may interact with fertilization level and water management and may affect the quality of plant residues potentially returned to the soil (Seneviratne et al. 1997). Nitrogen and lignin contents are major determinants of decomposition rates (Palm et al. 2001), with N_2-fixing plants playing important roles in a substitution of mineral N fertilizer. High-quality residues increase microbial anabolic activity (Yadvinder-Singh et al. 2005), promoting the production of microbial residues, thus increasing the C sequestration in soils (Liang et al. 2017). Furthermore, crops differing in root traits may impact SOC dynamics via various processes, e.g., finer roots and more branched root systems as well as mycorrhiza infections increase the aggregate stability mainly through the physical enmeshment of soil particles, which increases resistance to soil erosion (Bardgett et al. 2014). In annual cropping systems, species with high root to shoot ratios, such as pigeon pea and finger millet, which are traditionally grown in Bangalore, show higher contributions to SOC compared to plants with lower root shoot ratios, such as maize (Manjaiah et al. 2000; Moran-Rodas et al. 2022). Perennial crops generally deposit more C than annual species due to their permanent and deeper root systems, promoting the stabilization of SOC (Lal 2004; Paustian et al. 2016). These effects are mainly observed in tree plantations, hedges, and agroforestry systems, such as home gardens and alley cropping systems (Mapa and Gunasena 1995; Oelbermann et al. 2004; Tian et al. 2005; Follain et al. 2007; Radrizzani et al. 2011; Nath et al. 2018). However, studies of Bangalore´s perennial representatives are lacking.

4.2.2. Application of Crop Residues and Mulching

Residue return and mulching are practices oriented toward enhancing soil quality and crop yields by increasing SOC inputs, improving a soil's structure and water holding capacity (Lal 2004; Powlson et al. 2011) while preserving soil moisture (Liu et al. 2017; Chaudhary et al. 2018). Depending on the quality of the residue and turnover rates, the return of nutrients by mulching may even directly increase yields (Yadvinder-Singh et al. 2005). Furthermore, mulched crop residues provide protective litter layers against erosion (Palm et al. 2001). Mulching is practiced not only with harvest residues but also with tree pruning from leguminous trees and shrubs that increase C and N inputs into the soil (Srinivasarao et al. 2014). Thus, legume plants are considered four times more often by tropical agricultural studies analyzing the effects of substrate quality and nutrient release than non-legume species (Seneviratne 2000). In India, mulching is preferred for fruit orchards, flowers, and vegetables rather than for traditional food crops (Bhardwaj 2013).

Despite the potential need for and positive effects of mulch, especially in rainfed systems, its use is not frequent in India (Lal 2008b).

In the tropics, lower C inputs into soil are partly caused by higher demands for crop residues for alternative uses, such as livestock feeding, fuel, and fiber (Fujisaki et al. 2018). This is particularly true in India where, besides livestock feeding, there is a great demand to use residues for energy, especially for cooking (Lal 2004; Manna et al. 2003; Prasad et al. 2019). This lack of available crop residues is a major constraint for mulch applications as it is restricted cultivation during the dry season that causes increases in bare fallow and erosion (Manna et al. 2003; Lal 2004). Thus, low yields and reduced residue returns generate negative feedback loops with respect to SOC (Lal 2004). In this context, a higher urban demand for crop products and land may provide motivation to reduce bare fallow by using frequent cover crops, increasing crop productivity. In any case, all the above-mentioned factors reflect a need to identify viable supplementary sources of nutrients, measures against soil erosion (Palm et al. 2001), and viable alternative sources of fuel and fiber.

4.2.3. Use of Organic Manures and Fertilizers

Besides mulching, the application of organic manures increases nutrient cycling and C inputs into soil. Urban cattle in Bangalore are stallfed with purchased or farm-produced concentrates, while in rural locations, during the daytime, animals are allowed to graze on nearby vacant lands and on agricultural farmland. In both systems, dung collections and applications in crop production are low, highlighting a need to strengthen crop–livestock links by using back transfers of some of the products (Prasad et al. 2019). There is also a need to more efficiently manage urban cattle disposals that pollute water (Prasad et al. 2019). Thus, the recycling of cattle manure will prevent water pollution and will close C and nutrient cycles in agriculture. Green roughage is produced on a daily basis from the city environment and green spaces, while dry roughage is often purchased weekly and stored. In addition, unused vegetable and food wastes and compounded cattle feed or individually mixed concentrate are fed (Prasad et al. 2019), demonstrating the trade-offs between the crop residues used for mulching and feed. Besides the low dung return rate, a low frequency and amount of organic fertilizer application as well may be due to utilizations for further purposes, such as energy (Thilakarathna and Raizada 2015; Agegnehu and Amede 2017). In places where the availability of farmyard manure (FYM) is a major concern due to a decline in the livestock population, crop residues, compost, and municipal biosolids are considered alternative organic material inputs for sustainable crop production (Sathish et al. 2016). In India, the use of byproducts, such as press cake from the alternative biofuel species Jatropha, has increased plant yields and SOC accumulation (Anand et al. 2015). Compost and biochar are potentially more efficient at increasing SOC storage because on top of improvements in soil quality and productivity, they are decomposed more slowly than fresh plant residues (Powlson et al. 2011; Paustian et al. 2016). However, compost and biochar are less commonly applied in India, and few studies have included comparisons between compost and other organic amendments in relevant cropping systems (Nayak et al. 2009; Sharma et al. 2009; Srinivasarao et al. 2019), while none have included biochar. In irrigated rice-based cropping systems, the prominent means of maintaining SOM has historically been the incorporation of green manures, animal waste, and crop residues (Yadvinder-Singh et al. 2005). Under the specific dryland conditions of Bangalore, further analyses are required to compare the effects of different fertilizers on C sequestration.

Organic fertilizer is progressively supplemented or substituted with mineral fertilizer. An increased availability of mineral fertilizer and subsidized prices are probably important factors increasing such applications in many regions of the world (Chianu et al. 2012; Thilakarathna and Raizada 2015). The application of mineral fertilizers and combinations with organic amendments are recommended to counteract nutrient exports with harvested crops and nutrient losses during cultivations, while increasing soil aggregations, SOC contents, and water retentions of soils (Lal 2004; Powlson et al. 2011; Banger et al. 2010). N-fertilization effects on SOC fractions have not been observed in the short term (Moran-Rodas et al. 2022; Yagi et al. 2005; Vineela et al. 2008), whereas long-term individual studies demonstrated positive effects of N fertilization on SOC. However, the positive effects may be outweighed by negative effects due to increased N_2O emissions at high fertilization levels (Tian et al. 2012). In nutrient-limited soils, fertilization is recommended for sufficient plant growth with a high potential for increasing C inputs in these soils (Paustian et al. 2016). Once a soil has improved in quality, yields are maintained by using a smaller input of fertilizer (Powlson et al. 2011; Oldfield et al.

2019) as there is a threshold at which plant yields level off, despite increasing amounts of fertilizer being applied (Oldfield et al. 2019).

The potential of using manures and crop residues for short-term N provisions is limited in light of the manures' and residues' low N availabilities and N contents, the latter of which are often lower than 2%, although they can provide long-term benefits in maintaining SOM (Palm et al. 2001). Contrasting results observed in individual studies comparing farmyard manure (FYM) with mineral fertilizers or combinations of the two were probably due to differing contents of nutrients in organic manures and biotic as well as abiotic soil properties. Nonetheless, for tropical croplands, manure applications have been some of the most successful practices for increasing SOC compared to mineral fertilization, conservation tillage, and the application of crop residues alone (Fujisaki et al. 2018).

4.2.4. Water Management

In India, approximately one third of the country's arable land is irrigated, and increases in crop yields have been observed after irrigation (Lal 2004). However, access to water is limited and costly, emphasizing the importance of rainfed agriculture. Irrigation may induce contrasting effects on C sequestration. Introducing irrigation in dryland areas can increase C inputs (Sojka et al. 2007; Paustian et al. 2016) while enhancing decomposition rates. Likewise, the frequency of irrigation and intensities of wetting and drying cycles affect the soil's physical properties and microbial decomposition (Yadvinder-Singh et al. 2005), thus regulating C sequestration. The rapid mineralization of crop residues under optimal soil moisture conditions may explain why systems under irrigation do not effectively increase soil organic carbon stocks (Fujisaki et al. 2018). Furthermore, the effects of irrigation interact with other management measures as irrigated crops often receive higher fertilization rates and other chemical farm inputs with implications for soil health and the environment (Environmental Management & Policy

Research Institute 2015). However, the possible negative effects of irrigation, such as increased erosion rates and nutrient losses, are often overlooked (Sojka et al. 2007).

Nevertheless, water conservation practices, such as compartmental bunding, implementing ridges and furrows, and mulching, all increase plant yields and SOC stocks in Bangalore´s agricultural soil (Patil and Sheelavantar 2004; Chaudhary et al. 2018), maintaining the positive effects of improved water availability on agriculture. In terms of irrigation, the adoption of efficient irrigation techniques, such as drip irrigation, in Bangalore may be linked to crop choice decisions, while not all crops can be drip irrigated (Patil et al. 2019).

The irrigation sources in Bangalore are diverse, ranging from relatively less polluted rivers and underground sources to city wastewater (Patil 2018; Kulkarni et al. 2021). With wastewater, nutrients and organic matter are applied (Patil 2018), but access to water is the most limiting factor, especially for systems based on natural reservoirs that are constantly depleted (Patil et al. 2019; Kulkarni et al. 2021). Despite water's primary importance in most soil processes, published studies regarding water management and its relation to SOC dynamics are surprisingly scarce compared to studies concerning other practices, such as fertilization and mulching.

4.2.5. Tillage

In India and other countries in Southeast Asia, moldboard-plow tillage is frequently applied in crop rotations (Ghimire et al. 2017). Soil disruption and intensive tillage practices are classified as immediate causes of SOC declines, so reduced and zero tillage are important mitigation practices to prevent SOC losses. Tillage alters water interception and infiltration, soil porosity, aeration, aggregate distribution, and microclimates, increasing decomposition rates (Lal 2004; Yadvinder-Singh et al. 2005). Conservation tillage, leaving 30% or more of a soil's surface with crop residue (Conservation Technology Information Center 2002), is a good conservation strategy enhancing soil quality, yields, and thus SOC (Lal 2004). Zero tillage practices are defined as the complete absence of tillage and have been demonstrated to have great potential in increasing SOC accumulations worldwide (Mehra et al. 2018). In maize systems, zero tillage (Pandey et al. 2010; Kushwa et al. 2016) and reduced tillage (Kumar et al. 2018) have presented the highest increases in SOC. Studies about tillage's effects on SOC in India showed increased SOC levels for reduced tillage and non-tillage practices compared to conventional tillage in 90% of cases (Table S4.1). Nevertheless, Powlson et al. (2011) suggested that increases in SOC from reduced tillage appear to be much smaller than previously claimed and can be overestimated considering differences in the depth, bulk density, and depth distribution of SOC between tillage treatments.

4.3. Materials and Methods

4.3.1. Analysis of Published Data on Fertilization's Effects on SOC Dynamics in India

Study Selection

Among the most relevant management factors affecting SOM dynamics, we focused on the effects of different fertilization practices on SOC under pedoclimatic conditions of India for analysis. We excluded analysis of tillage practices that were only partially addressed in our survey study, while data on effects of mulching and water management in India are scarce and therefore were not suitable for statistical evaluation.

We selected long-term Indian studies that were based on rainfed agriculture and maize and/or finger millet cropping systems as single crops or in combination with other rotation crops as maize and millet are the major representatives of food crops in Bangalore with the largest cultivated area. To prevent pseudo replications, additional studies conducted on the same field experiments under the same treatments, but with variations in sampling time, were excluded. We collected data on further relevant factors on SOC dynamics, such as number of rotation crops, clay content, pH, rainfall, and study period (Table S4.2). Nevertheless, due to the fact that soil variables other than SOC were not analyzed in field replicates, it was not possible to include these factors as co-variables in the analysis of treatment effects in our study.

Data analysis

In the selected studies, FYM-N was mainly given as % of the recommended N dose. However, when FYM input was given in terms of fresh biomass per hectare, we calculated the N input (kg ha^{-1}) from the available information on % N content in FYM (Table 1). When SOC was given not in concentration units (g kg^{-1}) but in SOC stocks (Mg ha^{-1}), we used individual bulk density data (when available) to convert stocks into concentrations. If bulk density of different treatments was not available, the calculation was applied to all the treatments using the initial bulk density of the soil. The increases in SOC presented in our results for the different treatments were calculated with the formula

$$\Delta SOC = SOC_t - SOC_c \quad (1)$$

where SOC_t is the SOC concentration (g kg^{-1}) of each treatment and SOC_c is the SOC concentration (g kg^{-1}) of the control treatments, i.e., without any fertilizer application.

For statistical analyses, the Shapiro–Wilk test and Levene’s test were used to test normalities and variance homogeneities of the residuals, respectively. We used unbalanced analyses of variance to compare differences between fertilization management treatments, followed by post-hoc Tukey’s tests for individual differences. To analyze whether the treatments significantly differed from the controls (zero), we used the one-sample t test for each treatment. We performed Pearson correlations to analyze the relationships between grain yield and SOC with a selected data set from three experimental fields on finger millet using all treatment samples, including controls without fertilization. The abovementioned statistical analyses were performed in the R environment (R Core Team 2019).

Table 4.1 Input additions in ranges and calculated means for N, P, K, and farmyard manure, corresponding to fertilization treatments for finger millet and maize cropping systems in India from selected individual studies *; number of experiments per crop; and percentage of total studies with significant treatment effect on SOC content compared to control soils.

Treatment [1]	Input Range (kg ha^{-1})		Mean Input (kg ha^{-1})		No. of Experiments		Studies (%) with Treatment Effect on SOC Content	
	F. Millet	Maize	F. Millet	Maize	F. Millet	Maize	F. Millet	Maize
Mineral fertilization (Min)	50 N 50 P 25 K	60–120 N 26–60 P 40–50 K	50 N 50 P 25 K	100 N 39 P 45 K	5	4	60%	50%
Farmyard manure (FYM)	50 N	31 N	50 N	31 N	3	1	100%	0%
Complementary Min and FYM	25 N (Min) + 25 N (FYM)	25–90 N (Min) + 25–30 N (FYM)	25 N (Min) + 25 N (FYM)	41 N (Min)+ 28 N (FYM)	1	2	100%	100%
Added Min and FYM	50 N (Min) + 50 N (FYM)	100–120 N (Min) + 25–31 N (FYM)	50 N (Min) + 50 N (FYM)	110 N (Min) + 28 N (FYM)	3	2	100%	100%

* Fertilization practices, crop types, soils, environmental factors, locations, study periods, and references of the selected individual studies are provided in Table S4.2. [1] Complementary Min and FYM = mineral fertilization and FYM added up to the total recommended N dose for the specific crop; added Min and FYM = combination of total recommended N mineral fertilization with additional FYM.

4.3.2. Analysis of Survey Data on Farmers' Agricultural Practices in the Urbanizing Region of Bangalore

Study Site

Bangalore is a rising megacity located in South India. Its population increased from 5.8 million people in 2001 to 8.7 million in 2011 (Directorate of Census Operations Karnataka 2011a). Unofficial projections indicated that the population had grown to 12.6 million in 2021 (Population Stat 2021). Beside its population size, the city is characterized by many key characteristics of urbanization and globalization. The city is known as India's 'Silicon Valley' (Narayana 2011) and has a diverse off-farm employment sector that attracts large numbers of migrants (Sudhira et al. 2007). Despite this, the agricultural sector is still of importance as it provides a source of income for 49% of the labor force in the surrounding peri-urban and rural areas (Directorate of Census Operations Karnataka 2011b, 2011c).

Data Collection

We used survey data that was collected from 388 farm households located in two transects in the north and south of Bangalore between 02 February and 10 March, 2020. A map of the transects can be found in Supplementary figure S4.1. The sampling of villages and households was done in a previous survey phase in 2016/17 using a two-stage stratified sampling approach (Hoffmann et al. 2017). In the sampling process, a Survey Stratification Index (SSI) developed by Hoffmann et al. (Hoffmann et al. 2017) was used as a proxy for urbanization. The SSI was calculated from the distance to the city center of Bangalore and the percentage of non-built-up area around the villages. The SSI takes a value between 0 and 1, where 1 stands for most rural and 0 indicates most urban. The two transects were classified into six urban, peri-urban, and rural strata based on their degrees of urbanity. Within the strata, villages were randomly sampled proportional to the size of their stratum (Hoffmann et al. 2017). Finally, a random sample of farm and non-farm households was drawn proportionate to the size of each village based on household lists obtained from the mother and child care centers of the villages.

Due to the outbreak of the COVID-19 pandemic in India in March 2020, data collection of the second survey had to be suspended on 10 March 2020. 55% of the sampled farm households were interviewed. A total of 415 farm households in 50 out of 58 villages/neighborhoods with farm households were thus re-interviewed in second survey. Hence, attrition occurred within villages rather than across villages. We used a standardized questionnaire to collect data on socio-demographic household characteristics and farm management decisions (e.g., cropping decisions, fertilizer use, and use of sustainable agricultural practices). For our analysis, we focused only on the 388 crop-cultivating farm households as the sampled non-farm households and the farm households that were engaged in only dairy and livestock activities were not relevant to our study. We focused only on the data collected in the second survey in 2020 since data on certain farming practices (i.e., sustainable agricultural practices) that are essential for our analysis were not asked about in sufficient detail in the first survey.

Data Analysis

We start by providing a descriptive overview of farmers' crop choices, fertilizer use, and irrigation in the study area. For analysis of the socio-economic correlates of farmers' crop choices and the adoption of irrigation and conservation practices, we employed probit models. The linear probability model for each of the respective outcome variables was specified as:

$$P_i\,(A_i = 1 \mid x_i) = \beta_0 + \beta_1 D_i + \beta_2 H_i + \beta_3 L_i + \beta_4 F_i + \varepsilon_i \qquad (1)$$

The binary outcome A_i represent farmers' crop choices and the adoption of irrigation and conservation methods. P_i denotes farmer *i*'s probability of adoption and hence the probability that $A_i = 1$ (where $A_i = 1$ indicates that a farmer has adopted a crop from a certain category, irrigation, or a conservation method and $A_i = 0$ indicates if otherwise) (Wooldridge 2010).

Summary statistics of all outcome variables are provided in Table 4.2. Farmer *i*'s probability of adoption is conditional on the explanatory variables x_i. On the right-hand side of equation (2), vectors D_i, H_i, L_i and F_i include decision-maker, household, location, and farm characteristics, respectively. Summary statistics of the socio-economic variables are provided in Table 4.3. Decision-maker characteristics include the gender, education and age of the household head. We further included household characteristics: the number of adults (household members aged 15 years or older), whether the household belonged to a marginal caste, a count of the durable assets owned by the household as a proxy for wealth (durable assets refer to household assets as compared to transport and agricultural equipment), and a binary variable indicating whether any household member earned an off-farm income. For farm characteristics, we included farm size, whether the household owned dairy cows, whether it owned other livestock, and whether it owned a borewell. Market integration was measured as a binary variable and indicated whether the farm household had sold any crops in the market in the year preceding data collection. To measure urbanization, we included the SSI used to sample the households in our model. In addition, we controlled for the farmers' locations in either the northern or the southern transect to capture any differences between them, but this variable was not the focus of our analysis. In the models on adoption of irrigation and conservation practices, we also controlled for farmers' crop choices. In equation (2), β denotes the parameters to be estimated. The unobserved characteristics are captured by the random error term ε_i. Due to some missing observations of some of the independent variables, we estimated the probit models for a slightly smaller sample of 362 farm households.

Table 4.2 Summary statistics of dependent variables with respect to the adoption of farm management practices used in analysis (*N* = 362; household level).

	Mean	Std. dev.	Min	Max
Irrigation (1 = yes)	0.365	0.482	0	1
Conservation Practices				
Minimum/no tillage (1 = yes)	0.483	0.500	0	1
Mulching/crop residues/cover crops (1 = yes)	0.160	0.367	0	1
Farmyard manure (1 = yes)	0.660	0.474	0	1
Crop Choice				
Cereals (1 = yes)	0.856	0.351	0	1
Pulses (1 = yes)	0.472	0.500	0	1
Vegetables (1 = yes)	0.149	0.357	0	1
Fruits (1 = yes)	0.191	0.393	0	1
Flowers (1 = yes)	0.041	0.200	0	1
Herbs and spices (1 = yes)	0.072	0.259	0	1
Non-food commercial (1 = yes)	0.160	0.367	0	1
Fodder (1 = yes)	0.146	0.354	0	1
Lawn/turf grass (1 = yes)	0.019	0.138	0	1

Note: All variables are dummy variables that are equal to 1 if the farmer used the respective practice in 2019 and 0 if not. The column 'mean' indicates the share of farmers in the sample who were adopters. 'Std. dev.' stands for standard deviation. 'Min' stands for minimum; 'max' stands for maximum.

Table 4.3 Summary statistics of decision-maker, household, and farm characteristics and the SSI included as independent variables in the analysis ($N = 362$; household level).

	Mean	Std. dev.	Min	Max
Decision-maker Characteristics				
Female (1 = yes)	0.235	0.424	0	1
Education (years)	5.878	5.057	0	20
Age (years)	50.028	13.160	22	90
Household Characteristics				
No. of adults (HH members ≥ 15 years)	3.854	1.841	1	19
Non-marginal caste (1 = yes)	0.790	0.408	0	1
Durable assets owned (count)	11.992	6.026	0	48
Off-farm income (1 = yes)	0.588	0.493	0	1
Farm Characteristics				
Farm size (ha)	0.881	1.293	0	13
Dairy (1 = yes)	0.696	0.461	0	1
Livestock (1 = yes)	0.403	0.491	0	1
Owned borewell (1 = yes)	0.229	0.421	0	1
Market integration (1 = yes)	0.420	0.494	0	1
Location				
Rural–urban index (SSI)[1]	0.712	0.148	0	1
Northern transect (1 = yes)	0.541	0.499	0	1

Note: The column 'mean' indicates the share of farmers in the sample in case of dummy variables. 'Std. dev.' stands for standard deviation. 'Min' stands for minimum; 'max' stands for maximum.[1] The SSI takes a value between 0 and 1. The value 1 stands for most rural and 0 indicates most urban.

4.4 Results

4.4.1. Fertilization Management's Effects on Soil Organic Carbon (SOC) in Maize and Finger Millet Cropping Systems in India

We found two medium-term and seven long-term fertilization studies ranging from 4 to 6 and 10 to 44 years, respectively, of which five studies were based on finger millet and four studies were based on maize cropping systems (Table S4.2). The studies reported significant increases of SOC in top soils compared to control soils for most fertilization practices. The addition of farmyard manure increased the SOC in all studies in finger millet, whether alone or in combination with mineral N, while FYM alone did not increase SOC in the only individual study found for maize, but it did increase SOC in all studies that combined it with mineral fertilizer (Table 4.1). Compiling the nine individual studies, only mineral fertilization alone or a combination of the recommended dose of mineral fertilization with additional FYM (added min and FYM) increased SOC significantly compared to the control plots (Figure 4.1). Furthermore, the added min and FYM combination resulted in the highest SOC increase. Nevertheless, in the FYM treatments, N inputs into maize were lower than N inputs into millet (Vineela et al. 2008) despite the fact that maize required higher N doses. The lower N inputs into maize probably caused the lack of significance of this treatment (Figure 4.1). We additionally found a very strong positive correlation between the grain yields of finger millet and SOC concentrations (Figure 4.2).

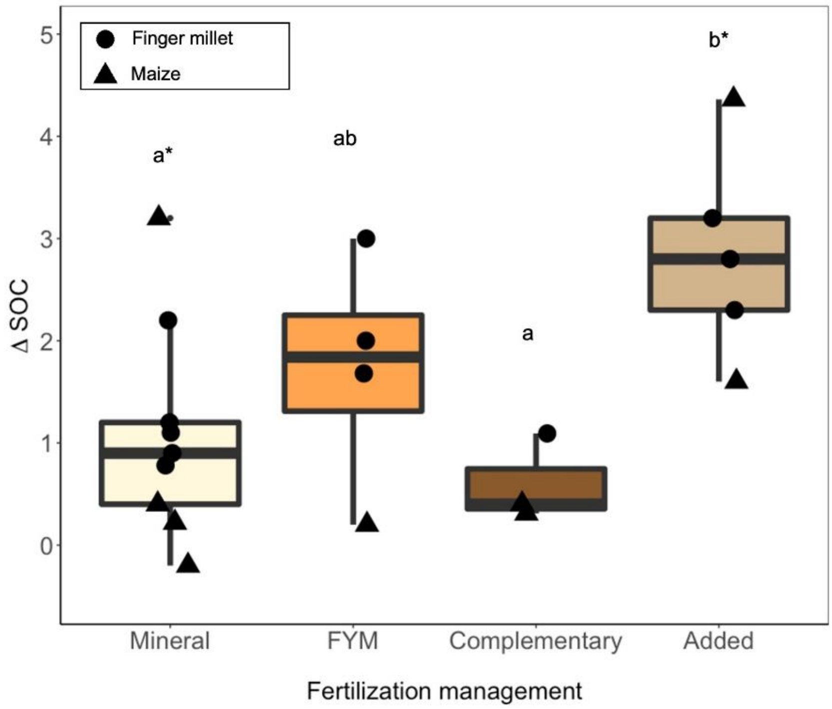

Figure 4.1 Increases in SOC (g kg^{-1}) relative to control soils (ΔSOC) from different fertilization treatments (min = mineral fertilization; FYM = farmyard manure; complementary = min and FYM added up to the total recommended N dose for the specific crop; added = combination of total recommended N mineral fertilization with additional FYM) in maize and finger millet cropping systems in India using data provided from the studies described in Table S4.2. Different letters represent significant differences between treatments after analyses of variance, and asterisks represent significant differences from zero after individual one-sample t tests ($p < 0.05$)

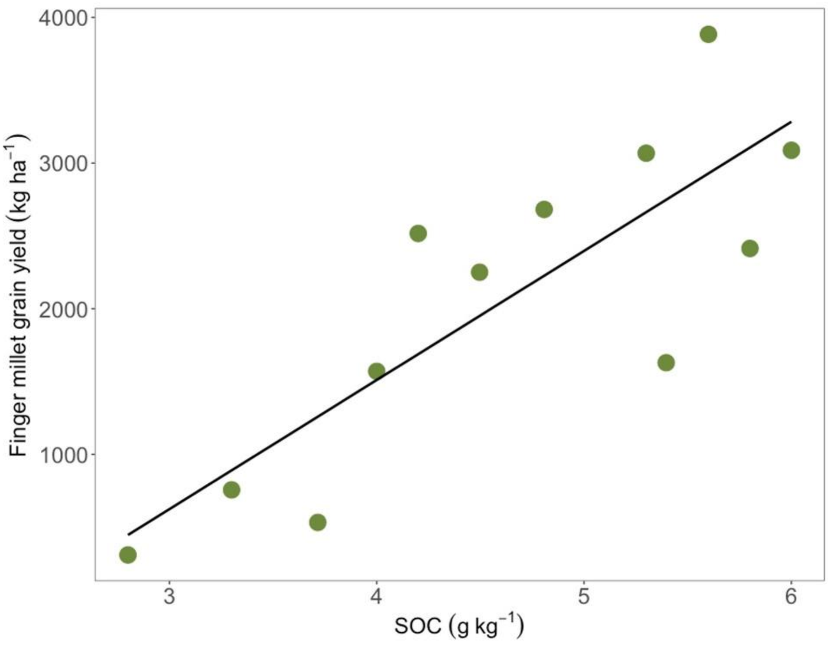

Figure 4.2 Relationships between finger millet grain yields and SOC concentrations (r = 0.82; $p < 0.001$) with data from different fertilization treatments, including controls. Data obtained from Sathish et al. (2016) and Prasad et al. (2016)

4.4.2. Management Practices in the Urbanizing Region of Bangalore

A large share of the interviewed farmers grew cereals (86%) and pulses (47%; Table 4.2). Fruits and vegetables were cultivated by 19% and 15% of the farmers, respectively, while 7% grew herbs/spices and 4% grew flowers. Fodder crops were cultivated by 15% of the farmers (note that fodder is defined here as the cultivation of Napier grass. Farmers may have also used crop residues from crops primarily grown for consumption, e.g., maize, that were classified here under another category, e.g., cereals). Moreover, 16% engaged in the cultivation of non-food commercial crops, such as eucalyptus and mulberry for silk production, while 2% of the farmers cultivated lawn/turf grass. A list of the crops that were included in the different crop categories is provided in Table S4.3.

In terms of irrigation, descriptive statistics suggested that lawn/turf grass and flowers were always irrigated (Figure 4.3). Vegetables, fodder, and fruits were also frequently irrigated. Almost 40% of non-food commercial crops were irrigated, while farmers irrigated only a small proportion of herbs and spices, cereals, and pulses. In our sample, 36.5% of the farmers used irrigation for at least one crop (Table 4.2).

Additionally, 37% of the farmers applied only mineral fertilizers on their farms, whereas 33% of them applied both mineral fertilizers and FYM (Table 4.4). Mineral and organic fertilizers were used by almost 20% of the farmers. The mineral fertilizers used by the farmers included, e.g., diammonium phosphate (DAP), gypsum, urea, and potassium chloride. The organic fertilizers included, e.g., compost, neem powder, neem oil, and vermicompost. We further differentiated between organic fertilizers and farmyard manure. A very small share of farmers (0.8%) applied exclusively farmyard manure. It should be noted that these observations were on the farm level and therefore only indicated whether the farmers used the respective fertilizers anywhere on their farms. Figure 4.4 suggests that the farmers did not necessarily apply the combinations of fertilizers to the same crop. For example, while some crops were fertilized with a combination of mineral fertilizer and FYM, no farmer applied both mineral and organic fertilizers to the same crop.

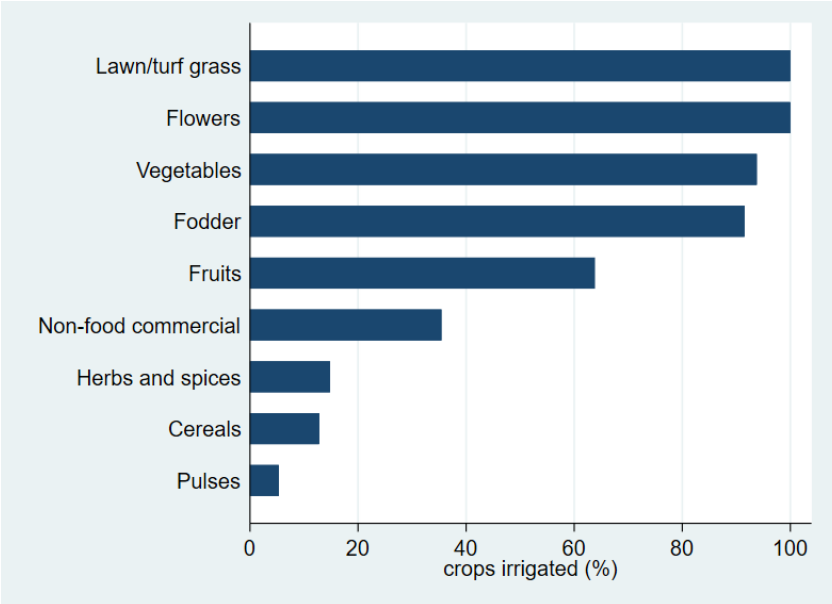

Figure 4.3 Percent of crops irrigated by crop category by farm households in the northern and southern transects of Bangalore ($N = 1091$; crop level).

Table 4.4 Fertilizer types used by farm households in the northern and southern transects of Bangalore ($N = 388$; household level).

	Mean	Std. dev.	Min	Max
Mineral	0.371	0.484	0	1
Mineral and FYM	0.330	0.471	0	1
Mineral and organic	0.196	0.397	0	1
Mineral, organic, and FYM	0.077	0.267	0	1
FYM	0.008	0.088	0	1

Notes: In all, 98% of the farmers in the sample used at least one type of fertilizer. All variables are dummy variables that are equal to 1 if the farmer used the respective (combination of) fertilizer in 2019 and 0 if not. The column 'mean' indicates the share of farmers in the sample who were adopters. 'Std. dev.' stands for standard deviation. 'Min' stands for minimum; 'max' stands for maximum.

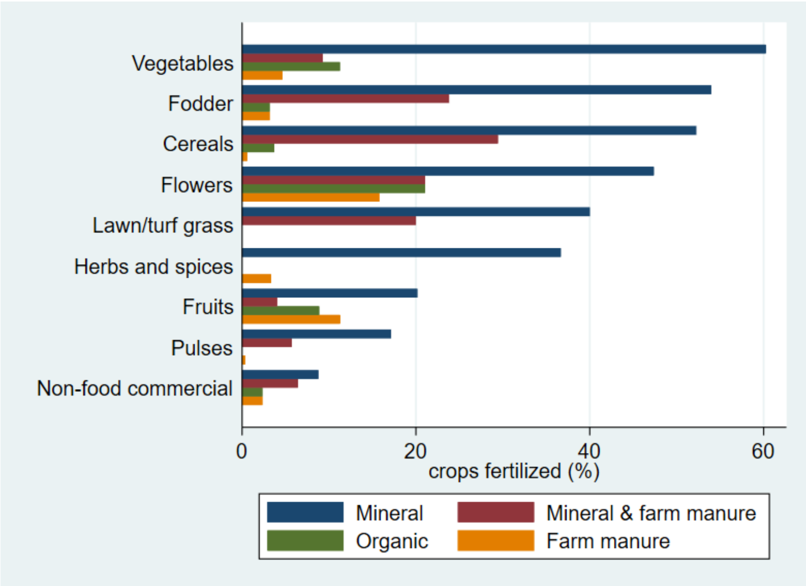

Figure 4.4 Percentage of crops fertilized by fertilizer type by crop category by farm households in the northern and southern transects of Bangalore (N = 1091; crop level).

4.4.3. Decision-Making in the Urbanizing Region of Bangalore

We next examined the household socio-economic and farm characteristics that were associated with farmers' choices of agricultural management practices that influence SOC. Table 4.5 shows the results of the probit models estimating the farmers' probabilities of adopting crops from the different crop categories. The category lawn/turf grass is omitted due to the small number of farmers who cultivated lawn/turf grass. The results indicate that an increase in the years of education that the main decision-maker had received was associated with an increase in the probability that a farmer would cultivate fruits but was negatively related to the cultivation of flowers. Belonging to a non-marginal caste was related to an increase in the likelihood that a farmer would cultivate non-food commercial crops by 16 percentage points, whereas it decreased this likelihood by 8 percentage points for the category herbs and spices. Farm size was positively associated with the adoption of cereals, vegetables, herbs and spices, and non-food commercial crops. Further, the results show that market integration, i.e., whether farmers sold any crop in the market, was correlated with a reduction in the likelihood that farmers would grow cereals, but it was associated with an increase in their probabilities of growing vegetables, fruits, flowers, herbs and spices, and non-food commercial crops. The ownership of a borewell, and thus having access to groundwater irrigation, was associated with farmers' crop choices in a similar way to market integration but was additionally positively related to growing fodder. Degree of urbanity, measured by using the rural–urban index (SSI), was not strongly associated with farmers' crop choices except for in the adoption of vegetables, which became less likely the more rural a farm household's location became.

The results for farmers' use of irrigation shown in Table 6 suggest that the farmers' probability of adopting irrigation is mainly related to the farms' characteristics. In terms of household characteristics, only an off-farm income was negatively associated with irrigation adoption. Dairy and livestock activities were related to increases in the probability that a farmer would irrigate any of his crops. Increasing farm size and market integration were significantly associated with an increase in the probability of irrigation adoption. A farmer who owned a borewell was 20 percentage points more likely to use irrigation than a farmer who did not own a borewell. Growing cereals, pulses, or herbs and spices was related to decreases in the farmers' probability of adopting irrigation, while the cultivation of fruits, vegetables, and fodder increased that likelihood. We now turn to the farmers' use of soil conservation methods that contribute to increasing SOC. Overall, 16% of the farm households in our sample adopted mulching, crop residues, or cover crops, while a larger share of farmers, i.e., 66%, used FYM (Table 2). Expectedly, the ownership of cows and other livestock was related to an increase in the farmers' probability of adopting FYM by 19 and 10 percentage points, respectively (Table 7). Having a female household head decreased the probability of applying FYM by 11 percentage points. Minimum/no tillage was practiced by 48% of the farm households. The results from the probit estimations suggest that decision-maker characteristics were correlated with adoption. A better education and the number of adults in the household were negatively correlated with the adoption of minimum tillage practices, suggesting that households with better educated household heads might have engaged in more intensive agriculture, although, conversely, we found a positive relationship between the number of durable assets owned, and thus wealth, and the adoption of minimum tillage.

Table 4.5 Association between the independent variables and farmers' crop choices in the northern and southern transects of Bangalore (N = 362; household level).

	Cereals	Pulses	Vegetables	Fruits	Flowers	Herbs and Spices	Non-Food Commercial	Fodder
Decision-Maker Characteristics								
Female (1 = yes)	−0.030 (0.044)	0.061 (0.066)	0.016 (0.043)	0.067 (0.046)		0.066 ** (0.028)	−0.057 (0.048)	−0.052 (0.047)
Age (years)	−0.001 (0.002)	0.001 (0.002)	−0.002 (0.001)	0.003 ** (0.002)	−0.000 (0.001)	0.001 (0.001)	−0.002 (0.002)	0.001 (0.001)
Education (years)	−0.003 (0.004)	−0.003 (0.006)	0.006 (0.004)	0.010 ** (0.004)	−0.005 ** (0.002)	−0.001 (0.003)	−0.006 (0.004)	−0.004 (0.004)
Household Characteristics								
Non-marginal caste (1 = yes)	−0.053 (0.048)	−0.059 (0.067)	−0.011 (0.041)	0.042 (0.047)	−0.030 (0.023)	−0.082 *** (0.028)	0.157 *** (0.060)	0.052(0.048)
No. of adults (HH members ≥ 15 years)	0.011 (0.011)	−0.014 (0.016)	−0.010 (0.010)	−0.019 * (0.010)	−0.002 (0.003)	0.000 (0.005)	0.000 (0.010)	−0.014 (0.009)
Durable assets owned (count)	0.002 (0.003)	0.005 (0.005)	0.002 (0.003)	0.008 *** (0.003)	0.003 * (0.001)	0.001 (0.002)	−0.002 (0.003)	0.002 (0.003)
Off-farm income (1 = yes)	−0.013 (0.034)	0.034 (0.055)	−0.031 (0.031)	−0.069 * (0.037)	−0.003 (0.017)	0.018 (0.027)	0.019 (0.035)	−0.025 (0.032)
Farm Characteristics								
Farm size (ha)	0.089 *** (0.034)	0.021 (0.021)	0.023 *** (0.009)	0.012 (0.012)	−0.005 (0.007)	0.019 ** (0.008)	0.025 * (0.014)	0.004 (0.012)

	Cereals	Pulses	Vegetables	Fruits	Flowers	Herbs and Spices	Non-Food Commercial	Fodder
Dairy (1 = yes)	−0.025 (0.041)	0.168 *** (0.057)	0.066 * (0.038)	0.017 (0.041)	−0.013 (0.023)	0.016 (0.027)	0.058 (0.044)	
Livestock (1 = yes)	0.036 (0.036)	0.070 (0.054)	0.004 (0.032)	0.001 (0.035)	0.008 (0.018)	0.014 (0.029)	0.036 (0.036)	0.071 ** (0.036)
Market integration (1 = yes)	−0.158 *** (0.036)	−0.064 (0.057)	0.199 *** (0.036)	0.128 *** (0.036)	0.101 *** (0.030)	0.051 * (0.027)	0.166 *** (0.037)	0.031 (0.038)
Owned borewell (1 = yes)	−0.151 *** (0.039)	−0.170 *** (0.066)	0.105 *** (0.034)	0.185 *** (0.036)	0.040 ** (0.020)	0.001 (0.030)	−0.002 (0.041)	0.148 *** (0.037)
Location								
Rural–urban index (SSI) [1]	0.002 (0.126)	−0.191 (0.187)	−0.244 ** (0.121)	0.051 (0.134)	0.030 (0.060)	−0.047 (0.084)	0.042 (0.128)	0.065 (0.153)
Northern transect (1 = yes)	0.087 ** (0.035)	0.106 ** (0.053)	−0.107 *** (0.032)	−0.147 *** (0.034)	0.075 *** (0.025)	−0.121 *** (0.030)	0.081 ** (0.036)	−0.181 *** (0.036)
N	362	362	362	362	362	362	362	362
Pseudo R^2	0.194	0.0652	0.351	0.313	0.338	0.232	0.174	0.215
Wald chi^2	54.61	27.58	86.61	83.47	47.57	42.05	60.85	50.26
Log pseudolikelihood	−120.0	−234.0	−98.95	−121.1	−41.33	−71.79	−131.6	−118.3

Note: Results of probit models. Average marginal effects reported with robust standard errors in parentheses; significance levels reported with * had a $p < 0.1$, ** had a $p < 0.05$, and had a $p < 0.01$. HH stands for household. For flowers, the variable female HH head perfectly predicted failure and was therefore dropped from the model. For fodder, cows perfectly predicted success and the variable was therefore dropped from the model. [1] The SSI takes a value between 0 and 1; 1 stands for most rural and 0 indicates most urban.

Table 4.6 Association between the independent variables and crop choice and farmers' use of irrigation in the northern and southern transects of Bangalore ($N = 362$; household level).

Decision-Maker Characteristics	
Female (1 = yes)	−0.046 (0.029)
Age (years)	−0.001 (0.001)
Education (years)	−0.004 (0.003)
Household Characteristics	
Non-marginal caste (1 = yes)	−0.051 (0.035)
No. of adults (HH members ≥ 15 years)	−0.004 (0.005)
Durable assets owned (count)	0.004 (0.002)
Off-farm income (1 = yes)	−0.080 *** (0.027)
Farm Characteristics	
Farm size (ha)	0.027 ** (0.011)
Dairy (1 = yes)	0.130 *** (0.031)
Livestock (1 = yes)	0.059 ** (0.026)
Market integration (1 = yes)	0.119 *** (0.027)
Owned borewell (1 = yes)	0.203 *** (0.035)
Cereals (1 = yes)	−0.154 *** (0.039)
Pulses (1 = yes)	−0.101 *** (0.026)
Fruit (1 = yes)	0.053 * (0.027)
Vegetables (1 = yes)	0.114 *** (0.036)
Herbs and spices (1 = yes)	−0.126 *** (0.049)
Non-food commercial (1 = yes)	0.010 (0.032)
Fodder (1 = yes)	0.151 *** (0.045)
Location	
Rural–urban index (SSI) [1]	−0.054 (0.082)
Northern transect (1 = yes)	−0.126 *** (0.030)
N	362
Pseudo R^2	0.755
Wald chi^2	103.0
Log pseudolikelihood	−58.19

Note: Result of probit model. Average marginal effects reported with robust standard errors in parentheses; significance levels reported with * had a $p < 0.1$, ** had a $p < 0.05$, and *** had a $p < 0.01$. HH stands for household. Growing flowers predicted success perfectly, and therefore, the variable was dropped from the model. [1] The SSI takes a value between 0 and 1; 1 stands for most rural and 0 indicates most urban.

Table 4.7 Association between the independent variables and farmers' crop choices and adoption of soil conservation practices in the northern and southern transects of Bangalore (N = 362; household level).

	Mulching/Crop Residues/Cover Crops	Farmyard Manure	Minimum/No Tillage
Decision-Maker Characteristics			
Female (1 = yes)	−0.014 (0.047)	−0.113 ** (0.057)	−0.047 (0.066)
Age (years)	−0.004 ** (0.002)	−0.002 (0.002)	0.001 (0.002)
Education (years)	−0.003 (0.005)	−0.007 (0.006)	−0.012 ** (0.006)
Household Characteristics			
Non-marginal caste (1 = yes)	−0.026 (0.047)	0.045 (0.060)	−0.107 (0.066)
No. of adults (HH members ≥ 15 years)	−0.004 (0.012)	−0.009 (0.013)	−0.033 ** (0.016)
Durable assets owned (count)	−0.002 (0.003)	0.004 (0.004)	0.020 *** (0.005)
Off-farm income (1 = yes)	0.092 ** (0.037)	0.054 (0.049)	0.039 (0.054)
Farm Characteristics			
Farm size (ha)	0.017 (0.010)	−0.016 (0.022)	0.035 * (0.021)
Dairy (1 = yes)	−0.006 (0.042)	0.192 *** (0.048)	0.057 (0.059)
Livestock (1 = yes)	0.032 (0.035)	0.099 ** (0.050)	0.044 (0.055)
Market integration (1 = yes)	0.135 *** (0.044)	0.017 (0.058)	−0.020 (0.062)
Owned borewell (1 = yes)	0.064 (0.043)	0.075 (0.070)	0.118 (0.073)
Cereals (1 = yes)	0.043 (0.057)	0.203 *** (0.079)	0.086 (0.083)
Pulses (1 = yes)	0.142 *** (0.035)	0.027 (0.049)	−0.093 * (0.053)
Vegetables (1 = yes)	0.084 * (0.049)	0.144 * (0.082)	−0.086 (0.085)
Fruit (1 = yes)	0.106 ** (0.045)	0.099 (0.076)	0.071 (0.074)
Flowers (1 = yes)		0.011 (0.151)	0.014 (0.136)
Herbs and spices (1 = yes)	−0.134 * (0.077)	0.078 (0.092)	−0.129 (0.106)
Non-food commercial (1 = yes)	0.046 (0.046)	0.112 (0.071)	−0.111 (0.073)
Fodder (1 = yes)	−0.080 (0.057)	0.123 (0.084)	−0.123 (0.084)
Location			
Rural–urban index (SSI) [1]	0.162 (0.121)	−0.055 (0.165)	0.387 ** (0.175)
Northern transect (1 = yes)	0.014 (0.038)	0.090 * (0.055)	0.060 (0.059)
N	362	362	362
Pseudo R^2	0.214	0.158	0.0939
Wald-chi^2	69.35	70.07	47.38
Log pseudolikelihood	−125.2	−195.3	−227.2

Note: Results of probit models. Average marginal effects reported with robust standard errors in parentheses; significance levels reported with * had a $p < 0.1$, ** had a $p < 0.05$, and *** had a $p < 0.01$. HH stands for household. Growing flowers predicted failure of using mulching perfectly; therefore, the variable was dropped from the model. [1] The SSI takes a value between 0 and 1; 1 stands for most rural and 0 indicates most urban.

For a more differentiated insight into the associations between crop choice and the adoption of soil conservation practices, we estimated probit models with crop choice and soil conservation practice observations on the plot level (Table S4.4). The results corresponded to the household-level analysis and suggest that the plots on which cereals and pulses were grown had higher likelihoods of being mulched, while cultivating cereals also increased the likelihood of farmers applying minimum tillage on the same plot. Plots on which vegetables or fruit were grown had higher probabilities that farmers would apply mulching practices, while the relationship was negative when farmers cultivated herbs and spices. On the household level, the degree of urbanity seemed to matter for only the adoption of minimum tillage practices to the extent that farmers who were located in less urbanized areas were more likely to use minimum tillage. The plot-level results similarly suggest a positive relationship between rurality and the adoption of mulching practices (Table S4.4).

4.5 Discussion

4.5.1. Crop Choice

The adoption of vegetables is more likely when urbanity increases and when farmers are integrated into markets, which suggests that being located in more urbanized areas provides farmers with marketing opportunities for vegetable crops, as shown in Patil et al. (2019). Compared with rural areas, farmers located closer to the city might cultivate high-value crops without reserving some land for subsistence purposes (Bon et al. 2010). Furthermore, farmers with higher socio-economic statuses are often more specialized and commercialized in their production (Pingali 2007). However, the SSI did not further explain the probability of crop choice. Yet, market integration highly affects preferences for crop choice. On the household level, the probability of growing vegetables, fruits, flowers, and herbs and spices increases in the vicinity of markets, whereas the probability of cultivating cereals decreases. This demonstrates the great importance of local markets for selling high-value crops in Bangalore. Furthermore, the cultivation of pulses, fruits, and vegetables increases the probability of mulching, and growing vegetables and cereals increases the likelihood that FYM is applied. Hence, most of the crop categories are related to some type of soil conservation practice, except for flowers, fodder, and non-food commercial crops. The negative correlation of herbs and spices with mulching may be compensated by using a rotation with other crops that are mulched. Furthermore, the possible negative effect on SOC of these two crop categories may be minor because of the low percentage of farmers growing flowers and herbs and spices. Therefore, the diversification of crop choice is the most relevant practice for SOC sequestration in the tropics (Fujisaki et al. 2018) .

4.5.2. Irrigation

Growing high-value crops, such as vegetables and fruits that are often sold in markets, is positively associated with irrigation adoption, while irrigation becomes less likely when farmers grow staple crops, in line with research by Patil et al. (2019). This suggests that irrigation might be a requirement for growing certain high-value crops but might also imply that farmers invest more in crops with higher monetary returns. The negative association between off-farm income and irrigation may be related to the proposed idea of increasing the opportunity cost of agricultural investments when other income options are available (Steinhübel and von Cramon-Taubadel 2021). Based on our literature review, this would imply that off-farm income activities that prevent farmers from having irrigated systems also prevent potential increases in SOC stocks from more productive irrigated systems. This may be true for the majority of crops in which irrigation increases the production of aboveground and belowground biomass inputs (Sojka et al. 2007) and thus SOC (Paustian et al. 2016), except for turf as its harvest removes all biomass, including roots, with an additional removal of mineral soil, including soil organic matter. The positive association between cattle (dairy) and irrigation is probably related to a greater involvement of cattle owners in farm activities and to a higher necessity of adopting such irrigation practices due to the household's reliance on agriculture and cattle for their livelihood. Napier grass, produced for fodder, is usually irrigated, probably increasing SOC, although not all dairy farms produce fodder.

Overall, 57% of the households irrigating at least a share of the crops owned borewells, whereas households that did not own borewells might resort to other water sources, such as surface water. Sewage irrigation is a common practice in Indian agriculture close to or in cities, but its effects on SOC and nutrient cycling may vary depending on the contents of organic matter and pollutants. For example, in rice–wheat systems in India, sewage irrigation has increased SOC in the long-term (Masto et al. 2009). Furthermore, beside the effects on water quality and irrigated crop type, the irrigation technique may cause soil erosion and thus SOC depletion (Sojka et al. 2007; Koluvek et al. 1993; Fernandez-Gomez et al. 2004). As one third of the fields in India are irrigated (Lal 2004), this management effect on SOC should be analyzed in future studies.

4.5.3. Mineral Fertilizer and FYM

In our survey, 98% of the farm households used some type of fertilizer and mostly both mineral and FYM or organic fertilizers on their farms. We found that all but 0.8% of the farmers who used fertilizer used mineral fertilizer on their farms, which corresponded to findings by Bon et al. (2010). This widespread adoption of fertilizers might be facilitated by several 'enabling conditions' associated with urbanization that spill over to the more rural hinterlands of cities (de Bruin et al. 2021). In our sample, the average SSI takes a value of 0.71 (Table 4.3), which implies that the majority of farmers lived in the more rural hinterlands of the study area rather than in the urban neighborhoods at the fringe of the city. However, since the maximum distance of villages to Bangalore was only 50 km in our sample compared to farmers living in very remote rural areas, the farmers in our sample might have had relatively easy access to farm inputs, such as fertilizers. This could be facilitated by the relative proximity to Bangalore and related access to road, transportation, and market infrastructures. Information and knowledge exchanges (e.g., extension services and mobile phones), as well as other institutional conditions might also enable adoption (de Bruin et al. 2021). Besides proximity to the city of Bangalore, several secondary towns along the two study transects (see the map in Supplementary figure S4.1) might provide access to farm inputs and agricultural markets where farmers could also sell their crops (de Bruin et al. 2021). Our results thus differ from studies focusing on tropical low-input small-holder farmers that had less access to mineral fertilizer (Thilakarathna et al. 2015; Agegnehu et al. 2017; Chianu et al. 2012). Therefore, the accessibility of mineral fertilizer is not restricted in the households of Bangalore. However, for an analysis on fertilizer's effects on SOC and the environment, data on the amounts applied to specific crops would be necessary.

A large percentage of farm households (70%) in Bangalore rear their own cows and therefore have access to FYM. A cattle-ranching culture is reflected in the relatively large number of studies that include FYM as a commonly used fertilizer in India. However, it is important to note that even though the percentage of dairy cow owners is high, less than half of the owners use FYM in combination with mineral fertilizer, and very few apply FYM alone. This suggests that many farmers use the manure produced by their cows for purposes other than their own crop's cultivation.

Given the significantly positive effect of FYM on SOC stocks in Indian soils revealed in the literature review, it is necessary to address the gender factor in this practice as we observed that households with female household heads were less likely to implement it in agriculture. Female education and awareness raising in terms of agricultural practices is therefore required to improve SOC on farms managed by women.

4.5.4. Mulching and Minimum Tillage

Mulching was positively associated with farmers who grew both staple crops (cereals and pulses) as well as high-value crops (vegetables and fruits), which was shown in research by Gupta et al. (2021). This probably indicates that some of these crops generate more residues that can be used as mulch, e.g., from tree pruning. Furthermore, farmers who do not use plant residues for purposes such as feeding may be more likely to adopt mulching. However, the probability that farmers will adopt mulching increases with rurality (plot level) even though it is positively related to vegetable cultivation, which is more likely in more urbanized areas (household level), as shown by the negative correlation between the SSI and the likelihood of vegetable adoption (Table 4.5). Possibly, one reason that farmers' probabilities of mulching increase with rurality is that farmers in more rural areas have bigger farms where they grow crops (e.g., staple crops) that also provide crop residues.

An interesting observation in our study was that education and a higher number of adult household members played negative roles in the likelihood of implementing minimum or no tillage. Although minimum or no tillage is considered an effective conservation practice in terms of SOC accumulation, such practices might be linked to lower yields (Sharma et al. 2009; Neogi et al. 2014). A higher number of adult household members might imply that more family labor is available to implement tillage on the farm and therefore decrease the likelihood of implementing minimum/no tillage if it might also lead to lower yields. Nevertheless, the probability of implementing this practice was strongly correlated with the durable assets owned by the households, which might indicate that better-off households can afford to implement this conservation practice even at the expense of potentially higher yields.

Our findings indicate a positive correlation between farm size and the likelihood of adopting minimum tillage as well as a positive relationship between a more rural location and the probability of minimum tillage use. These findings likely interact as farm size is positively correlated with rurality (the Pearson's correlation coefficient was 0.147, which suggests a significant positive correlation between farm size and the SSI ($p = 0.005$)). Thus, minimum or no tillage is more likely to be used on bigger farms in more rural locations. In other words, our findings might suggest that smaller farms that are located closer to the urban center are managed more intensively with a lower probability of minimum tillage and mulching on the plot level.

4.5.5. Limitations and Necessary Research

The survey data indicate the wide usage of fertilizer in the agricultural systems of Bangalore, and our analysis on fertilization practices from published studies in India shows their potential to increase SOC. However, the lack of quantitative data on fertilizer application rates and crop yields limits the explanatory power of the survey data on SOC dynamics. Mulching is associated with decisions in favor of vegetable–fruit and cereal staple crops, both groups contrastingly related to market integration. This demonstrates interactions between crop choice, probability of the adoption of soil conservation practices, and socio-economic variables. Data on the adoption of soil conservation practices for specific crops would be necessary to disentangle the interactions.

The rural–urban index used for this analysis measured urbanization as a combination of distance to the Bangalore city center and the percentage of built-up area (Hoffmann et al. 2017). However, even when not living in direct proximity to the city of Bangalore with large built-up areas, road infrastructures and transportation networks as well as household wealth and ownership of vehicles may determine farmers' access to markets and, in turn, their decisions to cultivate certain (perishable) crops, e.g., vegetables. For example, Damania et al. (2017) and Minten et al. (2013) found that increasing transaction costs and higher costs of transportation are important factors influencing farmers' technology choices and farming practices in Nigeria and Ethiopia. Vandercasteelen et al. (2021) measured urban proximity as travel time and found that an increased travel time affects the decision-making and productivities of rural dairy farmers who produce for urban markets. Such alternative indicators for urbanization were not considered in our study but were partly addressed by the factor market integration, which showed a good explanatory power for crop choice.

4.6. Conclusions

The present paper showed important relationships between socio-economic variables, crop choice, and the likelihood of adopting soil conservation practices that contribute to improvements in the SOC pools in Bangalore´s agricultural soils. The cropping of vegetables is increasingly correlated with urbanity, higher market integration, off-farm income, and the ownership of borewells and goes along with intensive management, e.g., the application of mineral fertilizer and irrigation, while increasing the probability of farmers adopting conservation practices, such as mulching and the application of farmyard manure. The cultivation of cereals is negatively associated with market integration and irrigation but positively associated with all measures of soil conservation practices, although it is not associated with rurality. Our results therefore confirmed Hypotheses 1 and 2 but rejected Hypothesis 3. Considering that 66, 48, and 16% of farms adopt farmyard manure applications, minimum tillage, and mulching, respectively, there is further potential to increase these conservation practices in rural–urban Bangalore. Further implementations of conservation practices will depend on the availability of resources, experience with climatic shocks, and alternative income opportunities. Our data reveal that the role of gender, age, and education in farm households should be addressed in the interest of achieving an increased application of soil conservation practices. We show that, in general, regardless of the degree of urbanity, the socio-economic advantages of farmers in Bangalore generally translate into a higher likelihood of improved management practices that will support SOC. Hence, improved farmers' welfare is a prerequisite for an increased implementation of sustainable agriculture, thus increasing the currently depleted SOC levels in Bangalore.

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Informed Consent Statement: Written informed consent was obtained from all farmers involved in the study.

Data Availability Statement: The authors can make the interview data available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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5 General Conclusions

The sensitivity of microbial communities to changes in crop choice, fertilization or soil properties was reduced while SOC levels were increased in the more homogeneous irrigated Nitisol-field. Yet, Bangalore's microbial communities are characterized by a persistent C limitation even under irrigated conditions. Chapter two and three of this study provide evidence that lower SOC concentrations in the rainfed Acrisol are not due to lower microbial efficiency. Instead, lower plant inputs to the soil are responsible for the lower SOC levels. While chapter four shows a positive relationship between higher crop yields and SOC levels and, a low implementation of SOC-related conservation practices. Thus, this study reflects the necessity of improving poor residue-management strategies in Bangalore's fields where above-ground plant residues are usually exported from the fields.

In this situation, crop type plays an important role. Larger yields and larger amount of removed biomass from the fields imply larger nutrient exports and larger nutrient deficiencies. On the other hand, larger root to shoot ratios and belowground biomass production contributes to increase SOC.

Acidic conditions do not increase the metabolic demand of the addressed microbial communities of Bangalore. In fact, this research revealed that when microbial residues are considered, more SOC may be sequestered under low-pH constrains, due to limited decomposition of litter and SOC. This finding creates a paradox for Bangalore´s soils where there is a compromise between soil fertility improvements and potentially reduced SOC sequestration capacity/efficiency under improved pH conditions through liming. However, according to the role of decomposer fungi, this group may have the potential to balance the trade-off between improved pH and CUE in favor of more fertile, SOC-richer soils in the longer term. This can happen due to expected increases in fungal biomass under favored conditions, because such fungal-biomass increase would increase CUE via incorporation of fresh plant inputs into newly formed microbial biomass.

Even when there was no evident effect of increased N-fertilization on microbial functions after two years of treatment, this research shows that in the longer term, N fertilization contributes to increase SOC levels, and, that these effects can be greater when N fertilization is a combination of both mineral N and farmyard manure. The effect of water management is entangled in other effects such as crop type, liming, and other practices like livestock raising.

The link between agricultural intensification and improved soil-microbial functions does not go straightforward for Bangalore's soils. It is characterized by interactions between crop choice, management- and conservation practices. At the same time these interactions are influenced by socio-economic variables, many of which are affected by urbanization. For example, cultivation of vegetables, although more intensively managed and associated to urbanization variables, is associated to the implementation of mulching and FYM application as well.

In other words, regardless of the degree of urbanity, the socio-economic advantages of farmers in Bangalore generally translate into a higher likelihood of improved management practices that will support SOC. Currently, this is mainly attributed to intensified commercial crops, because besides irrigation and fertilization, additional beneficial practices such as mulching are applied to those crops. However, traditional crops such as cereals and pulses have the potential to improve SOC stocks if conservation practices and, especially, an improved management of crop residues are applied more extensively to these crops. Furthermore, this study adds up to the body of evidence that shows the importance of market integration for selling high-value crops in urbanizing regions.

Additionally, crop diversification is necessary to improve SOC dynamics, because different crops are associated to different degree of intensification, conservation practices and intrinsic beneficial traits (e.g., root/shoot ratio, litter quality).

It is encouraged for future studies to evaluate regional effects of specific management practices other than N-fertilization on SOC dynamics. In addition to the approaches taken in this study, ideally, the evaluation should include direct measurements of SOC levels and C inputs across the farms to directly associate them to plot-management practices and compare them between crops and crop rotations. Furthermore, studies that evaluate the effects of irrigation practices in croplands are needed to understand how this affects microbial communities and SOC dynamics. At last, additional information about C turnover (including turnover of microbial residues) from medium- and long-term studies is still required.

6 Supplementary material

6.1 Supplementary material Chapter 3

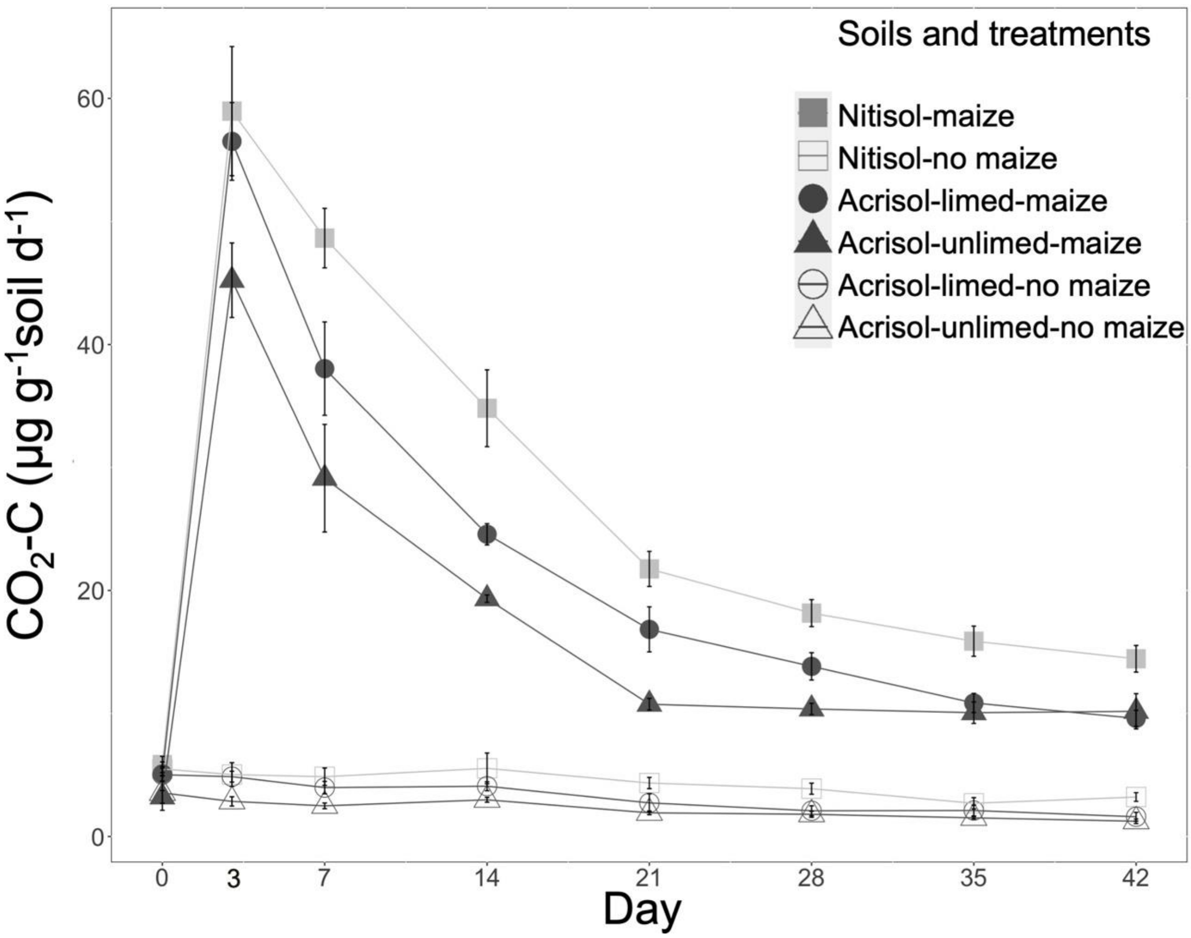

Figure S3.1 Respiration rate along six weeks on a weekly interval, except for the first week in which it was measured after day 3 and day 7, for the unlimed Nitisol and limed and unlimed treatments of the Acrisol amended with maize litter and for all their corresponding controls (without litter amendment). Solid symbols indicate treatments with litter addition and empty symbols, those without litter (controls). Different symbols indicate different soils and lime treatments

6.2 Supplementary material Chapter 4

Table S4.1 Tillage practices implemented in agricultural field studies across India and the effects on SOC concentrations in different cropping systems under rainfed and irrigated agriculture.

Cropping System	Irrigation	Conventional Tillage (CT)	Reduced Tillage (RT)	No Tillage (NT)	Significant Effects on SOC for Treatments	Reference
Rice–barley Rainy season and beginning dry season	Rainfed	X	X	X	Aboveground harvest residues withdrawn: RT > NT > CT; aboveground harvest residues retained: RT > CT > NT	(Kushwaha et al. 2001)
Soybean–pigeon pea; soybean–wheat; maize–pigeon pea; maize–gram Dry and rainy seasons	Rainfed	X	X	X	RT > NT > CT	(Kumar et al. 2018)
Maize–okra Rainy season and beginning dry season	Rainfed	X	X	X	NT + weed mulching > RT + weed burial > CT + weed removal	(Pandey et al. 2010)
Sorghum–mung Bean (one every year) Rainy season	Rainfed	X	X	-	No tillage effect	(Sharma et al. 2009)
Soybean wheat Dry and rainy seasons	Partially irrigated	X	X	X	NT > RT > CT	(Kushwa et al. 2016)
Maize–wheat–green gram Dry and rainy seasons	Irrigated	X	-	X	In macro- and micro-aggregates NT > CT	(Modak et al. 2020)

Maize–maize–field pea Dry and rainy seasons	Partially irrigated	X	-	X	NT > CT	(Yadav et al. 2021)
Rice–maize–cowpea Dry and rainy seasons	Irrigated	X	X	-	RT > CT	(Neogi et al. 2014)
Rice–Rice Dry and rainy seasons	Irrigated	X	X	X	RT > NT > CT	(Yadav et al. 2017)
Soybean–wheat Dry and rainy seasons	Not applied	-	X	X	Depth 0–5: NT > RT; Depth 5–15: RT > NT	(Lenka et al. 2015)

X = included tillage treatment; and - = not included in the study.

Table S4.2 Fertilization practices, crop types, soils, environmental factors, locations, and study periods of the individual studies analyzed.

No.	Compared Fertilization Practices	Main Crop	Number of Crops in a Rotation	Initial SOC (g kg^{-1})	Clay (%)	pH	Annual Rainfall (mm)	Location (India)	Duration (Years)	Reference
1	Min; added min and FYM	F. millet	3	N/A	31	8.5	N/A	Coimbatore	29	(Vineela et al. 2008)
2	Min; FYM; added min and FYM	F. millet	1	3.3	N/A	5	666	Bangalore	20	(Sathish et al. 2016)
3	Min; FYM; added min and FYM	F. millet	2	3.3	N/A	5	666	Bangalore	20	(Sathish et al. 2016)
4	Min; FYM; complementary min and FYM	F. millet	3	4	N/A	5.2	922.7	Bangalore	10	(Prasad et al. 2016)
5	Min	F. millet	3	5.5	N/A	N/A	N/A	Bangalore	10	(Manna et al. 2003)
6	Min; FYM; added min and FYM	Maize	2	N/A	60	9	N/A	Bellary	23	(Vineela et al. 2008)
7	Min; added min and FYM	Maize	2	4.4	14	8.3	650	New Dehli	44	(Ghosh et al. 2018)
8	Min; complementary min and FYM	Maize	2	4	25	7.7	650	New Dehli	4	(Verma et al. 2010)
9	Min; complementary min and FYM	Maize	2	4.2	N/A	7.5	658	Rajasthan	6	(Srinivasarao et al. 2019)

Min = mineral fertilization; FYM = farmyard manure; complementary min and FYM = mineral fertilization and FYM added up to the total recommended N dose for the specific crop; and added min and FYM = combination of total recommended N mineral fertilization with additional FYM.

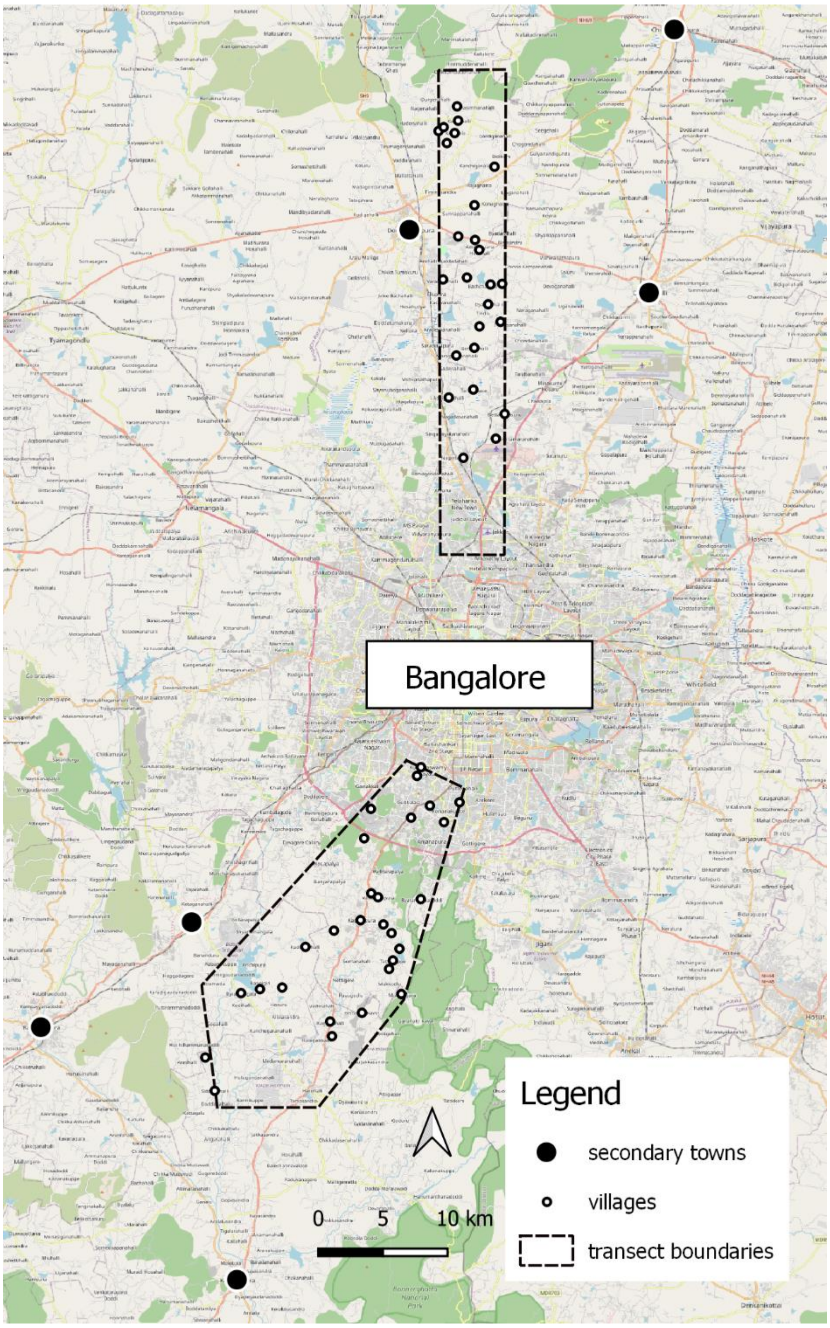

Figure S4.1. Map of the study transects used for the farmers' household interviews. Source: Own illustration based on survey data.

Table S4.3 Crops contained in crop categories used for the analysis of socio-economic survey data from farmers in the northern and southern transects of Bangalore.

Category	**Crop**
Cereals	Jowar/sorghum/jola
	Maize
	Paddy/rice
	Ragi/finger millet
	Small millet
	Wheat
Pulses	Avare/lablab
	Bengal gram/chickpea
	Black gram
	Cluster beans
	Cowpea/alasunde
	Green gram/mung bean/masur/tharguni
	Ground nut/peanut
	Horse gram/hulli kalu/hurali/urali kal
	Masoor
	Tur/ahar/red gram/pigeon pea/cajanus cajan/togari
	Velvet bean
Vegetables	Amaranth, amaranthus
	Beans/field bean
	Beet root
	Bitter gourd/haagalakaayi
	Brinjal/eggplant
	Cabbage
	Capsicum
	Carrot
	Cauliflower
	Chikidikaayi/bean/vine
	Chilli, green chilli
	Cucumber
	Dantu (leafy vegetable)
	Drumstick/moringa

	Garlic
	Harave soppu (leafy vegetable)
	Ivy gourd/thondekayi
	Ladiesfinger/okra
	Maize (sweet/baby corn)
	Onion
	Potato/allu/aloo
	Pumpkin
	Raddish
	Ridge gourd/hire gida hee/irekai/heere kayi
	Sabbbakki/dillseed (leafy vegetable)
	Snake gourd
	Soregida/bottle gourd
	Spinach/palak
	Tomato
	Turnip
Fruits	Arecanut
	Banana
	Coconut
	Grapes
	Guava
	Jackfruit/halasina
	Lemon/citrus
	Mango
	Papaya
	Pomegranate
	Sapota
Herbs and spices	Basil, basil leaves
	Castor
	Coriander
	Curry leaf/curry leaves
	Dill
	Fenugreek/menthya
	Ginger

	Huchellu/nitella
	Mustard
	Niger seed
	Sesamum
Flowers	Batha flower
	Button flower
	Chanduvva flower/marigold
	Chrysanthemum
	Crossandra flower
	Flower general
	Gladiolus
	Gerbera
	Jasmine
	Kakada flower
	Rose
	Sunflower
Fodder	Napier grass
Non-food commercial	Acacia
	Eucalyptus/nilagiri tree
	Forest/timber
	Mulberry
	Ornamental plants
	Palm
	Silk
	Silver oak
	Teak
	Sugar cane
Lawn/turf grass	

Table S4.4 Association between independent variables, crop choices, and farmers' adoption of soil conservation practices in the northern and southern transects of Bangalore ; $N = 558$; plot-level).

	Mulching/Crop Residues/Cover Crops	Farmyard Manure	Minimum/No Tillage
Decision-Maker Characteristics			
Female (1 = yes)	−0.044 (0.037)	−0.045 (0.051)	−0.087 * (0.053)
Age (years)	−0.005 *** (0.001)	−0.002 (0.002)	0.001 (0.002)
Education (years)	−0.004 (0.004)	−0.007 (0.005)	−0.012 ** (0.005)
Household Characteristics			
Non-marginal caste (1 = yes)	−0.031 (0.037)	0.062 (0.053)	−0.113 ** (0.056)
No. of adults (HH members ≥ 15 years)	0.006 (0.006)	0.009 (0.008)	−0.015 (0.010)
Durable assets owned (count)	−0.001 (0.002)	0.002 (0.003)	0.016 *** (0.003)
Off-farm income (1 = yes)	0.046 * (0.028)	−0.005 (0.041)	0.046 (0.042)
Dairy (1 = yes)	−0.045 (0.032)	0.185 *** (0.044)	0.012 (0.050)
Livestock (1 = yes)	0.045 (0.028)	0.138 *** (0.041)	−0.057 (0.043)
Owned borewell (1 = yes)	0.107 *** (0.033)	−0.026 (0.048)	0.070 (0.050)
Location			
Rural–urban index (SSI) [1]	0.215 ** (0.093)	−0.092 (0.131)	0.331 ** (0.136)
Northern transect (1 = yes)	0.008 (0.030)	0.050 (0.045)	0.129 *** (0.045)
Plot Characteristics			
Plot size (ha)	0.003 (0.011)	−0.042 * (0.026)	0.041 (0.025)
Marketing crop from plot (1 = yes)	0.129 *** (0.036)	0.061 (0.051)	0.046 (0.052)
Cereals plot (1 = yes)	0.114 *** (0.037)	0.107 * (0.058)	0.322 *** (0.056)
Pulses plot (1 = yes)	0.130 *** (0.029)	0.018 (0.045)	0.008 (0.047)
Vegetable plot (1 = yes)	0.077 * (0.042)	0.110 (0.076)	0.111 (0.075)
Fruit plot (1 = yes)	0.114 *** (0.039)	0.097 (0.068)	0.072 (0.064)
Flower plot (1 = yes)	−0.128 (0.106)	−0.024 (0.131)	0.089 (0.133)
Herbs and spices plot (1 = yes)	−0.171 ** (0.083)	0.035 (0.089)	−0.033 (0.101)
Non-food commercial plot (1 = yes)	−0.017 (0.052)	−0.041 (0.073)	0.038 (0.076)
Fodder plot (1 = yes)	−0.073 (0.058)	0.124 (0.079)	0.054 (0.076)
N	558	558	558
Pseudo R^2	0.197	0.0889	0.102
Wald chi^2	70.32	58.39	72.04
Log pseudolikelihood	−176.9	−326.6	−341.4

Note: Results of probit models. Average marginal effects reported with robust standard errors in parentheses. Significance levels reported with * ($p < 0.1$), ** ($p < 0.05$), and *** ($p < 0.01$). HH stands for household. [1] The SSI takes a value between 0 and 1; 1 stands for most rural and 0 indicates most urban.

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