

NUTRIENT CYCLING ON SMALLHOLDER FARMS IN UGANDA AND MALAWI

By

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Crop and Soil Sciences – Doctor of Philosophy

2021

ABSTRACT

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Sustaining and enhancing soil organic carbon (SOC) and nitrogen (N) is critical to crop health and productivity, particularly in the low-input, resource-limited smallholder agriculture widely found across sub-Saharan Africa (SSA). In the managed environment of the agroecosystem, farmer practices directly shape soil processes. Farmer surveys and soil and agronomic analyses conducted in Uganda and Malawi detail and elucidate farmer practices and their impacts on SOC and N cycling and overall soil health.

In western Uganda, use of fertilizer and external inputs is extremely low, and legume crops like groundnut provide the main source of N input into soil, making management of legume residues key to soil N and C gains. A partial N-balance of groundnut fields constructed from collected field and soils data, farmer responses, and values from the literature, found that groundnut residues retained on fields could potentially contribute substantial N inputs, but that burning and removal of groundnut residues in approximately half of the surveyed fields conferred minimal N contributions. Chi-square analysis revealed a relationship between farmer perception and valuation of groundnut residues and residue management practices. A comparison to the uncultivated soils of adjacent Kibale National Park showed that SOC and total N were lower in groundnut field soils and that groundnut residue management practices did not have an observed effect. Within the same region in western Uganda, detailed

agronomic surveys and soil sampling were conducted to quantify and map the flow of organic resources and measure SOC and N within 19 case study farms. Home banana plantations located directly next to homesteads received the majority of organic inputs and had positive N balances, while fields further away received few inputs and had negative N balances, even when cropped to legumes. Despite receiving more inputs, home banana plantations did not have higher SOC and N, and there was no evidence of a management gradient related to field distance from the homestead. Farms with greater resource endowments had more organic resources, but did not fully utilize available resources or have soils with higher SOC or N compared to farms with less resources, highlighting the heterogeneity of soils across the landscape, as well as the importance of other factors, such as timing of planting and harvesting, labor availability, and seed quality.

As in Uganda, smallholder farmers in Malawi intercrop and rotate with legumes. On-farm, participatory trials established in three agroecological zones in Central Malawi in 2012 provided the opportunity to evaluate impacts of crop diversification on SOC pools within a “doubled-up” legume rotation system compared to simplified systems. After six years of trial establishment, SOC was measured in bulk soils, aggregate fractions and in faster cycling C pools that respond more rapidly to management practices. The groundnut and pigeonpea DLR system accumulated more SOC than sole pigeonpea or sole groundnut in rotation with maize, and all legume systems acquired more SOC than continuous maize. Cropping treatment differences were not seen in bulk SOC or total N, but differences were apparent in SOC pools characterized by a shorter turnover time. Readily decomposable and biologically active SOC pools are shown to be early indicators of SOC dynamics and the effects of crop rotation and diversification.

This dissertation is dedicated to Parks Marion, my wonderful partner, and Xenia Witcombe-Marion, my amazing kiddo.

ACKNOWLEDGEMENTS

I would like to thank all my committee members for their invaluable support throughout my studies. Thank you to my advisor, Dr. Lisa Tiemann, for providing this opportunity and for your continuous guidance and support. Thank you to Dr. Sieglinde Snapp for the opportunity to collaborate and work in Malawi, for always reaching out, and for offering prompt, helpful feedback. Thank you to Dr. John Kerr for your steady guidance and encouragement. Thank you to Dr. Phil Robertson for your thoughtful input and questions.

This research was made possible through the support of many people and organizations in Uganda, in Malawi and at Michigan State University. I want to extend my deep thanks and gratitude to the smallholder farmers in Uganda and Malawi for welcoming me into their fields and homes and for generously sharing their time and knowledge. Thanks to the Makerere University Biological Field Station, the Uganda Wildlife Authority, Dr. Stephanie Grand, and the incredible field assistants in Uganda, especially Tugume Emmanuel, Micheal Kato, and Mbabazi Edith. In Malawi, I am forever grateful to the Africa RISING project team for their amazing support, special thanks to Dr. Regis Chikowo, to Emmanuel Jambo and Edward Mzumara for their help in field work, and to Dr. Vimbayi Chimonyo for her masterful project organization and for hosting me in Lilongwe. I am thankful to the University of Malawi, Chancellor College, and to Dr. Placid Mpeketula for his kind assistance and allowing me the use of his lab space, and I extend my thanks to the lab assistants.

I am grateful to the faculty and staff of the Plant, Soil, and Microbial Sciences Department, and I especially want to thank Dr. Brian Teppen, Dr. Krista Isaacs, and Dr. Jessica

Miesel for their mentorship, and Mackenzie Graham and Christiina Donley for their friendly assistance. Many, many thanks to the Tiemann lab, Snapp lab, and Isaacs lab members for their support, camaraderie, friendship, inspiring discussions, and for always being willing to lend a hand. I am deeply grateful to the lab managers, lab technicians and undergraduate lab assistants who helped me out over the years – special thanks to Amanda Harden, Expery Omollo, Chase Kasmerchak, Maxwell Oerther, and Vanessa Thomas. Thank you to the fellow graduate students from whom I learnt so much and who brought light and perspective to this experience, especially Brooke Comer, Chiwimbo Mwika, Leah Mungai, Amy Wisner, Katie Kohn, Nzube Egboluche, and Jaron Adkins.

Thank you to all the family and friends who bolstered me with love and laughter throughout this journey. I am so grateful for the friendship and love of our Michigan family, Brooke, Donny, Anilie, and Gaia Comer. Thank you to my mother-in-law, Janese Trivette, for making multiple trips from Virginia to Michigan to help with childcare and for all the ways you support us. Thank you to my mom and dad, Rosemary and Christopher, and to my sister, Giulia, for your tremendous support and unwavering love. And finally, thank you to Xenia, my kiddo, who arrived halfway through my PhD journey- you brighten my world, and to Parks Marion, my incredible partner, who has provided continual support, encouragement, and amazing food – you are my rock (and you know how much I love rocks).

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Introduction

Soil organic carbon (SOC) is a primary indicator of soil health and fertility and key to crop growth and productivity, particularly within the often low-input, resource-limited smallholder agroecosystems in sub-Saharan Africa (SSA) (Chivenge et al., 2007; Feller and Beare, 1997). SOC is a measurable component of soil organic matter (SOM), which is integral to and strongly affects soil biological, chemical, and physical properties and processes, including nutrient and water holding capacity, soil structure, and soil microbial diversity and species composition (Powlson et al., 2011; Tiessen et al., 1994). Microbial decomposition of above- and belowground biomass drives the formation of SOM and microbial decomposition of SOM releases N, P, S, and other essential nutrients for plant growth (Cotrufo et al., 2013). Microbes act as a filter between inputs and SOC and it is largely microbial products that compose stable (protected from decomposition) SOM (Cotrufo et al., 2013; Kallenbach et al., 2016).

A recent synthesis of SOC changes in tropical croplands determined that the quantity of carbon (C) inputs and management practices were two of the main driving factors in SOC accumulation (Fujisaki et al., 2018). Farmer management influences the quantity and quality of organic inputs through practices such as crop rotation, intercropping, legume intensification, residue retention, tillage, and use of organic and mineral fertilizers (Chivenge et al., 2007; Fujisaki et al., 2018). Increasing agroecosystem plant diversity through intercropping or rotation can increase both aboveground and belowground NPP and belowground plant C inputs, potentially creating a feedback loop of increased plant biomass and organic inputs into the soil and microbial nutrient cycling (Bartelt-Ryser et al., 2005; Jing et al., 2017; Jobbágy and Jackson,

2000; Kremen and Miles, 2012; Lange et al., 2015). Belowground root inputs can add more C than shoots and are thought to play a crucial role in SOC stabilization due to their close associations with microbes and mineral surfaces and their contributions to soil aggregate formation (Jastrow, 1996; Kong and Six, 2010; Puget and Drinkwater, 2001; Schmidt et al., 2011). Crop diversification can boost belowground C inputs through biotic and physical changes stimulated by the addition of diverse plant root morphologies, root biomass, rhizodeposition, and root exudates (Kong and Six, 2010; Rasse et al., 2005; Schmidt et al., 2011). The changes elicited by increased plant diversity influence microbial community composition and growth, in turn impacting SOC pools and nutrient cycles and crop growth (Soares and Rousk, 2019).

SOC and N are closely linked and organic input and soil N concentrations impact whether N is taken up and immobilized by microbes or available to plants (Chen et al., 2018). N is the major limiting nutrient for crop production in SSA, as it is in virtually all cropping systems around the world (Sanchez et al., 1997). N is removed from soils through crop harvest, leaching, and other means and is nearly continuously in need of replacement (Giller et al., 1997; Smithson and Giller, 2002). Crop diversification with legumes has been highly recommended in SSA because of legumes' ability to generate N through symbiotic biological N-fixation (BNF) (Giller, 2001; Snapp et al., 1998). Through BNF, legumes can provide N critical to both healthy soil functioning and to subsequent crops through N-rich residues, and often legumes are the only source of N in low-input systems in SSA (Snapp et al., 1998; Giller, 2001). As an alternative or accompaniment to inorganic fertilizers, intercropped or rotated legumes can conserve soil nitrogen, breakup pest and disease cycles, and deliver substantial N-rich organic matter. More plant available N can lead to greater crop productivity and biomass, which in turn can impact

plant C inputs. Legumes grown for soil fertility and soil regeneration purposes such as legume green manures, leguminous trees, and legume cover crops are preferable to grain or forage legumes, as a portion of the plant biomass and N fixed by grain or forage legumes is removed upon harvest (Snapp, Mafongya, and Waddington, 1998). However, grain legumes appeal to farmers because of their provision of food and income, as well as BNF benefits.

This dissertation explores the effects of smallholder farmer management practices on organic matter and N inputs and subsequent impacts on SOC and N in Uganda and Malawi. Detailed analysis of farmer residue management practices, organic resource management, and the potential for grain legumes to impact SOC and N, contributes important field-scale knowledge of on-farm practices and addresses gaps in the knowledge of legume effects on SOC and N and methods to detect those changes.

REFERENCES

REFERENCES

- Bartelt-Ryser, J., Joshi, J., Schmid, B., Brandl, H., Balser, T., 2005. Soil feedbacks of plant diversity on soil microbial communities and subsequent plant growth. *Perspect. Plant Ecol. Evol. Syst.* 7, 27–49. <https://doi.org/10.1016/j.ppees.2004.11.002>
- Chen, J., Heiling, M., Resch, C., Mbaye, M., Gruber, R., Dercon, G., 2018. Does maize and legume crop residue mulch matter in soil organic carbon sequestration? *Agric. Ecosyst. Environ.* 265, 123–131. <https://doi.org/10.1016/j.agee.2018.06.005>
- Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P., Six, J., 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. *Soil Tillage Res.* 94, 328–337. <https://doi.org/10.1016/j.still.2006.08.006>
- Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Denef, K., Paul, E., 2013. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Glob. Chang. Biol.* <https://doi.org/10.1111/gcb.12113>
- Feller, C., Beare, M.H., 1997. Physical control of soil organic matter dynamics in the tropics. *Geoderma* 79, 69–116. [https://doi.org/10.1016/S0016-7061\(97\)00039-6](https://doi.org/10.1016/S0016-7061(97)00039-6)
- Fujisaki, K., Chevallier, T., Chapuis-Lardy, L., Albrecht, A., Razafimbelo, T., Masse, D., Ndour, Y.B., Chotte, J.L., 2018. Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: A synthesis. *Agric. Ecosyst. Environ.* 259, 147–158. <https://doi.org/10.1016/j.agee.2017.12.008>
- Giller, K.E., 2001. *Nitrogen Fixation in Tropical Cropping Systems*, CABI. Wallingford, UK.
- Jastrow, J.D., 1996. Soil aggregate formation and the accrual of particulate and mineral-associated organic matter. *Soil Biol. Biochem.* 28, 665–676. [https://doi.org/10.1016/0038-0717\(95\)00159-X](https://doi.org/10.1016/0038-0717(95)00159-X)
- Jing, Z., Chen, R., Wei, S., Feng, Y., Zhang, J., Lin, X., 2017. Response and feedback of C mineralization to P availability driven by soil microorganisms. *Soil Biol. Biochem.* 105, 111–120. <https://doi.org/10.1016/j.soilbio.2016.11.014>
- Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.* 10, 423–436. [https://doi.org/10.1890/1051-0761\(2000\)010\[0423:TVDOSO\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2)

- Kallenbach, C.M., Frey, S.D., Grandy, A.S., 2016. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. *Nat. Commun.* 7. <https://doi.org/10.1038/ncomms13630>
- Kong, A.Y.Y., Six, J., 2010. Tracing Root vs. Residue Carbon into Soils from Conventional and Alternative Cropping Systems. *Soil Sci. Soc. Am. J.* 74, 1201. <https://doi.org/10.2136/sssaj2009.0346>
- Kremen, C., Miles, A., 2012. Ecosystem services in biologically diversified versus conventional farming systems: Benefits, externalities, and trade-offs. *Ecol. Soc.* 17. <https://doi.org/10.5751/ES-05035-170440>
- Lange, M., Eisenhauer, N., Sierra, C.A., Bessler, H., Engels, C., Griffiths, R.I., Mellado-Vázquez, P.G., Malik, A.A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B.C., Trumbore, S.E., Gleixner, G., 2015. Plant diversity increases soil microbial activity and soil carbon storage. *Nat. Commun.* 6. <https://doi.org/10.1038/ncomms7707>
- Powlson, D.S., Whitmore, A.P., Goulding, K.W.T., 2011. Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. *Eur. J. Soil Sci.* 62, 42–55. <https://doi.org/10.1111/j.1365-2389.2010.01342.x>
- Puget, P., Drinkwater, L.E., 2001. Short-Term Dynamics of Root- and Shoot-Derived Carbon from a Leguminous Green Manure. *Soil Sci. Soc. Am. J.* 65, 771–779. <https://doi.org/10.2136/sssaj2001.653771x>
- Rasse, D.P., Rumpel, C., Dignac, M.F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant Soil* 269, 341–356. <https://doi.org/10.1007/s11104-004-0907-y>
- Schmidt, M.W.I.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. a., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D.A.C.C., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478, 49–56. <https://doi.org/10.1038/nature10386>
- Snapp, S.S., Mafongoya, P.L., Waddington, S., 1998. Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. *Agric. Ecosyst. Environ.* 71, 185–200. [https://doi.org/10.1016/S0167-8809\(98\)00140-6](https://doi.org/10.1016/S0167-8809(98)00140-6)
- Soares, M., Rousk, J., 2019. Microbial growth and carbon use efficiency in soil: Links to fungal-bacterial dominance, SOC-quality and stoichiometry. *Soil Biol. Biochem.* 131, 195–205. <https://doi.org/10.1016/j.soilbio.2019.01.010>
- Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic matter in sustaining soil fertility. *Nature* 371, 783–785. <https://doi.org/10.1038/371783a0>

Chapter 1 : Estimating the contribution of groundnut residues to soil N and the influence of farmer management in western Uganda

Abstract

Through symbiotic biological nitrogen fixation (BNF), grain legumes, such as groundnuts, can enhance soil nitrogen (N) and be an important source of N fertility, as well as a critical component of human nutrition and food security. Because legumes obtain N from soil N stocks as well as BNF, legume residues are key to capturing potential N benefits for soils. Here, I conducted a detailed survey at household and field level within a six-village corridor along the western boundary of Kibale National Park (KNP) in western Uganda. I focused on groundnut production and residue management practices and soil organic carbon (SOC) and total N (TN) in fields managed by 100 different households. I also determined SOC and TN in adjacent uncultivated KNP soils. I tested for relationships between socioeconomic factors and farmer groundnut management practices. I calculated a partial N balance and estimated potential N benefits under three scenarios for groundnut BNF. Within the study area, groundnut residue management varied greatly with 51% of surveyed farmers retaining residues on fields through spreading or incorporation, and 49% removing residues, either by transfer to banana groves or burning. Groundnut population density was relatively high with 43% of fields having greater than 30 plants m⁻². However, there was no observed effect of groundnut residue management practices on SOC, TN, or soil C:N ratios. Compared to uncultivated KNP soils, groundnut fields had lower mean levels of SOC and TN and wider C:N ratios. These values are consistent with cultivated soils but comparatively lower than losses previously reported for conversion from

tropical forest to agricultural use. I found that farmer valuation and perception of groundnut residues were influential factors in residue management practices. Overall, I estimated that groundnut residues had the potential to contribute to SOC and TN stocks if retained in the field, but, conversely, removal will result in sizable losses. I find that both environmental and social contexts must be taken into consideration when recommending legumes for N provisioning services.

Introduction

Nutrient depletion is a primary factor in soil degradation and low and declining crop yields across sub-Saharan Africa (SSA) (Stoorvogel and Smaling, 1990; Tully et al., 2015). Among countries in SSA, Uganda experiences some of the highest rates of land degradation, resulting in lower agricultural productivity (Nkonya et al., 2005; Stoorvogel and Smaling, 1990; Wortmann and Kaizzi, 1998). Compared to global averages, inorganic fertilizer use across SSA is very low at 16 kg ha arable land⁻¹ year⁻¹, and it is extremely low in Uganda at 1.8 kg ha arable land⁻¹ year⁻¹ (World Bank, 2016). Organic inputs are often the main option for smallholder farmers in Uganda, as inorganic fertilizer accessibility, availability, and affordability is limited (Omamo, 2003). However, resource-limited farmers often find organic fertilizers, such as animal manure or compost, challenging to obtain or employ, especially at recommended amounts (Nandwa and Bekunda, 1998). Similarly, farmers face multiple pressures and trade-offs with crop residues, which in addition to being organic inputs, are frequently used as livestock feed and cooking fuel, among other purposes (Erenstein et al., 2015; Tittonell et al., 2015; Valbuena et al., 2015). Nationally, only 15% of Ugandan households reported adding organic or inorganic

fertilizers or pesticides to common beans (*Phaseolus vulgaris* L.), and only 14% added these inputs to maize (*Zea mays* L.) (UBOS, 2013).

Nitrogen (N) is most often the main limiting nutrient for plant growth and crop yields (Sanchez et al., 1997). In natural ecosystems and low-input cropping systems such as those found across SSA, legumes can play a vital role in N provisioning. Legumes access N from the atmosphere via biological N fixation (BNF) to support growth and the production of high protein grains and N-rich residues (Giller, 2001; Snapp et al., 1998). Legume residues can supply immediate and short-term N to subsequent crops, as well as contribute to long-term N and soil fertility by stimulating microbial biomass production, nutrient cycling and maintenance of or gains in soil organic matter (SOM) (Franke et al., 2018; Kermah et al., 2018; McDonagh et al., 1993; Promsakha et al., 2005; Srichantawong et al., 2005; Toomsan et al., 1995). Legumes are therefore widely recommended as an organic N source for low-input, resource-limited agroecosystems in SSA where they can supply N critical to both healthy soil functioning and crop production and potentially replenish SOM in degraded soils (Giller, 2001; Snapp et al., 1998, 2016). Importantly, legumes are also critical for human health, nutrition, and dietary diversity as a key source of protein, diverse amino acids, micronutrients, dietary fiber, and phytochemicals (Foyer et al., 2016; Messina, 1999). Indeed, poorer households in SSA rely on legumes for a large proportion of their dietary protein (Akibode and Maredia, 2012) and because of their importance, legumes can often be sold for high prices at local and international markets, generating substantial income for resource-poor households (S. Snapp et al., 2018). Because of their many potential benefits, legumes are recommended as part of Integrated Soil Fertility Management (ISFM) and conservation agriculture schemes in SSA with

the ultimate goal of improving soil health, and thus the sustainability and resiliency of low-input agroecosystems (Thierfelder et al., 2013; Vanlauwe et al., 2015).

Across SSA, farmers grow grain legumes for provision of food and income, in addition to BNF benefits. The two most widely grown grain legumes in SSA and in Uganda are common bean and groundnut (*Arachis hypogaea L.*) (S. Snapp et al., 2018; UBOS, 2014). Because common bean has been shown to have low rates of BNF, supplying limited amounts of N in rotation with cereals, I chose to focus on groundnuts. Groundnuts are capable of fixing substantial amounts of N and have a moderate-to-low harvest index, and so can supply a relatively high quantity of N in rotation with cereals (Franke et al., 2018; Giller et al., 1997; Ojiem et al., 2014). Despite N-rich grain removal with harvest, grain legumes with a relatively low harvest index can deliver substantial N benefits to soil; groundnut residues have been found to provide up to 139 kg N ha⁻¹ (Ojiem et al., 2014). While N contributions can be substantial, N credits or gains from legumes are notoriously challenging to determine in the field (Cadisch et al., 2000; Unkovich and Pate, 2000). Fixation levels and volume of N fixed can vary dramatically depending on legume variety, agroecological conditions (e.g. site, climate, weather, soil type and fertility), and management practices (e.g. cropping patterns, fertilization) (Dakora and Keya, 1997; Mokgehle et al., 2014; Peoples and Craswell, 1992; Wani et al., 1995). Because legume N fixation is highly variable across cultivar, agroecology, and management, legume N credits are almost always an estimation of potential legume N contributions. In order to fully understand the potential for legume N credits on smallholder farms, I need more long-term data and site and context specific information, including farmer residue management

practices, which are key to maximizing both N and C contributions of legume residues to soil (Giller et al., 1997; Kermah et al., 2018; Wani et al., 1995).

Within the full context of an agroecosystem, including soil fertility, climate, and management practices, nutrient balances that calculate the N inputs and outputs of a farming system can serve to estimate or quantify legume N benefits (Tully et al., 2015). Nutrient balances help to highlight the advantages and/or disadvantages of inputs, outputs, and/or management practices in terms of economic, agricultural, and ecological sustainability (Haileslassie et al., 2007; Nkonya et al., 2005). In conjunction with nutrient balances, examination of the relationships among household demographic/socioeconomic characteristics and management practices can identify the factors driving farmer decision-making and further contextualize and assess the sustainability of agroecosystems (Ebanyat et al., 2010; Nkonya et al., 2005). Socioeconomic and demographic factors such as gender of the household head or crop planner (Mugisa et al., 2015; Nijuki et al., 2008; Tanellari et al., 2014), land tenure (Kassie et al., 2015; Place and Otsuka, 2002), ethnic group (Kirner, 2010; Naughton-Treves, 1997), and field distance from the homestead (Tittonell et al., 2005b, 2013; Zingore et al., 2007a) have been shown to drive farmer practices and affect farmer access to, use, and decisions regarding resources like residues (Barrett and Bevis, 2015).

Few studies have examined the potential N benefit from grain legumes in SSA while simultaneously adjusting and accounting for farmer legume management practices. I present a case study of farm management and residue practices with a focus on groundnuts within smallholder agroecosystems in western Uganda. I collected soils, GIS, socioeconomic and agronomic data and estimated three levels of potential N addition via groundnut BNF. My

objectives were: (1) to chronicle and assess differences in groundnut residue management; (2) to estimate the potential N benefit from groundnut residues based on their management; (3) to determine if groundnut residue management impacts SOC and TN; and (4) to explore soil and socioeconomic factors driving groundnut residue management practices. I hypothesized that groundnut residue retention had the potential to deliver positive N balances at the field-scale. I expected TN to be greater and soil C:N to be narrower in fields in which groundnut residues were consistently retained versus fields in which groundnut residues were continually removed. Lastly, I predicted that socioeconomic factors previously identified in the literature as drivers of farmer practices would also be linked to groundnut residue management practices.

Materials and methods

Study area

Research was conducted along the western border of Kibale National Park (KNP) in Burahya County, Kabarole district, western Uganda (Figure 1.1). KNP and the surrounding area fall within the Albertine Rift, a biodiversity hotspot that is part of Africa's Rift Valley (Lepp and Holland, 2006). KNP received its national park designation in 1993, but it has existed as a forest preserve since 1932 (Struhsaker, 1997). The park is a remnant of transitional forest isolated within a densely populated agricultural landscape; in 2006, the population density within 5 km of the park boundary was estimated to be approximately 300 individuals km⁻² (Hartter and Southworth, 2009). Outside KNP, the hilly landscape is dominated by small-scale agriculture, tea plantations, grassland, and fuelwood plantations (Chapman and Lambert, 2000; Majaliwa et al., 2010). Smallholder farms adjacent to the park are impacted by crop raiding by park animals

and resulting crop losses are fairly common, though it mainly impacts those within 1 km of the boundary (Hartter, 2010). The main regional cash crops are banana (*Musa spp.*), tea (*Camellia sinensis* L.), coffee (*Coffea arabica* and *Coffea canephora*), and maize, but smallholder farmers grow over 20 species of subsistence crops (Hartter and Southworth, 2009). Kabarole district is characterized as an area of “high agricultural potential” (de Jager et al., 2004), and approximately 84% of households engage in crop growing or livestock agriculture (UBOS, 2014). The district had the highest maize production in the western region (UBOS, 2010). Kabarole district lies within the Lake Albert Crescent zone, which has good to moderate soils (FAO, 2010). Related to the high population density, the western region has the smallest average landholdings at 0.8 ha compared to the national average of 1.1 ha (UBOS, 2010). Limited land and high population density have led to small landholdings (Hartter & Southworth, 2009).

The study area covered the villages of Kanyawara, Kyakabuzi, Isunga, Iruhuura, Nyabweya, and Kajumiro, which fall along an approximately 22-km north-south transect along the edge of the KNP’s western boundary (Figure 1). The study area is located between latitude 0.57°–0.39° N and longitude 30.35°–30.32° E and lies along an elevational gradient north to south from 1550–1100 m above sea level. The climate is tropical with an average daily temperature range of 15–23°C (Struhsaker, 1997). Rainfall in the region is bimodal with two rainy seasons separated by two dry seasons. The first dry season from early December to late February is followed by a rainy season occurring from approximately early March through mid-to-late May. A second dry season extends until early September followed by a rainy season from September through November (Hartter et al., 2012). Planting commences at the start of each rainy season, allowing for two growing seasons each year. Mean annual rainfall ranges

from 1100 to 1700 mm with rainfall decreasing and temperature increasing when moving from north to south along the elevational gradient (Struhsaker, 1997). Soils are classified as eutrophic volcanic ash and ferrallitic sandy clay loams. Study area soils were previously established to be inherently medium to highly fertile (Jameson, 1970).

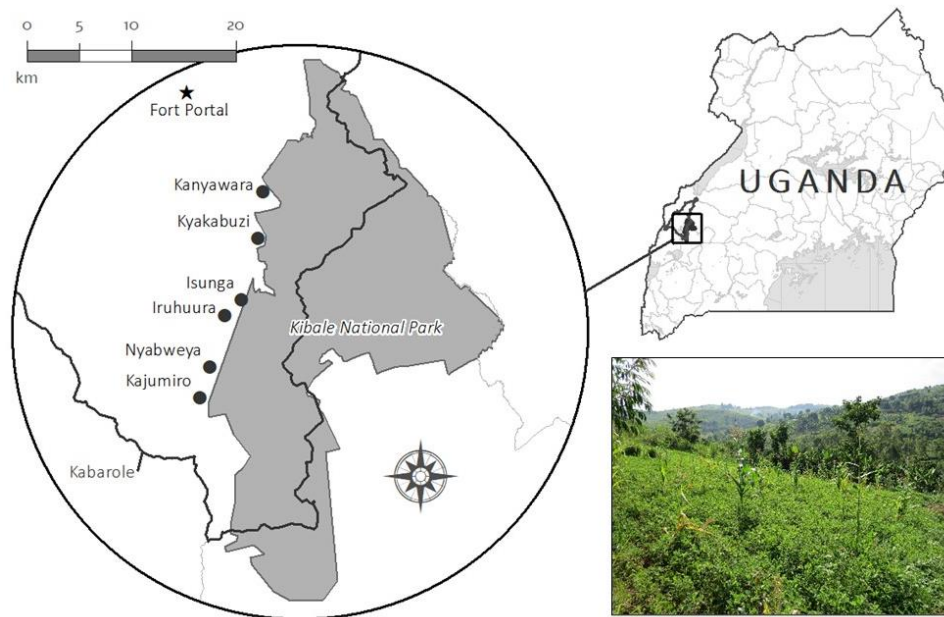


Figure 1.1. Map of study area, with a focus on areas surrounding six villages along the western border of Kibale National Park in Kabarole district, western Uganda. The inset photo shows a surveyed field in which groundnut is planted as a ground cover with maize sparsely interplanted within a hilly terrain, representative of the majority of fields surveyed for this study.

Surveys and data collection

I conducted a survey and soil sampling within the six village areas in July 2015, coinciding with the final growing stage and harvest of groundnuts and maize (July harvest for groundnut and July to early August harvest for maize) planted at the start of the first rainy season (March-April planting for groundnut and February-March for maize). The study

comprised 100 households that had actively been growing groundnuts (Kanyawara $n=9$, Kyakabuzi $n=9$, Isunga $n=21$, Iruhuura $n=18$, Nyabweya $n=16$, Kajumiro $n=27$). All households were located within approximately 1.6 km of the closest park boundary. Ugandan field assistants translated survey questions and responses from English into Rutooro and Rukiga, the respective languages of the resident Batooro and Bakiga ethnic groups. Households within each village were approached at random and asked if they grew groundnuts and were willing to participate in a survey. A two-part survey instrument was used: (1) a household socioeconomic and overall farm survey, which collected information on household demographics, education level, ownership status and size of agricultural fields, livestock ownership, crop planting and harvesting dates, crop yields, crop use, income received for specific crops, perceived causes for declines in crop yields, land management decisions, and resource concerns; and (2) a survey of farmer management for the farmer-identified primary groundnut field, which provided information on any and all inputs and outputs into that field, field preparation, any steps taken or practices used to increase or maintain soil fertility, the field's cropping history for the two previous seasons (September 2014-February 2015 and March-August 2014), and detailed information on all crops grown in the field that season (March-August 2015), including planting and harvesting dates and methods, yields or expected yields for that season, crop use (household, saved, or sale), and detailed residue management with reasons for specific practices. The residue management practices described by respondents were categorized into four main practices: (1) "remove" included residues removed from the field and transported to another location, (2) "burn" included residues burned within the field, (3) "spread" comprised residues that were kept on the field as mulch and spread on the field surface, and (4)

“incorporate” constituted residues that were retained and buried into the soil. A simple relative wealth ranking of the study area farms was constructed by assigning a value to assets including homestead dwelling construction and livestock ownership (“yes” and “no” responses to whether they owned cattle, pigs, goats, chickens, other) (Hockett and Richardson, 2018); values were summed and then categorized into “below average”, “average”, and “above average” based on the interquartile range.

The first part of the survey instrument (the household and whole farm survey) had previously been implemented with 14 households in July 2013 and eight households in June 2014. I used these prior responses in my analysis. In July 2015, these households participated in the second part of the survey instrument, the field survey.

The survey was administered at the homestead and at the field. The homestead and the corresponding field were marked as waypoints on a handheld Garmin GPS 62s unit. Respondents or a capable household member walked us around or clearly indicated the perimeter of the groundnut field, which was saved as a track to the GPS unit. The GPS data was retrieved from each unit and read into ArcGIS 10.4 software. A map of the household locations, field locations, and field perimeter tracks was created using ArcGIS. I calculated the area within the perimeter track to determine the size of each surveyed field and determined the Euclidean distance between the homestead and groundnut field. Fields within 50 m of the homestead were categorized as “homefields”, and fields further than 50 m were categorized as “outfields” (Zingore et al., 2007b).

Within each surveyed field, I used quadrats and total plant counts to measure plant density for groundnut and any other crop present. In each field, I measured the groundnut crop

by counting the number of individual plants within four 50 x 50 cm quadrats; the location of each of the four quadrats was randomly determined along a diagonal field transect. The large variation in the density of crops interplanted in a groundnut field necessitated different measurement techniques according to intercrop species and/or field size. Intercrop plant density was measured either by counting plants within four 50 x 50 cm quadrats (beans) or three 3 x 3 m quadrats (all other crops except banana and coffee) or by counting the total number of plants in the field (coffee, banana or intercrops in fields smaller than approximately 0.03 ha). If groundnut or an intercrop had already been fully harvested, I asked respondents to provide an estimate of the crop density by indicating the plant layout within a quadrat.

Soil sampling and analysis

In each groundnut field, three soil samples were taken at random to a depth of 15 cm using a 2-inch diameter soil probe and composited to represent each field. I used a set of KNP reference soils ($n=12$) collected from uncultivated forest areas (Tiemann, unpublished data) proximal to each village in the study area as a baseline comparison to groundnut field SOC and N values. Soils were air-dried in Uganda and shipped to Michigan State University (MSU) in East Lansing, MI, USA for analysis.

Soil samples were passed through a 2 mm mesh sieve and 5 g placed into 20 ml scintillation vials to oven-dry at 60°C for 24 hours. Oven-dried soils were ground on a roller mill and subsamples weighing approximately 20 mg were packed into tins to measure SOC and TN on an elemental analyzer (ECS 4010, Costech Analytical Technologies, Inc., Valencia, CA, USA).

Partial N balance

To construct partial N balances, I used the measured plant population density data with farmer-reported data on groundnut yields and residue management, and published values.

Based on literature values from on-farm experiments conducted in similar agroecological zones in western Kenya, I assumed that there was approximately 0.7 g N groundnut plant⁻¹ and that 70% of N was derived from fixation (Ojiem et al., 2007). I calculated crop N and fixed N as:

$$\text{Crop N (kg ha}^{-1}\text{)} = (0.7 \text{ g N} \times \text{groundnut plants ha}^{-1})/1000 \quad (1)$$

$$\text{Fixed N (kg ha}^{-1}\text{)} = \text{Crop N} \times (\% \text{N derived via BNF}/100) \quad (2)$$

As the proportion of N derived from BNF can be highly variable, I conducted a sensitivity analysis whereby I adjusted the proportion, or what I term the BNF efficiency, to 30% and 50%, in addition to the 70% scenario. These values for N groundnut plant⁻¹ and for the proportion of N derived via BNF fall within the range of published groundnut N and fixation values for SSA (Ebanyat et al., 2010; Franke et al., 2017; Kermah et al., 2018; Mokgehle et al., 2014; Ncube et al., 2007; Nyemba and Dakora, 2010; Ojiem et al., 2007; Oteng-Frimpong and Dakora, 2018). I assumed that groundnut grain was 4.5% N (Nijhof, 1987). The potential N input from stover was calculated as:

$$\text{Potential N input (kg ha}^{-1}\text{)} = \text{Stover N (kg ha}^{-1}\text{)} - \text{Soil N (kg ha}^{-1}\text{)} \quad (3)$$

Stover N is the groundnut plant N content minus the harvested grain N and soil N is the plant N taken up from the soil, which was calculated by subtracting N derived via BNF from total groundnut plant N.

The groundnut N input was adjusted according to farmer-reported residue management practices. When farmers reported removing or burning all groundnut residue, I estimated that

residues would provide 5% (incomplete burning or removal) of their total potential N benefit to field soils, or if farmers provided an estimated percentage of residues remaining, this value was used instead. For groundnut residues that were incorporated into the soil or spread on the field surface, I estimated that 100% of the potential N benefit could be delivered. Estimated N input with management factored in was calculated as:

$$\text{Potential N input with management} = \text{Potential N input} \times \text{management value} \quad (4)$$

I calculated a partial, single season, field-level N balance for 77 groundnut fields; out of the 100 fields, 12 were missing field area measurements because of an error with the handheld GPS, four were missing groundnut plant density measurements, and seven fields were excluded because the reported groundnut yield weights were extreme outliers ($>3000 \text{ kg ha}^{-1}$, more than 1.5 times interquartile range). Within the context of groundnut residue management practices, I balanced BNF input from groundnut residues with groundnut grain N.

Additionally, to illustrate the maximum and minimum mean N input according to groundnut residue management, I present two field-level scenarios. In the first scenario (S1), all residues are retained in the field and N additions from stover corrected for soil N removal based on the BNF efficiency and groundnut grain N removal. In the second scenario (S2), all residues are removed from the field and the N addition from estimated 5% residues remaining (roots and missed residues) is corrected for soil N removal based on BNF efficiency and grain N removal.

Data analysis

Descriptive statistics, Pearson's chi-squared tests, Wilcoxon rank-sum test, and analysis of variance (ANOVA) were performed with STATA/IC 14.2 statistical software (StataCorp, College Station, TX).

Pearson's chi-square test of independence was used to measure the strength of relationships between the four residue management practices and socioeconomic factors, including ethnicity, village, gender of the household head, crop planner, land tenure, wealth ranking, distance from the field to the homestead, and factors related to a household's valuation of groundnut. The factors related to valuation of groundnut were derived from three different survey questions asking: which crop do you sell the most of, which crop do you make the most profit on, and which crop is the best to plant if you want to improve crop yields/soil fertility. Because data were not normally distributed, I applied the Wilcoxon rank sum test to test for differences between groundnut field soils and KNP reference soils (Corder and Foreman, 2009).

Groundnut field SOC and TN values were normalized by calculating the difference from proximal KNP baseline soils. I performed a one-way analysis of variance (ANOVA) on the normalized C and N values by groundnut residue management practice.

Results

Household and farm-level characteristics

Household demographic and socioeconomic characteristics are presented in Table 1.1. Households ranged in size from 1 to 20 people with a mean of 6.3 members ($sd=3.30$), with 61% of members under the age of 15. Most respondents identified as belonging to the Bakiga ethnic

group (72%) and 25% identified as Batooro. Households were predominately designated as male-headed (74%). Despite this, 44% identified a woman as the crop planner, i.e., the person responsible for planning the planting and harvesting schedule (29% of male-headed households had a female crop planner), 26% identified a man, and 29% identified multiple planners.

Land ownership was high with 75% of households owning all their land and 24% of households renting a portion of their land. Mean, farmer-estimated, household land use was 3.3 ha. The majority (57%) of households had similar, average wealth, while 24% were below average and 19% were above average. The above average wealth ranking includes households that owned cattle (12%) in addition to other livestock and had a dwelling constructed of concrete (10%); average households owned goats, pigs, and/or chickens and had homes with mud-wattle construction and an iron-sheet roof; and below average households owned chickens or no livestock and had traditional thatch-roofed homes or homes with dirt floors.

In addition to groundnuts, households grew a large diversity of crops at the farm-level with, in order of frequency, maize, common bean, banana, cassava, Irish potato, and sweet potato grown by over half the households (Table 2). Crop production at the farm-level was strongly characterized by intercropping (99%) and crop rotation (82%). Maize was often intercropped with groundnut (68%), and of the 70% of farms that reported practicing a set crop rotation, 77% reported that they included groundnut in the rotation. The top three reasons for intercropping were limited land (45%), greater harvest (22%), and greater profit (16%). When asked which crop(s) were best to plant for improving soil fertility, 57% included groundnut, though 30% of respondents also listed at least one non-legume crop.

Maize was reported as the most sold crop (48%) with groundnut the second most sold crop (22% of households). Groundnut was reported to be the most profitable crop in 34% of households, followed closely by maize (31%), then rice (14%) and Irish potatoes (10%). Most households (77%) categorized themselves as “very much” dependent on income from crop sales.

The large majority of farmers (93%) reported seeing year-to-year declines in crop yields with declines most often reported in maize (68%), followed by groundnut (48%), common bean (46%), and Irish potato (27%); 6% of farmers reported declines in all crops. The reasons cited for declining crop yields included factors relating to soil fertility (soil fertility loss, old soils, poor soils, 43%), climate (heavy rains, drought, delayed rains, climate change, 34%), crop management (poor seeds, crop type, delayed planting, 5%), and a combination of soil, crop, and climate factors (11%); 7% said they did not know the reason.

Table 1.1. Demographic and socioeconomic characteristics of the 100 surveyed groundnut-growing households along the western edge of Kibale National Park in western Uganda.

Variable	%
Land Tenure, own all land	75
Ethnicity of respondent	
Batooro	25
Bakiga	72
Other ^a	3
Household Head Gender	
Female	25
Male	74
Crop Planner	
Woman	44
Man	26
Multiple	29
Wealth Ranking ^b	
Below average	24
Average	57
Above average	19
Households with livestock	
Cattle	12
Pigs	60
Goats	73
Chickens	82
None	8
Intercrop maize with groundnut	68
Rotate maize with groundnut	54
Groundnut most sold crop	22
Groundnut most profitable	34
Groundnut best for soil fertility	57
"Very much" dependent on crop sales	77

a Other includes Bakonjo, Iteso, and Munyankole

b Wealth ranking is based on the assignation of numerical values to housing materials and livestock assets. The assets were summed to create a continuous variable representative of wealth. (Hockett & Richardson, 2016)

Table 1.2. Across all farms surveyed, the frequency of each crop grown at the household level with normal seasonal yields, and the frequency of each crop grown in the groundnut field surveyed during the 2015 study season (crops other than groundnut indicate intercrops) and for the two prior growing seasons. The “Residues removed” column indicates the percentage of fields from which over half of the residues were consistently removed or burned over the span of three seasons.

Farm-level			Groundnut field crop frequency			
Crops	Farm production frequency %	Mean Yield ^a (kg farm ⁻¹ season ⁻¹)	Study season ^b %	Previous season %	Two seasons prior %	Residues removed ^c %
Groundnut	100	189	100	3	7	49
Maize	100	963	73	46	44	57
Common bean	96	134	2	31	31	58
Cassava	92	.	54	7	3	41
Banana	89	314 bunches	11	3	2	0
Irish potato	82	499	4	16	7	0
Sweet Potato	75	374	0	5	12	40
Millet	41	.	0	7	8	13
Rice	37	490	0	20	10	20
Soyabean	15	.	2	2	0	50
Sorghum	14	.	2	1	2	40
Pea	14	.	4	5	1	40
Coffee	12	.	6	2	1	0
Taro	10	.	6	0	0	50
Tomato	7	.	0	1	1	0
Onion	6	.	0	1	1	50
Fruits ^d	5	.	0	0	0	na
Other ^e	10	.	6	2	1	11

a Farm level yield data collected for select crops; values reported per farm, total farm area not measured

b Study growing season March-Aug 2015, previous season Sept 2014-Feb 2015, two seasons prior March-Aug 2014

c All or over half of residues removed from or burned in the field, averaged over the three seasons

d Fruits include avocado, jackfruit, mango, guava, pineapple

e Tea, cabbage, pumpkin, sugarcane, hot pepper, eggplant, eucalyptus

Groundnut field characteristics: production and use

Groundnut fields ranged from 0.01 ha up to 0.58 ha with a mean area of 0.095 ha (Table

3). The distance between the surveyed groundnut fields and the homestead was at minimum 5

m and maximum of 1.7 km. The distance was less than 50 m for 40% of households thereby characterized as homefields and greater than 50 m for 60%, which were classified as outfields.

One hundred percent of fields were rainfed and were prepared and worked manually with a hand hoe. Only 14 fields had received any kind of external input; seven fields had manure added, four had herbicide applications, and application of chemical fertilizer, household waste, or residues from another source occurred in single fields. The remaining 86 fields did not receive any external inputs other than seeds or starts at planting. Weed biomass was retained on 96% of fields, and 93% of fields were weeded 1-2 times per season with the remainder weeded more frequently.

Fields had been planted to groundnut for a mean of 3.6 seasons and the majority (81%) of fields had been in groundnut for at least two seasons with a maximum of 13 seasons. In most fields, groundnut was interplanted with at least one other crop and up to as many as five other crops; only eight fields were planted solely to groundnuts. The most common intercropping combination was groundnut-maize-cassava which was present in 21% of fields and that combination plus additional intercrops was present in another 18% of fields.

Farmers practiced crop rotation in 66% of the surveyed fields, and in those rotations, the most commonly included crops were groundnut (79%), common bean (74%), maize (56%), Irish potatoes (56%), rice (36%), cassava (21%) and sweet potatoes (21%). Groundnut was included every third season in 83% of the rotations, which contextualizes the fact that only 10% of households reported planting groundnut in the surveyed field in the two seasons prior to the 2015 study season. Though, 52% of households grew maize and 50% grew common bean at

least once during the two prior seasons, with 18% growing maize and 10% growing common bean both previous seasons (Table 1.2).

For the surveyed groundnut field, household consumption accounted for around half of the groundnut harvest (48%), while 26% of the harvest was sold and 25% was saved for seed. All households except one intended a portion of the groundnut yield for household use, 80% of households saved part of the harvest for seed and 58% sold a portion of the groundnut harvest.

Bunch-type groundnut was found in all fields with varieties identified as local. The mean planting density for groundnut was 29 plants m^{-2} (Table 3), with 43% of households planting 30 or more groundnut plants m^{-2} . In all surveyed fields, groundnut was planted as a ground cover over the entire field. Maize and cassava were interplanted at much lower densities and widely dispersed with respective mean planting densities of 0.44 ($SEM=0.62$) and 0.18 ($SEM=0.04$) m^{-2} . Planting density for the other less common intercrops (Table 2) was also low, ranging from less than 0.01 to 0.63 plants m^{-2} with a mean of 0.136 m^{-2} ($SEM=0.03$). Regression of groundnut yield on groundnut planting density indicated no linear relationship ($R^2=0.015$) between the two; the exclusion of outliers did not increase the R^2 above 0.1.

All farmers harvested groundnuts by pulling the entire plant out of the ground. Of the 100 groundnut-producing households, 49% removed or burned groundnut residues and 51% retained groundnut residues on fields, either incorporating or spreading the stover as a mulch (Table 2). Groundnut residues were removed from 19% of fields, burned in 30%, spread on the surface for 31%, and incorporated into the soil in 20%. For maize, the most common intercrop, I found that farmers removed maize residues to mulch bananas in 46% of fields, surface spread in 32%, incorporated in 11%, and burned in 11%. Approximately 41% of cassava residues were

removed to use as firewood or animal feed, and 59% of residues were replanted as stem cuttings or remained in the fields.

Respondents provided a variety of reasons and explanations for residue management practices for groundnut and other crops planted in the field over the course of the three seasons (Figure 1.2). However, of all the different crop residues, only groundnut residues were described as having potentially negative impacts on the soil or crop yields (Figure 1.2). A total of 18 respondents said they burned or removed groundnut residues because the residues were either bad for the soil or caused infertility. Conversely, residues were described as adding fertility by 26 respondents who spread, incorporated, or removed residues to use as mulch in other fields. Residue decomposition was mentioned often with 10 respondents stating that they burned or removed groundnut residues because they did not easily decompose, whereas 11 respondents said they spread or incorporated residues so they would decompose.

Table 1.3. Groundnut field characteristics and agronomic data across 100 smallholder farms along the western edge of Kibale National Park in Western Uganda.

Variables	n	Mean	Minimum	Maximum	SEM
Field Size (ha)	88	0.095	0.01	0.58	0.01
Distance from homestead (m)	100	199	5	1658	29
Gnut planting density (m^{-2})	96	29	5	60	1.07
Maize planting density (m^{-2})	68	0.44	0.004	1.44	0.05
Groundnut yield (kg ha^{-1})	88	1143	47	4752	114
Groundnut yield designated for: household use (%)	99	48	0	100	0.03
saved seed (%)	99	25	0	100	0.02
sale (%)	99	26	0	88	0.03
Maize yield (kg ha^{-1})	66	751	9	3581	101
Maize yield designated for: household use (%)	68	85	0	100	0.04
saved seed (%)	68	4	0	100	0.02
sale (%)	68	12	0	75	0.03

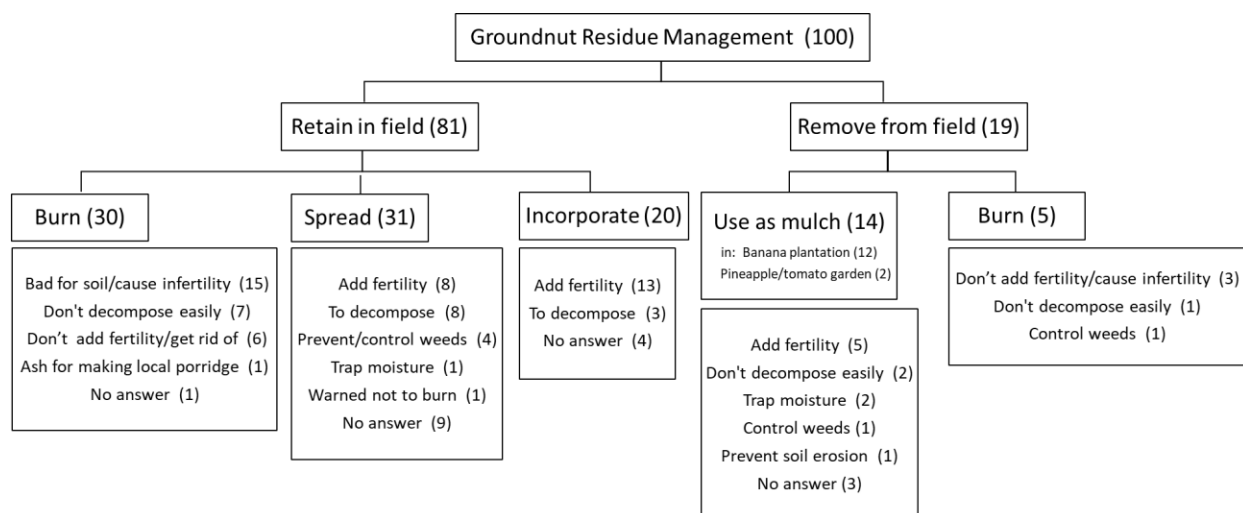


Figure 1.2. Tree diagram illustrating potential fates of groundnut residues with farmer provided explanations for each of the five practices. Number of farmer responses for each management practice or explanation are in parentheses.

Soil fertility

Study area soils are high in organic matter with relatively high C and N values and low C:N (Table 1.4). In comparison to uncultivated reference soils from KNP that represent total potential soil nutrient stocks, the cultivated groundnut field soils contained 24% less total SOC, 44% less TN, and had a 35% wider C:N ratio. An analysis of variance on the normalized groundnut field SOC and TN values found that groundnut residue practices did not significantly alter SOC ($p = 0.695$) or TN ($p = 0.742$) (Figure 1.3).

Table 1.4. SOC, TN, and soil C:N ratios in soils collected from groundnut fields and the uncultivated reference, Kibale National Park (KNP). Values are mean followed by one standard error of the mean (SEM; in parentheses) and letters, where different, indicate significant differences between groundnut cultivated soil compared to KNP soils.

Location	SOC g kg ⁻¹	TN g kg ⁻¹	C:N
Kanyawara	43.62 (5.25)	3.11 (0.35)	13.89 (0.68)
Kyakabuzi	62.67 (5.53)	4.46 (0.36)	13.95 (0.25)
Isunga	53.59 (2.01)	3.31 (0.14)	16.36 (0.46)
Iruhuura	52.95 (3.45)	3.34 (0.22)	15.94 (0.36)
Nyabweya	42.35 (1.67)	2.89 (0.10)	14.65 (0.23)
Kajumiro	33.22 (2.22)	2.16 (0.13)	15.27 (0.27)
Groundnut fields	46.03 (1.52)	3.02 (0.10)	15.27 (0.17)
KNP reference	60.36 (8.22)	5.32 (0.65)	11.50 (0.63)

P-values for comparison of KNP to groundnut fields: SOC $p=0.044$; TN $p=0.000$; C:N $p=0.000$

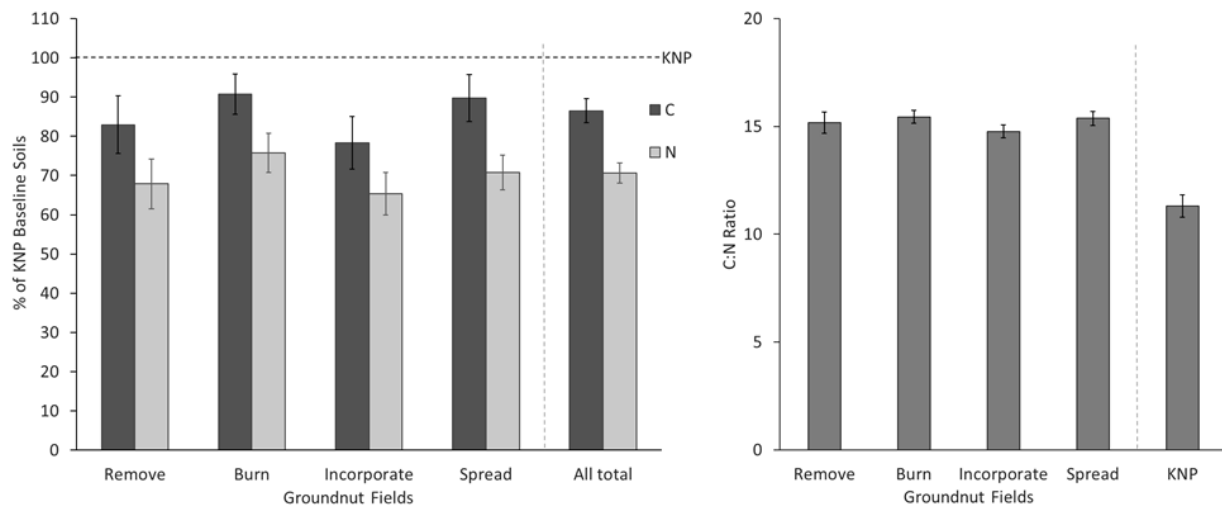


Figure 1.3. Mean groundnut field SOC and TN as a percentage of uncultivated Kibale National Park (KNP) reference soils (A) and groundnut field soil C:N ratios compared to the C:N ratio of KNP soils (B). Across all groundnut fields, SOC ($p=0.044$) and TN ($p=0.000$) were significantly reduced compared to KNP soils. By residue management practice, there were no significant differences between KNP and groundnut fields in SOC, TN or soil C:N ratios. Data are means $\pm$ one standard error.

Groundnut field N balance

The scenario N balances revealed that groundnut stover could contribute positive N balances at all levels of BNF efficiency if residues were fully retained (S1), and that balances would be strongly negative at all levels of BNF efficiency with full stover removal (S2; Figure 1.4). If all residues were retained (S1), groundnut stover could deliver a mean of 23, 65, and 107 kg N ha⁻¹ at the respective BNF efficiency levels of 30, 50, and 70%. At the same respective levels, full groundnut residue removal (S2) could result in mean extant soil N losses of 63, 105, and 147 kg N ha⁻¹ (Figure 1.4).

The partial N balance showed that at the three BNF efficiencies there was no N benefit from groundnut residues unless residues were retained, i.e., spread or incorporated, in which case, mean BNF efficiency benefits ranged from of 22 kg N ha⁻¹ up to 120 kg N ha⁻¹ (Figure 1.5). Removal and burning of groundnut residues resulted in N loss at all levels of BNF efficiency with the greatest losses of 147 and 141 kg N ha⁻¹ respectively, at 30% BNF efficiency (Figure 1.5).

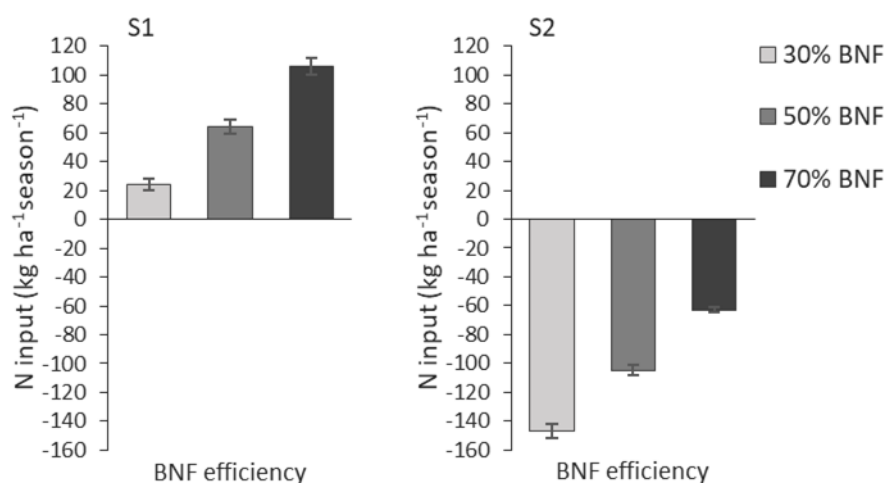


Figure 1.4. Potential N contributions from groundnut stover after grain harvest in 2015 calculated at three BNF efficiencies, i.e., percentage plant N from BNF relative to total plant N demands, under scenario 1 (S1; **A**), full retention of groundnut stover, or scenario 2 (S2; **B**), total removal of groundnut stover. Data are means +/- one standard error.

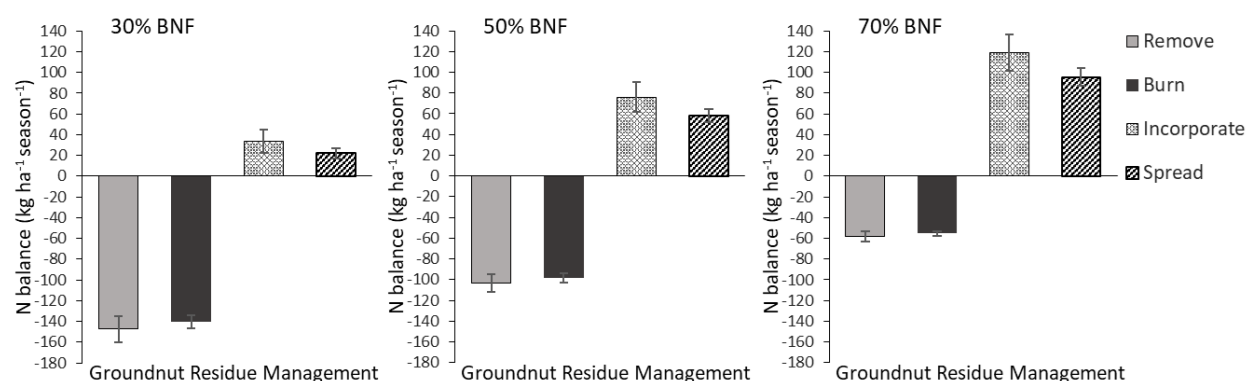


Figure 1.5. Potential N balances for farm fields surveyed in 2015 accounting for N removal through grain harvest calculated at three BNF efficiencies, i.e., percentage groundnut plant N from BNF relative to total plant N demands and grouped by residue management practice. Data are means +/- one standard error.

Determinants of groundnut residue management

Household socioeconomic characteristics were not strongly related to groundnut residue management practices, but variables related to valuation of groundnuts were.

Pearson's chi-squared measures of association did not find significant relationships between groundnut residue management and the ethnicity of respondent, gender of the household head, crop planner, land tenure, wealth ranking, distance from the field to the homestead, or if groundnut was the most sold crop (Table 1.5). There was a significant relationship between the removal of groundnut residues and village with more respondents than expected removing residues in Kanyawara, and fewer than expected in the remaining villages, except for Isunga ($p < 0.05$).

Households that considered groundnut as one of the best crops for improving soil fertility were significantly associated with residue incorporation and residue spread ($p < 0.05$) (Table 1.5). Households that designated groundnut as the most profitable crop were

significantly associated with burning (Table 1.5). Finally, farmers who perceived groundnut residues as “bad” for soil or crop fertility were significantly associated with burning ($p<0.0001$) and were not associated with spreading ($p<0.01$) or incorporating residues ($p<0.05$).

Table 1.5. Chi-square test for relationships between demographic and socioeconomic characteristics, farmer preferences, and groundnut residue management practices in smallholder farm fields along the western border of Kibale National Park (n=100). Data from surveys conducted in July 2015.

				Percent respondents				
				<i>n</i> 100	Remove (<i>n</i> =19)	Burn (<i>n</i> =30)	Incorporate (<i>n</i> =20)	Spread (<i>n</i> =31)
Ethnicity	Batooro	25	24	24	12	40		
	Bakiga	72	17	32	24	28		
	Other	3	33	33	0	33		
	<i>P</i> value		0.59	0.75	0.31	0.52		
Village	Iruhuura	18	6	39	22	33		
	Isunga	21	29	33	14	24		
	Kajumiro	27	15	26	33	26		
	Kanyawara	9	56	11	0	33		
	Kyakabuzi	9	11	22	22	44		
	Nyabweya	16	13	38	13	38		
	<i>P</i> value		0.03*	0.67	0.28	0.85		
	Household Head Gender	Female	25	20	28	28	24	
Male		74	19	31	18	32		
<i>P</i> value			0.88	0.77	0.47	0.24		
Crop Planner		Woman	44	14	39	20	27	
	Man	26	31	15	12	42		
	Multiple	29	17	31	28	24		
	<i>P</i> value		0.33	0.43	0.48	0.20		
Land Tenure, own all land	Yes	75	20	31	16	33		
	No	24	17	29	33	21		
	<i>P</i> value		0.83	0.80	0.16	0.17		
	Wealth Ranking	Below average	24	17	29	13	42	
Average		57	16	28	25	32		
Above average		19	32	37	16	16		
<i>P</i> value			0.3	0.77	0.41	0.19		
Distance from homestead	Homefields	40	15	30	23	33		
	Outfields	60	22	30	18	30		
	<i>P</i> value		0.41	1.00	0.61	0.79		
	Groundnut most sold	Yes	22	18	36	14	32	
No		78	19	28	22	31		
<i>P</i> value			0.91	0.46	0.40	0.93		
Groundnut most profitable		Yes	34	15	47	15	24	
	No	66	21	21	23	35		
	<i>P</i> value		0.43	0.01*	0.34	0.25		
	Groundnut best soil fertility	Yes	57	21	28	28	23	
No		43	16	33	9	42		
<i>P</i> value			0.55	0.63	0.02*	0.04*		
Groundnut residue "bad" for fertility		Yes	18	17	83	0	0	
	No	82	20	18	24	38		
	<i>P</i> value		0.78	0.00***	0.02*	0.00**		

*Significant at $P < 0.05$

**Significant at $P < 0.01$

***Significant at $P < 0.001$

Discussion

In this study I took an agroecological approach, integrating biophysical, social, and economic data, to determine the extent and drivers of SOC and TN relative to groundnut management within smallholder farm fields in western Uganda. I documented the smallholder household, farm and groundnut field characteristics in the western region, an agroecosystem that is not well-profiled in the literature. I found that SOC and especially TN have been depleted relative to uncultivated soils. However, losses are less than those reported for other smallholder farming systems in SSA, which is likely related to the soil parent material and the diverse, intercropping, and rotational cropping systems. Despite groundnut appearing to be the most promising source of N for these fields, my hypothesis that TN would be greater and C:N ratios narrower in fields where groundnut residues were consistently retained was not supported; there were no discernible significant differences by groundnut residue management practice. Differences may have been masked by the highly complex, on-farm environment and highly fertile soils, or perhaps there were not enough groundnut-growing seasons to detect changes (the range was 1-13 seasons with an average of 3.6 seasons). These results may also suggest that groundnut residues do not have a large impact on soil C and N, which could be due to: residue application methods (factors including timing, location, and quantity); limited impact of harvest residues compared to belowground inputs and/or leaf fall throughout the season; or because the fertile soils are not responsive to N addition. Though no effect of groundnut residue practice was evident in SOC and TN, the estimated partial N balances supported my hypothesis that groundnut residues could deliver positive N balances at the field-scale. Residues could make up for grain N losses and deliver substantial N in these low input

fields, even at 30% BNF. The considerable estimated N input is a consequence of the high population density of groundnut plants in combination with moderate to low yields. Importantly, only half of surveyed farmers retained groundnut stover in their fields, and removal or burning of residues resulted in N losses at all levels of BNF, thus negating the potential for groundnut residues to mediate SOM and soil N losses. Residue management practices were not clearly linked to socioeconomic factors related to gender and wealth, but rather highly driven by perception and valuation of groundnut residues as either good or bad for soil fertility or crop yields. I identify important knowledge gaps with respect to groundnut management, residue management and SOM or N benefits from legumes in SSA, as well as the importance of including information about residue management and variety selection to maximize BNF efficiency when legumes are recommended as a component of ecological nutrient management.

Current SOC and N

On average, the cultivated groundnut field soils are degraded compared to the uncultivated KNP reference soils. However, the mean difference in SOC (24%) is less than the reported C decline in other studies comparing tropical forest soils to cultivated fields (Tiessen, Cuevas, & Chacon, 1994; Moebius-Clune et al., 2011). A global meta-analysis examining SOC stocks after land use change found that conversion from native forest to crop resulted in a decline of approximately 50% in the top 30 cm (Guo and Gifford, 2002). A chronosequence in Kenya with similar bimodal precipitation found that the degree of soil degradation in cultivated fields versus primary forest was highly influenced by soil parent material (Moebius-Clune et al.,

2011). The andic soils in the study area have relatively young overlays or rift volcanics that exhibit inherently high levels of fertility, renewed through mineral weathering and characterized by amorphous mineral colloids with large active surfaces to which organic matter readily binds (Young, 1976). The soils have low bulk density, high water holding capacity, and good drainage, making them optimal for plant growth (Shoji et al., 1993). These properties have likely buffered the soils against degradation and C loss in the surveyed fields.

Farmer field management may also have contributed to maintaining or even recouping SOC lost due to forest conversion as farmers intercrop and/or rotate a large diversity of crops (Table 1.2). According to a review of SOC change after adoption of different management practices in tropical croplands, the strongest predictors of C change were quantity of C inputs, experiment duration, and management practices; soil and climate variables did not have an effect (Fujisaki et al., 2018). The review determined that the management practice that resulted in the highest SOC was diversified crop rotation. In the current study, farmers practiced diversified crop rotation, but high rates of crop residue removal (Table 1.2) diminished the quantity of organic matter inputs. Removal of groundnut stover, relatively high in N content, not only removes important organic matter from the system but also a prime N source. The wider C:N ratio found in groundnut fields compared to uncultivated KNP soils is indicative of high N demands that are not being met by organic matter inputs. Instead, competition for N is high, which results in microbial N mining of extant SOM (Craine et al., 2007). The addition of high-quality groundnut residues could provide N and help to narrow the C:N ratio of SOM in farmer fields.

Impact of groundnuts on SOC and TN

The potential N contribution from groundnut stover could increase N availability and thus boost yields and biomass of following crops, creating a positive cycle for C and N additions to the soil (Figures 4 and 5). However, I did not detect evidence of positive benefits of groundnut residue retention to SOM (Figure 1.3). Normalized groundnut field SOC, TN and C:N ratios did not differ significantly by groundnut residue management practice. While these results are somewhat surprising, there are several potential explanations. First, greater production of other intercrops or rotated crops with subsequent removal of their residues may reduce or cancel out potential benefits of groundnuts to the soil. For example, I found that 57% of farmers consistently removed maize residues, either through removal to the banana plantation as mulch or through burning (Table 1.2). For other commonly planted crops like common bean, cassava, and sweet potatoes, residue removal was also high at 58%, 40%, and 37%, respectively (Table 1.2). Without residual biomass retention from maize, common bean, and other crops within these fields, potential for SOM gains from groundnut stover are severely limited.

Second, groundnut residues alone are not enough to influence SOM. Instead, the N they provide stimulates productivity of intercropped or rotated crops such that residue inputs are increased with positive impacts on SOM. Approximately 55% of farmers reported rotating groundnut every third season (i.e., every other year, similar to legume-maize rotations in tropical systems with unimodal precipitation) on the surveyed groundnut field, and only 10% of farms reported planting groundnut in either of the two seasons prior to the study. Here, the N inputs from groundnut stover retention versus non-retention were possibly not great enough,

frequent enough, or available at the necessary time or place to significantly impact productivity and residue inputs from other crops. Timing and placement of residues affect decomposition rates and the potential for N loss through volatilization, denitrification, or leaching. It is also possible that the fertile study area soils could have less agronomic use efficiency of N-rich, high fertilizer equivalent, organic residues, and that the soils could be characterized as fertile, “non-responsive” or “less-responsive” as described by Tifton et al. (2008) and Vanlauwe et al. (2011). In rich, non-responsive or less-responsive soils, N inputs have minimal to no apparent effect on crop productivity. In other systems, groundnuts have been shown to significantly impact grain yields and N availability to subsequent crops. For example, in a study in Zimbabwe, maize crops following a poor groundnut crop still had almost double the grain yield compared to continuous maize (Waddington and Karigwindi, 2001). This benefit of groundnuts to a subsequent maize crop was observed even when the bulk of groundnut stover was grazed by animals and the crops were unfertilized and grown on sandy, low N soil (Waddington and Karigwindi, 2001). In fact, groundnuts in rotation have been shown to almost double the yields of cereal crops compared to continuous cereals, particularly in the case of little-to-no fertilizer N addition (Franke et al., 2018; McDonagh et al., 1993). Leaf fall and belowground N additions from groundnut root exudates and rhizodeposition over the course of the season might explain some of this effect (Giller et al., 1997; Waddington and Karigwindi, 2001). The ‘N-sparing’ effect of legumes (when the majority of harvested N comes from fixation rather than soil N), especially when higher proportions of N are fixed in low soil N conditions, might also help explain increased cereal yields, as might legumes’ disruption of pest and disease cycles within continuous cereal crops (Giller and Cadisch, 1995; Peoples et al., 1995). Because groundnuts

can increase intercrop or rotated crop productivity, which can lead to larger inputs of organic matter, I would expect accumulation of SOM and increases in total SOC in the long-term. However, a review of the effects of grain legume rotations across SSA found few studies ($n=5$) that examined changes in SOM, and those studies generally did not observe effects of a legume-cereal rotation on SOM compared to continuous cereals (Franke et al., 2018). However, as noted by Franke et al. (2018), this may be due to the short duration of most trials, which were less than four years long. Nevertheless, in one study, residue addition was found to significantly increase SOC and TN after each of three consecutive seasons of a maize-soybean rotation and conservation tillage experiment in the bimodal system of western Kenya (Anyanzwa et al., 2010). My study and the studies included in the review (Franke et al., 2018), focused on total SOC and TN, which usually change over the longer term and often may take many years to exhibit significant changes by management practice (West and Post, 2002). Measurement of SOC and TN in more management sensitive, rapid-cycling SOM pools (e.g., within aggregates, dissolved organic carbon (DOC) and nitrogen (DON)) may better capture the impact of grain legumes on SOC and N dynamics .

Finally, the lack of a detectable effect of retention versus removal of groundnut residues is also surprising given that in the study area, groundnut was planted at a density higher than the official recommendation by Uganda's National Agricultural Research Organization (NARO) of 15 plants m^{-2} for unirrigated production and closer to the recommended 30 plants m^{-2} for irrigated fields (Kefa, 2013). Also, all farmers planted groundnut over the whole field rather than the recommended spacing of 30 to 45 cm rows (Kefa, 2013); broad field coverage has many possible advantages including reduced soil erosion and weed competition. "Square

spacing,” or the equal spacing of groundnut plants over the growing area, has been shown to have positive benefits and to maximize both total plant biomass and groundnut yield (Gardner and Auma, 1989; Jaaffar and Gardner, 1988). Results in the literature are mixed regarding groundnut plant population density and its effect on grain yield and stover production, groundnut variety and growth habit (bunch versus runner) and environmental conditions are critical to the density at which yields and biomass are maximized; maximum density values ranged from 20 to 50 plants m⁻² (Bell et al., 1987; Bell and Wright, 1998; Tarimo and Blarney, 1999). Documentation of on-farm groundnut planting density and spacing is lacking in the literature, and I found only one study that documented groundnut plant density as practiced on-farm by farmers in SSA and not in researcher-mandated, on-farm trials (Nyemba and Dakora, 2010). Bell and Wright (1998) observed that groundnuts grown in humid tropical environments had low pod yields and low harvest indices, necessitating high plant densities to maximize production. In this study, the high plant density did not correlate to high yields, but yields could be affected by a number of factors including groundnut variety, seed quality, environmental conditions, intraspecific or interspecific competition, pests and disease, timing of planting, or because yield data was farmer-reported/estimated and yields were not determined at a standardized moisture content. Nevertheless, the farmer-reported yields were comparable to on-farm trial yields reported by Ojiem et al. (2007) from similar agroecological zones in western Kenya, though in that study the groundnut planting density was 20 plants m⁻². If the high planting density equated to a large volume of aboveground biomass with correspondingly low grain yield, the potential net C and N input should be sizable, yet I saw no evidence of this potential benefit in SOC and TN.

Groundnut residue management practices

If aboveground residues are retained on fields, farmers can maximize the full N benefits from groundnut BNF to soil, as well as contribute to SOM. However, in the current study, I found that 49% of farmers did not retain groundnut residues. The assumption that legumes like groundnuts can improve soil fertility and increase crop yields is largely based on best management practices. Studies that specifically address farmer management of groundnut residues are rare in the literature. Several studies in Thailand attempted to address groundnut residue management practices, but these studies present what may be considered an optimal potential N credit from groundnut residues in that the groundnut crop was treated and managed according to recommended best practices (e.g. seeded and fertilized at the recommended rates, and managed for weeds, pests and disease), which is often not achieved or realistic on smallholder farms (McDonagh et al., 1993; Phoomthaisong et al., 2003; Srichantawong et al., 2005; Toomsan et al., 2000, 1995). Also, in these studies, the groundnut residues returned to the fields were chopped to 10 cm lengths, which would greatly impact rates of decomposition and timing of N availability to a subsequent crop, and is a labor-intensive step that the majority of smallholder farmers are unlikely to take (McDonagh et al., 1993; Phoomthaisong et al., 2003; Srichantawong et al., 2005; Toomsan et al., 2000, 1995). While groundnut residues retained on fields could contribute N to a following crop, another potential hurdle is the timing of N release from residues, and the N demand by a following crop is difficult to predict and synchronize (Robertson et al., 1997). Two studies that looked at the time gap between the planting of the next crop and the post-harvest surface-application or incorporation of groundnut residues found no significant differences in N delivery from surface-

applied versus incorporated residues (Promsakha et al., 2005; Srichantawong et al., 2005).

Overall, there is a lack of studies on groundnut residue contributions to soil N and none seem to fully replicate resource-limited, smallholder farmer management practices.

Factors driving groundnut residue management practices

In the study area, groundnut residue management practices appear to be driven by perceptions and valuation of groundnut stover. Respondents gave various explanations for groundnut residue management decisions, and these decisions seem to be largely based on the perception of groundnut residue fertility or utility (Figure 1.2). Most farmers explained that they incorporated or spread groundnut residues in the field or as mulch in the banana plantation because residues added fertility. Bananas are the main staple food crop, and the transfer of residues to the banana plantation to boost yields through the benefits of added fertility, trapped soil moisture or weed prevention, makes sense in these resource-limited agroecosystems. On the contrary, most farmers who burned residues in the field, or removed residues and burned them elsewhere, perceived groundnut residues as “bad” for the soil, causing soil infertility or not benefiting soil fertility (Figure 1.2). Respondents were often not able to explain their reason for believing groundnut stover was “bad,” but several farmers mentioned burning had been recommended in the past as means to eradicate disease and/or pests, which are noted concerns with residue retention (Erenstein, 2002). The basis for the negative perception of groundnut residue within the study area warrants further investigation. I found that perception of residues as “bad” was significantly linked to the practice of burning residues, while in contrast a significant proportion of farmers who named groundnut as one of

the best crops to plant to improve crop yields or soil fertility also reported spreading or incorporating groundnut stover (Table 1.5).

In western Uganda, the bimodal rainfall and two possible growing seasons usually dictate a short, approximately two-month, gap between groundnut harvest and the field preparation and planting of a following crop. This shortens the time period for residue decomposition and means that farmers may have to deal with ample amounts of residue biomass in field preparation, which might help explain why 10% of farmers responded that they burn or remove groundnut residues because they do not easily decompose (Figure 1.2). Furthermore, a wide variety of crops (Table 1.2) are intercropped and rotated in these fields and relay cropping is common, which, though not explicitly stated by any respondent, may present another challenge to residue retention and the incorporation and/or surface spreading of residues among crops present in the field.

I found no strong relationships between groundnut residue management practices and social and economic factors that have previously been shown in the literature to be drivers of farmer management decisions in SSA (e.g., gender of the household head, crop planner, ethnic group, land ownership, wealth rank, field distance from the homestead). This suggests that perception of groundnut fertility and farmer resources affecting residue management practices are unrelated to these factors (Table 1.5). A commonly identified tradeoff in the literature is the use of residues as livestock feed (Tittonell et al., 2015; Valbuena et al., 2015), but livestock holdings are low in the study area and no household indicated that groundnut residues were used to feed livestock; only sweet potato and cassava residues were distinguished as animal feed. Respondents who listed groundnut as their most profitable crop were more likely to burn

the residues, which is a relationship that requires further testing and exploration as it could be linked to various different drivers, such as time and labor availability, residue biomass amount, and management at farm-scale. There was also a significant relationship among the village and removal of groundnut residues, with residue removal occurring more frequently than expected in the village of Kanyawara, but this relationship may be exaggerated because of the small sample size.

In order to make effective recommendations and to enhance adoption of beneficial practices it is important for any extension or agricultural development agency working within the region to know and understand drivers of management practice. This knowledge is necessary for devising and implementing local or regional policy, for example residue burning regulations.

Groundnut residue management impacts on soil N balance

The groundnut field N balances were calculated using estimated N input from groundnut residues minus the N exported by groundnut grain while also factoring in residue management practices (i.e., spreading, incorporating, removing, or burning). The N input from fully-retained groundnut residues (S1) could provide a substantial N credit at all three levels of BNF (Figure 1.4). The mean benefit from groundnut residues at 30% BNF is approximately 22 kg N ha⁻¹ season⁻¹, while at 70% BNF it is approximately 120 kg N ha⁻¹ season⁻¹; both values are considerable in a no-to-low-input system. Giller and Cadisch (1995) estimated that to offset N losses in SSA, a legume crop needed to fix an average of 30 kg N ha⁻¹ year⁻¹. At higher levels of BNF, a groundnut crop could deliver that level of N in residues alone, and if additional

belowground N inputs were included, groundnut would likely surpass that requirement.

However, there are a number of factors that combine to determine the N provisioning potential of groundnut stover, most of which have been inadequately researched, including: stover quantities and N concentrations under different climates and soil types; roots and rhizodeposition; BNF efficiencies across varieties and environmental conditions and intercrop arrangements; management of residues (e.g., timing of addition, spreading versus burying); and residue decomposition and potential volatilization and leaching of N.

To estimate the N contribution from groundnut stover, I used an initial estimation of 0.7 g N plant⁻¹ as this fell in the mid-range of N values per groundnut plant in SSA (Mokgehle et al., 2014; Ncube et al., 2007; Nyemba and Dakora, 2010; Ojiem et al., 2007; Oteng-Frimpong and Dakora, 2018), and it was similar to the mean value for plants grown in high and medium fertility fields in similar agroecosystems and environmental conditions in western Kenya (Ojiem et al., 2007). Although similar, the soils in the current study region contained almost twice the soil N and almost three times the SOC as the high and medium fertility soils in the Kenyan study (Ojiem et al., 2007). I did not find examples in the literature in which groundnut BNF had been determined on fields with higher fertility. I found one study from Uganda that calculated groundnut BNF on farmers' fields, but it was from the eastern region and in that study no grain yield was obtained due to late-season drought, which likely also led to the groundnut N plant⁻¹ being extremely low (135-595 mg plant⁻¹) and having a wide-ranging N contribution from BNF (8% to 70%) (Ebanyat et al., 2010).

I performed a sensitivity analysis to examine a span of BNF efficiencies, not only to reflect the fact that BNF can fluctuate by variety and season-to-season (Mokgehle et al., 2014;

Oteng-Frimpong and Dakora, 2019), but also because there is no precedent for groundnut BNF on soils with such high TN, where legume nodulation and BNF may be suppressed by large pools of available soil N (Giller and Cadisch, 1995). A study in South Africa determined N fixation levels for 25 groundnut cultivars grown at three different sites and concluded that lower N fixation rates at one site were due to higher endogenous levels of soil N, which resulted in groundnut fixing less N and, instead, taking up more soil N (Mokgehle et al., 2014). However, Ojiem et al. (2007) found that BNF generally decreased with soil fertility levels and BNF was less in low fertility versus high fertility fields, suggesting potential for other limiting nutrients (e.g., phosphorus) to play a role in BNF. Intercropping legumes with cereals and other non-N fixing crops, as was the case in 88% of the groundnut fields I surveyed, can lead to reductions in soil N concentrations that then promote greater nodulation and BNF (Giller and Cadisch, 1995), but only if BNF is not limited by other nutrients.

Residue management is also critical to achieving an N benefit and if all groundnut stover were removed (S2), groundnut would be a heavy miner of soil N at all levels of BNF (Figure 1.4). Even the simplified N balances confirm the importance of management in combination with BNF as field balances were only positive when residues were spread and incorporated (Figure 1.4). I chose to use the maximum of 100% N delivery for residues that were spread or incorporated to help illustrate the full potential N benefit of groundnut stover. If there was loss of retained residue (e.g., through livestock grazing or pests) or retained residue N (e.g., through ammonia volatilization or nitrate leaching), which is likely, then nutrient balances would be reduced (Figures 5). Further, I chose to use a minimum of 5% N delivery for residues that were burned or removed, though it is probable that the total combustion of residues is inconsistent,

as is the proportion of residue material left in the field. Importantly, the field-scale partial N balance establishes reference points for farmers, extension agents, and policymakers when estimating a *potential* N credit from groundnut residues within the context of management practices.

While the partial N balances do not account for the N loss from the diverse number of additional crops grown at the field-scale and other potential inputs and outputs, the estimated N inputs suggest that full retention of residues at the higher levels of BNF could reduce or counter additional N exports. The average seasonal maize yield for western Uganda is approximately 2600 kg ha⁻¹ season⁻¹ (UBOS, 2010), which would remove about 41 kg N ha⁻¹ season⁻¹ at a maize grain N concentration of 1.57% (Kaizzi et al., 2012a). This output could be balanced by groundnut residues if BNF efficiency was 50% or greater and residues were retained (Figures 4 & 5). Notably, the N balances only considered the N input from aboveground groundnut residues and did not account for leaf fall during the season or potential belowground N additions from unrecovered roots and nodules and rhizodeposition, contributions, which have been estimated to account for 30 to 50% of plant N (Giller et al., 1997; Herridge et al., 2008; Unkovich and Pate, 2000). Additionally, there could be N contributions from the other legume crops grown on these farms (i.e. common bean and pea), but their N contributions are likely far less relative to groundnut as common bean has been shown to be poor at BNF and pea is not widely grown (Franke et al., 2018; Herridge et al., 2008).

With substantial N inputs concentrated on fields planted to groundnut, these results suggest that overall N balances at the farm-level would be negative considering the mean yields

and diversity of other crops (Table 1.2). Negative farm-level N balances would be in line with previously published nutrient balances in Uganda which found negative or near zero N, P, and K values at all levels of scale across all regions of the country, with few exceptions (Bekunda and Manzi, 2003; Briggs and Twomlow, 2002; de Jager et al., 2004; Ebanyat et al., 2010; Lederer et al., 2015; Mubiru et al., 2011; Nkonya et al., 2005; Sheldrick and Lingard, 2004; Stoorvogel and Smaling, 1990; Wortmann and Kaizzi, 1998). More neutral farm-level N balances might be achieved through an increase in groundnut production.

Increasing groundnut grown through more frequent rotations or land planted to groundnut could contribute to greater N inputs, but after household groundnut needs are met, there would need to be market opportunities to support greater production. Planting groundnut more frequently could lead to greater incidences of pest and disease, and advice from Uganda's NARO is to plant groundnut every three years or more to prevent such buildups (Okello et al., 2014). Farmers are already planting groundnut more frequently than this recommendation as approximately 55% of farmers reported rotating groundnut every third season on the surveyed field. Farmers in the study area are land-limited as evidenced by the small field sizes, and 45% of farmers who intercropped said they did so because of limited land. Thus, expanding the area cropped to groundnut may not be feasible or meet household needs.

Another possible means to boost groundnut growth, fixation, and overall productivity could be the addition of phosphorus (P), as P deficiency has been found to constrain legume yield and plant tissue N concentration (Giller and Cadisch, 1995). In eastern Uganda, Ebanyat et al., (2010) saw up to 40% increases in groundnut N fixation in fields with inputs of 30 kg ha⁻¹ P versus fields without added P, though differences were not significant and highly inconsistent.

In fertilizer response trials conducted at six different locations in Uganda, groundnut grain yields increased significantly with application of P fertilizer, but the response differed by variety (Kaizzi et al., 2012b). The authors concluded that groundnut grain yield was not related to soil properties, e.g. SOM, or previous crop, which they found to be in agreement with earlier research by Foster (1980)(Kaizzi et al., 2012b).

Groundnut yield increases are challenged by the fact that an estimated 80% of the groundnut seed is saved, may be of more inferior quality, and it is overwhelmingly from traditional, low-yielding varieties (Okello et al., 2010). There is a tradeoff between grain production and soil inputs because yield increases can lead to larger amounts of N exported in grain resulting in lower soil N balances, thus, in this regard, low-yielding varieties could be considered advantageous for soil fertility (Kermah et al., 2018; Ojiem et al., 2007). Crop yields and BNF are affected by climate and water availability, and within the study region, rainfall has been shown to be highly variable in its timing, and, while total rainfall has not changed significantly, the intra-seasonal distribution has (Hartter et al., 2012). Climate change and changes to the timing and distribution of rainfall heighten the uncertainty for all crop production, including groundnut, which in turn heightens the impact and importance of farmer management decisions and practices.

Conclusion

Grain legumes like groundnut have the potential to contribute N-rich residues to boost SOC and TN and increase N available to other crops. Here, I estimated groundnut residue N delivery within minimal input, smallholder fields and found that a high plant population density

combined with moderate yields resulted in a potentially substantive net N input, even at low BNF efficiency. This benefit can be fully realized if farmers retained residues on fields. However, after normalizing surveyed field soils using uncultivated reference soils from KNP, I did not find any evidence of differences in SOC or TN from fields where groundnut residues were retained versus fields where they were removed. The high soil fertility inherent to the study area and the prevalence of diverse crop rotations, intercropping, and residue practices may have masked effects. It is also possible that leaf fall or belowground additions throughout the season had more of an impact than groundnut residue addition or removal. The number of seasons that groundnut was included in rotation may also not have been enough to capture SOC and TN changes that generally occur slowly.

I found that the main groundnut residue tradeoff was its use as mulch in banana plantations, and, unexpectedly, that 35% of farmers did not value groundnut as an input or saw residues as “bad” with negative soil fertility and yield consequences. The valuation of groundnut residue as a soil fertility input was significantly related to management practices and linked to whether farmers spread, incorporated, burned, or removed residues. Socioeconomic factors connected to gender and wealth that previously have been identified in the literature as drivers of farmer practice in SSA were not found to be significant.

While this study focused on groundnut contributions to soil health, sustainability, and agricultural productivity, groundnut also provides essential nutrition and generates crucial income to support the health and wellbeing of smallholder farmers. Approximately half of the groundnut harvest in the surveyed fields was intended for household consumption, while approximately 25% of the harvest was sold. Nutrient-rich groundnuts increase food security

and diversify diets by providing protein, micronutrients, and phytochemicals to resource-poor households. Sale of groundnuts can generate high profits and bring in important income that may also contribute to food security. Though groundnut was second to maize in terms of household crop sales, households identified groundnut as the most profitable crop (34%) with maize a close second (31%). The majority of households (77%) categorized themselves as “very much” dependent on income from crop sales, thus groundnuts generate vital income for these smallholder households.

This study presents a valuable snapshot of a growing season, but multi-year studies are needed to fully assess the impact of groundnut on SOC and TN. There is a dearth of long-term studies examining the effects of grain legume rotations on SOM and soil properties in SSA. I recognize that there is a need to move beyond examination of legumes’ potential benefits to soil and to institute trials to document changes over the long-term. Studies have mainly focused on changes in SOC and TN, as I did here, but I recommend quantification and analysis of more management sensitive, early indicators of SOC and N change, such as C and N within aggregates and DOC/DON. I used literature values to construct the N balance, and, in the process, I found few studies that examined groundnut plant total N, plant N partitioning, and N derived via BNF in farmer fields. I also did not find studies examining high plant population density and spacing effects on groundnut N uptake and BNF. Similarly, few studies examine the effects of farmer practices like removal, burning, incorporation, and surface spreading of groundnut residues on N retention in soil and N availability; I found several studies from other regions that addressed some of these practices but no in-depth analyses from SSA. Future research is needed to address these knowledge gaps, to gain a better understanding of groundnut’s impact on soil

fertility and to elucidate residue management practices that maximize short-term and long-term benefits to farmers and soil.

REFERENCES

REFERENCES

- Akibode, S., Maredia, M., 2012. Global and Regional Trends in Production, Trade and Consumption of Food Legume Crops, Department of Agricultural, Food and Resource Economics, Department of Agricultural, Food and Resource Economics Michigan State University Staff Paper. <https://doi.org/10.22004/ag.econ.136293>
- Anyanzwa, H., Okalebo, J.R., Othieno, C.O., Bationo, A., Waswa, B.S., Kihara, J., 2010. Effects of conservation tillage, crop residue and cropping systems on changes in soil organic matter and maize-legume production: A case study in Teso District. *Nutr. Cycl. Agroecosystems* 88, 39–47. <https://doi.org/10.1007/s10705-008-9210-2>
- Barrett, C.B., Bevis, L.E.M., 2015. The self-reinforcing feedback between low soil fertility and chronic poverty. *Nat. Geosci.* 8, 907–912. <https://doi.org/10.1038/ngeo2591>
- Bekunda, M., Manzi, G., 2003. Use of the partial nutrient budget as an indicator of nutrient depletion in the highlands of southwestern Uganda. *Nutr. Cycl. Agroecosystems* 67, 187–195. <https://doi.org/10.1023/A:1025509400226>
- Bell, M.J., Muchow, R.C., Wilson, G.L., 1987. The effect of plant population on peanuts (*Arachis hypogaea*) in a monsoonal tropical environment. *F. Crop. Res.* 17, 91–107. [https://doi.org/10.1016/0378-4290\(87\)90085-2](https://doi.org/10.1016/0378-4290(87)90085-2)
- Bell, M.J., Wright, G.C., 1998. Groundnut growth and development in contrasting environments 1. Growth and plant density responses. *Exp. Agric.* 34, 99–112. <https://doi.org/10.1017/S001447979800101X>
- Briggs, L., Twomlow, S.J., 2002. Organic material flows within a smallholder highland farming system of South West Uganda. *Agric. Ecosyst. Environ.* 89, 191–212. [https://doi.org/10.1016/S0167-8809\(01\)00164-5](https://doi.org/10.1016/S0167-8809(01)00164-5)
- Cadisch, G., Hairiah, K., Giller, K.E., 2000. Applicability of the natural N-15 abundance technique to measure N-2 fixation in *Arachis hypogaea* grown on an Ultisol. *Netherlands J. Agric. Sci.* 48, 31–45. [https://doi.org/10.1016/S1573-5214\(00\)80003-2](https://doi.org/10.1016/S1573-5214(00)80003-2)
- Chapman, C.A., Lambert, J.E., 2000. Habitat alteration and the conservation of African primates: Case study of Kibale National Park, Uganda. *Am. J. Primatol.* 50, 169–185. [https://doi.org/10.1002/\(SICI\)1098-2345\(200003\)50:3<169::AID-AJP1>3.0.CO;2-P](https://doi.org/10.1002/(SICI)1098-2345(200003)50:3<169::AID-AJP1>3.0.CO;2-P)
- Corder, G.W., Foreman, D.I., 2009. Nonparametric statistics for non-statisticians: a step-by-step approach.

- Craine, J.M., Morrow, C., Fierer, N., 2007. Microbial nitrogen limitation increases decomposition. *Ecology* 88, 2105–2113. <https://doi.org/10.1890/06-1847.1>
- Dakora, F.D., Keya, S.O., 1997. Contribution of legume nitrogen fixation to sustainable agriculture in sub-saharan Africa. *Soil Biol. Biochem.* [https://doi.org/10.1016/S0038-0717\(96\)00225-8](https://doi.org/10.1016/S0038-0717(96)00225-8)
- de Jager, A., Onduru, D., Walaga, C., 2004. Facilitated learning in soil fertility management: Assessing potentials of low-external-input technologies in east African farming systems. *Agric. Syst.* 79, 205–223. [https://doi.org/10.1016/S0308-521X\(03\)00071-4](https://doi.org/10.1016/S0308-521X(03)00071-4)
- Ebanyat, P., de Ridder, N., de Jager, A., Delve, R.J., Bekunda, M.A., Giller, K.E., 2010. Drivers of land use change and household determinants of sustainability in smallholder farming systems of Eastern Uganda. *Popul. Environ.* 31, 474–506. <https://doi.org/10.1007/s11111-010-0104-2>
- Ebanyat, P., de Ridder, N., de Jager, A., Delve, R.J., Bekunda, M.A., Giller, K.E., 2010. Impacts of heterogeneity in soil fertility on legume-finger millet productivity, farmers' targeting an economic benefits. *Nutr. Cycl. Agroecosystems.* <https://doi.org/10.1007/s10705-009-9329-9>
- Erenstein, O., 2002. Crop residue mulching in tropical and semi-tropical countries: An evaluation of residue availability and other technological implications. *Soil Tillage Res.* 67, 115–133. [https://doi.org/10.1016/S0167-1987\(02\)00062-4](https://doi.org/10.1016/S0167-1987(02)00062-4)
- Erenstein, O., Gérard, B., Tittone, P., 2015. Biomass use trade-offs in cereal cropping systems in the developing world: Overview. *Agric. Syst.* 134, 1–5. <https://doi.org/10.1016/j.agsy.2014.12.001>
- FAO, 2010. Crop calendar – An information tool for seed security, Uganda agro-ecological zones [WWW Document]. URL <http://www.fao.org/agriculture/seed/cropcalendar/aezones.do?isocode=UGA> (accessed 11.9.19).
- Foster, H.L., 1980. The influence of soil fertility on crop performance in Uganda. 2. Groundnuts., *Tropical Agriculture*.
- Foyer, C.H., Lam, H.M., Nguyen, H.T., Siddique, K.H.M., Varshney, R.K., Colmer, T.D., Cowling, W., Bramley, H., Mori, T.A., Hodgson, J.M., Cooper, J.W., Miller, A.J., Kunert, K., Vorster, J., Cullis, C., Ozga, J.A., Wahlqvist, M.L., Liang, Y., Shou, H., Shi, K., Yu, J., Fodor, N., Kaiser, B.N., Wong, F.L., Valliyodan, B., Considine, M.J., 2016. Neglecting legumes has compromised human health and sustainable food production. *Nat. Plants* 2, 1–10. <https://doi.org/10.1038/NPLANTS.2016.112>

- Franke, A.C., Brand, van den, G.J., Vanlauwe, B., Giller, K.E., 2018. Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. *Agric. , Ecosyst. Environ.* 261, 172–185. <https://doi.org/10.1016/j.agee.2017.09.029>
- Fujisaki, K., Chevallier, T., Chapuis-Lardy, L., Albrecht, A., Razafimbelo, T., Masse, D., Ndour, Y.B., Chotte, J.L., 2018. Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: A synthesis. *Agric. Ecosyst. Environ.* 259, 147–158. <https://doi.org/10.1016/j.agee.2017.12.008>
- Gardner, F.P., Auma, E.O., 1989. Canopy structure, light interception, and yield and market quality of peanut genotypes as influenced by planting pattern and planting date. *F. Crop. Res.* 20, 13–29. [https://doi.org/10.1016/0378-4290\(89\)90020-8](https://doi.org/10.1016/0378-4290(89)90020-8)
- Giller, K.E., 2001. *Nitrogen Fixation in Tropical Cropping Systems*, CABI. Wallingford, UK.
- Giller, K.E., Cadisch, G., 1995. Future benefits from biological nitrogen fixation: An ecological approach to agriculture. *Plant Soil* 174, 255–277. <https://doi.org/10.1007/BF00032251>
- Giller, K.E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W.D., Mafongoya, P.L., 1997. Building Soil Nitrogen Capital in Africa, in: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), *Replenishing Soil Fertility in Africa*, SSSA Spec. Publ. 51. SSSA and ASA, Madison, WI, pp. 151–192. <https://doi.org/10.2136/sssaspecpub51.c7>
- Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis 8, 345–360. <https://doi.org/10.1046/j.1354-1013.2002.00486.x>
- Hailelassie, A., Priess, J. a., Veldkamp, E., Lesschen, J.P., 2007. Nutrient flows and balances at the field and farm scale: Exploring effects of land-use strategies and access to resources. *Agric. Syst.* 94, 459–470. <https://doi.org/10.1016/j.agry.2006.11.013>
- Hartter, J., 2010. Resource Use and Ecosystem Services in a Forest Park Landscape. *Soc. Nat. Resour.* 23, 207–223. <https://doi.org/10.1080/08941920903360372>
- Hartter, J., Southworth, J., 2009. Dwindling resources and fragmentation of landscapes around parks: Wetlands and forest patches around Kibale National Park, Uganda. *Landsc. Ecol.* 24, 643–656. <https://doi.org/10.1007/s10980-009-9339-7>
- Hartter, J., Stampone, M.D., Ryan, S.J., Kirner, K., Chapman, C.A., Goldman, A., 2012. Patterns and perceptions of climate change in a biodiversity conservation hotspot. *PLoS One* 7. <https://doi.org/10.1371/journal.pone.0032408>
- Herridge, D.F., Peoples, M.B., Boddey, R.M., 2008. Global inputs of biological nitrogen fixation in agricultural systems. *Plant Soil* 311, 1–18. <https://doi.org/10.1007/s11104-008-9668-3>

- Hockett, M., Richardson, R.B., 2018. Examining the drivers of agricultural experimentation among smallholder farmers in Malawi. *Exp. Agric.* 54, 45–65. <https://doi.org/10.1017/S0014479716000673>
- Jaaffar, Z., Gardner, F.P., 1988. Canopy Development, Yield, and Market Quality in Peanut as Affected by Genotype and Planting Pattern. *Crop Sci.* 28, 299–305. <https://doi.org/10.2135/cropsci1988.0011183x002800020024x>
- Jameson, J.D., 1970. *Agriculture in Uganda*. 2nd ed., Agriculture in Uganda. 2nd ed. London, UK: Oxf. Univ. Press.
- Kaizzi, K.C., Byalebeka, J., Semalulu, O., Alou, I., Zimwanguyizza, W., Nansamba, A., Musinguzi, P., Ebanyat, P., Hyuha, T., Wortmann, C.S., 2012a. Maize response to fertilizer and nitrogen use efficiency in Uganda. *Agron. J.* <https://doi.org/10.2134/agronj2011.0181>
- Kaizzi, K.C., Byalebeka, J., Semalulu, O., Alou, I.N., Zimwanguyizza, W., Nansamba, A., Odama, E., Musinguzi, P., Ebanyat, P., Hyuha, T., Kasharu, A.K., Wortmann, C.S., 2012b. Optimizing smallholder returns to fertilizer use: Bean, soybean and groundnut. *F. Crop. Res.* 127, 109–119. <https://doi.org/10.1016/j.fcr.2011.11.010>
- Kassie, M., Teklewold, H., Jaleta, M., Marennya, P., Erenstein, O., 2015. Understanding the adoption of a portfolio of sustainable intensification practices in eastern and southern Africa. *Land use policy.* <https://doi.org/10.1016/j.landusepol.2014.08.016>
- Kefa, O.H., 2013. *Groundnut Production Guide for Uganda : GROUNDNUT PRODUCTION GUIDE FOR UGANDA : Recommended practices for farmers*, National Agricultural Research Organisation, Entebbe.
- Kermah, M., Franke, A.C., Adjei-nsiah, S., Ahiabor, B.D.K., Abaidoo, R.C., Giller, K.E., 2018. N₂ - fixation and N contribution by grain legumes under different soil fertility status and cropping systems in the Guinea savanna of northern Ghana. *Agric. Ecosyst. Environ.* 261, 201–210. <https://doi.org/10.1016/j.agee.2017.08.028>
- Kirner, K., 2010. *Agricultural Variation and Change Among Batoro and Bakiga*. University of Florida.
- Lederer, J., Karungi, J., Ogwang, F., 2015. The potential of wastes to improve nutrient levels in agricultural soils: A material flow analysis case study from Busia District, Uganda. *Agric. Ecosyst. Environ.* 207, 26–39. <https://doi.org/10.1016/j.agee.2015.03.024>
- Lepp, A., Holland, S., 2006. A comparison of attitudes toward state-led conservation and community-based conservation in the village of Bigodi, Uganda. *Soc. Nat. Resour.* 19, 609–623. <https://doi.org/10.1080/08941920600742377>

- Majaliwa, J.G.M., Twongyirwe, R., Nyenje, R., Oluka, M., Ongom, B., Sirike, J., Mfitumukiza, D., Azanga, E., Natumanya, R., Mwerera, R., Barasa, B., 2010. The Effect of Land Cover Change on Soil Properties around Kibale National Park in South Western Uganda. *Appl. Environ. Soil Sci.* 2010, 1–7. <https://doi.org/10.1155/2010/185689>
- McDonagh, J.F., Toomsan, B., Limpinuntana, V., Giller, K.E., 1993. Estimates of the residual nitrogen benefit of groundnut to maize in Northeast Thailand. *Plant Soil* 267–277. <https://doi.org/10.1007/BF00012532>
- Messina, M.J., 1999. Legumes and soybeans: Overview of their nutritional profiles and health effects. *Am. J. Clin. Nutr.* 70. <https://doi.org/10.1093/ajcn/70.3.439s>
- Moebius-Clune, B.N., van Es, H.M., Idowu, O.J., Schindelbeck, R.R., Kimetu, J.M., Ngoze, S., Lehmann, J., Kinyangi, J.M., 2011. Long-term soil quality degradation along a cultivation chronosequence in western Kenya. *Agric. Ecosyst. Environ.* 141, 86–99. <https://doi.org/10.1016/j.agee.2011.02.018>
- Mokgehele, S.N., Dakora, F.D., Mathews, C., 2014. Variation in N₂ fixation and N contribution by 25 groundnut (*Arachis hypogaea* L.) varieties grown in different agro-ecologies, measured using ¹⁵N natural abundance. *Agric. Ecosyst. Environ.* 195, 161–172. <https://doi.org/10.1016/j.agee.2014.05.014>
- Mubiru, L.S., Romney, D., Halberg, N., Tenywa, J.S., 2011. Development of nutrient management strategies based on mapping of nitrogen flows and balances in dairy production systems in Uganda. *Livest. Sci.* 137, 116–123. <https://doi.org/10.1016/j.livsci.2010.10.009>
- Mugisa, I.O., Karungi, J., Akello, B., Ochwo Ssemakula, M.K.N., Biruma, M., Okello, D.K., Otim, G., 2015. Assessing the effect of farmers practices on the severity of groundnut rosette virus disease in Uganda. *African J. Agric. Res.* 10, 995–1003. <https://doi.org/10.5897/ajar2014.9171>
- Nandwa, S.M., Bekunda, M.A., 1998. Research on nutrient flows and balances in East and Southern Africa: State-of-the-art. *Agric. Ecosyst. Environ.* 71, 5–18. [https://doi.org/10.1016/S0167-8809\(98\)00128-5](https://doi.org/10.1016/S0167-8809(98)00128-5)
- Naughton-Treves, L., 1997. Farming the forest edge: vulnerable places and people around Kibale National Park, Uganda. *Geogr. Rev.* 87, 27–46. <https://doi.org/10.2307/215656>
- Ncube, B., Twomlow, S.J., Van Wijk, M.T., Dimes, J.P., Giller, K.E., 2007. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in southwestern Zimbabwe. *Plant Soil* 299, 1–15. <https://doi.org/10.1007/s11104-007-9330-5>
- Nijhof, K., 1987. The Concentrations of Macro-elements in Economic Products and Residues of

Subtropical Field Crops, Staff working paper : Centre for World Food Studies. Centre for World Food Studies.

- Nijuki, J.M., Mapila, M.T., Zingore, S., Delve, R., 2008. The dynamics of social capital in influencing use of soil management options in the Chinyanja Triangle of Southern Africa. *Ecol. Soc.* 13, 13(2):[1-16]. <https://doi.org/10.5751/es-02539-130209>
- Nkonya, E., Kaizzi, C., Pender, J., 2005. Determinants of nutrient balances in a maize farming system in eastern Uganda. *Agric. Syst.* 85, 155–182. <https://doi.org/10.1016/j.agsy.2004.04.004>
- Nyemba, R.C., Dakora, F.D., 2010. Evaluating N₂ fixation by food grain legumes in farmers' fields in three agro-ecological zones of Zambia, using ¹⁵N natural abundance. *Biol. Fertil. Soils* 46, 461–470. <https://doi.org/10.1007/s00374-010-0451-2>
- Ojiem, J.O., Franke, A.C., Vanlauwe, B., de Ridder, N., Giller, K.E., 2014. Benefits of legume-maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya. *F. Crop. Res.* <https://doi.org/10.1016/j.fcr.2014.08.004>
- Ojiem, J.O., Vanlauwe, B., De Ridder, N., Giller, K.E., 2007. Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms. *Plant Soil* 292, 119–135. <https://doi.org/10.1007/s11104-007-9207-7>
- Okello, D.K., Biruma, M., Deom, C.M., 2010. Overview of groundnuts research in Uganda: Past, present and future. *African J. Biotechnol.* 9, 6448–6459. <https://doi.org/10.5897/AJB09.013>
- Okello, D.K., Okori, P., Puppala, N., Bravo-Ureta, B., Deom, C.M., Ininda, J., Anguria, P., Biruma, M., Asekenye, C., 2014. Groundnut seed production manual for Uganda. Entebbe, Uganda.
- Omamo, S.W., 2003. Fertilizer Trade and Pricing in Uganda. *Agrekon* 42, 310–324. <https://doi.org/10.1080/03031853.2003.9523626>
- Oteng-Frimpong, R., Dakora, F.D., 2019. Multienvironment Testing for Trait Stability and G × E Interaction on N₂ Fixation, Plant Development, and Water-Use Efficiency of 21 Elite Groundnut (*Arachis hypogaea* L.) Genotypes in the Guinea Savanna. *Front. Plant Sci.* 10, 1–12. <https://doi.org/10.3389/fpls.2019.01070>
- Oteng-Frimpong, R., Dakora, F.D., 2018. Selecting elite groundnut (*Arachis hypogaea* L) genotypes for symbiotic N nutrition, water-use efficiency and pod yield at three field sites, using ¹⁵N and ¹³C natural abundance. *Symbiosis* 75, 229–243. <https://doi.org/10.1007/s13199-017-0524-1>
- Peoples, M.B., Craswell, E.T., 1992. Biological nitrogen fixation: Investments, expectations and

- actual contributions to agriculture. *Plant Soil* 141, 13–39.
<https://doi.org/10.1007/BF00011308>
- Peoples, M.B., Herridge, D.F., Ladha, J.K., 1995. Biological Nitrogen-Fixation - an Efficient Source of Nitrogen for Sustainable Agricultural Production. *Plant Soil* 174, 3–28.
<https://doi.org/10.1007/BF00032239>
- Phoomthaisong, J., Toomsan, B., Limpinuntana, V., Cadisch, G., Patanothai, A., 2003. Attributes affecting residual benefits of N₂-fixing mungbean and groundnut cultivars. *Biol. Fertil. Soils*. <https://doi.org/10.1007/s00374-003-0676-4>
- Place, F., Otsuka, K., 2002. Land tenure systems and their impacts on agricultural investments and productivity in Uganda. *J. Dev. Stud.* 38, 105–128.
<https://doi.org/10.1080/00220380412331322601>
- Promsakha, S., Sakonnakhon, N., Toomsan, B., Cadisch, G., Baggs, E.M., Vityakon, P., Limpinuntana, V., Jogloy, S., Patanothai, A., 2005. Dry season groundnut stover management practices determine nitrogen cycling efficiency and subsequent maize yields. *Plant Soil* 272, 183–199. <https://doi.org/10.1007/s11104-004-4780-5>
- Robertson, G.P., Klingensmith, K.M., Klug, M.J., Paul, E.A., Crum, J.R., Ellis, B.G., 1997. Soil resources, microbial activity, and primary production across an agricultural ecosystem. *Ecol. Appl.* 7, 158–170. [https://doi.org/10.1890/1051-0761\(1997\)007\[0158:SRMAAP\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1997)007[0158:SRMAAP]2.0.CO;2)
- Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.-M.N., Mkwunye, A.U., Kwesiga, F.R., Ndiritu, C.G., Woomer, P.L., Sanchez, P.A., Calhoun, F., Sanchez, P.A., Shepherd, K.D., Soule, M.J., Place, F.M., Buresh, R.J., Izac, A.-M.N., Mkwunye, A.U., Kwesiga, F.R., Ndiritu, C.G., Woomer, P.L., 1997. Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital, in: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), *Replenishing Soil Fertility in Africa*. Soil Science Society of America and American Society of Agronomy, Madison, WI, pp. 1–46. <https://doi.org/10.2136/sssaspecpub51.c1>
- Sheldrick, W.F., Lingard, J., 2004. The use of nutrient audits to determine nutrient balances in Africa. *Food Policy* 29, 61–98. <https://doi.org/10.1016/j.foodpol.2004.01.004>
- Shoji, S., Nanzyo, M., Dahlgren, R.A., 1993. Volcanic ash soils: genesis, properties and utilization. *Volcan. ash soils genesis, Prop. Util.* [https://doi.org/10.1016/0016-7061\(95\)90034-9](https://doi.org/10.1016/0016-7061(95)90034-9)
- Snapp, S.S., Mafongoya, P.L., Waddington, S., 1998. Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. *Agric. Ecosyst. Environ.* 71, 185–200. [https://doi.org/10.1016/S0167-8809\(98\)00140-6](https://doi.org/10.1016/S0167-8809(98)00140-6)
- Snapp, S., Grabowski, P., Musumba, M., Palm, C., Chikowo, R., Bekunda, M., 2016. Development

of a sustainable intensification indicators framework : reports from the frontline in Malawi 2002.

- Snapp, S., Rahmanian, M., Batello, C., 2018. Pulse Crops for Sustainable Farms in Sub-Saharan Africa, Pulse Crops for Sustainable Farms in Sub-Saharan Africa. <https://doi.org/10.18356/6795bfaf-en>
- Srichantawong, M., Toomsan, B., Limpinuntana, V., Cadisch, G., Jogloy, S., Patanothai, A., 2005. Evaluation of groundnut stover management strategies in a legume-rice rotation. *Biol. Agric. Hortic.* 23, 29–44. <https://doi.org/10.1080/01448765.2005.9755306>
- Stoorvogel, J.J., Smaling, E.M.A., 1990. Assessment of soil nutrient depletion in Sub-Saharan Africa: 1983–2000. Winand Staring Centre, Wageningen, Netherlands.
- Struhsaker, T.T., 1997. Ecology of an African rain forest: logging in Kibale and the conflict between conservation and exploitation., University Press of Florida. University Press of Florida.
- Tanellari, E., Kostandini, G., Bonabana-Wabbi, J., Murray, A., 2014. Gender impacts on adoption of new technologies: the case of improved groundnut varieties in Uganda. *African J. Agric. Resour. Econ.* 9, 300–308. <https://doi.org/10.22004/ag.econ.197017>
- Tarimo, A.J.P., Blarney, F.P., 1999. Effects of plant population density and cultivar on growth, yield and yield components in groundnut (*Arachis hypogaea* 1.). *South African J. Plant Soil* 16, 74–78. <https://doi.org/10.1080/02571862.1999.10634850>
- Thierfelder, C., Chisui, J.L., Gama, M., Cheesman, S., Jere, Z.D., Trent Bunderson, W., Eash, N.S., Rusinamhodzi, L., 2013. Maize-based conservation agriculture systems in Malawi: Long-term trends in productivity. *F. Crop. Res.* <https://doi.org/10.1016/j.fcr.2012.11.010>
- Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic matter in sustaining soil fertility. *Nature* 371, 783–785. <https://doi.org/10.1038/371783a0>
- Tittonell, P., Gérard, B., Erenstein, O., 2015. Tradeoffs around crop residue biomass in smallholder crop-livestock systems – What ’ s next ? *Agric. Syst.* 134, 119–128. <https://doi.org/10.1016/j.agsy.2015.02.003>
- Tittonell, P., Muriuki, a, Klapwijk, C.J., Shepherd, K.D., Coe, R., Vanlauwe, B., 2013. Soil Heterogeneity and Soil Fertility Gradients in Smallholder Farms of the East African Highlands. *Soil Sci. Soc. Am. J.* 77, 525–538. <https://doi.org/10.2136/sssaj2012.0250>
- Tittonell, P., Shepherd, K.D., Vanlauwe, B., Giller, K.E., 2008. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya-An application of classification and regression tree analysis. *Agric. Ecosyst. Environ.*

- 123, 137–150. <https://doi.org/10.1016/j.agee.2007.05.005>
- Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. *Agric. Ecosyst. Environ.* 110, 149–165. <https://doi.org/10.1016/j.agee.2005.04.001>
- Toomsan, B., Cadisch, G., Srichantawong, M., Thongsodsaeng, C., Giller, K.E., Limpinuntana, V., 2000. Biological N₂ fixation and residual N benefit of pre-rice leguminous crops and green manures. *Netherlands J. Agric. Sci.* 48, 19–29. [https://doi.org/10.1016/S1573-5214\(00\)80002-0](https://doi.org/10.1016/S1573-5214(00)80002-0)
- Toomsan, B., McDonagh, J.F., Limpinuntana, V., Giller, K.E., 1995. Nitrogen fixation by groundnut and soyabean and residual nitrogen benefits to rice in farmers' fields in Northeast Thailand. *Plant Soil* 175, 45–56. <https://doi.org/10.1007/BF02413009>
- Tully, K., Sullivan, C., Weil, R., Sanchez, P., 2015. The State of soil degradation in sub-Saharan Africa: Baselines, trajectories, and solutions. *Sustain.* <https://doi.org/10.3390/su7066523>
- Tully, K.L., Wood, S.A., Almaraz, M., Neill, C., Palm, C., 2015. The effect of mineral and organic nutrient input on yields and nitrogen balances in western Kenya. *Agric. Ecosyst. Environ.* 214, 10–20. <https://doi.org/10.1016/j.agee.2015.08.006>
- UBOS, 2014. 2014 Statistical Abstract, Uganda Bureau of Statistics. Kampala, Uganda.
- UBOS, 2013. Uganda National Panel Survey (UNPS) 2011/2012: Wave III Report. Kampala, Uganda.
- UBOS, 2010. UBOS Census of Agriculture 2008/2009 Volume IV: Crop Area and Production Report. Kampala, Uganda.
- Unkovich, M.J., Pate, J.S., 2000. An appraisal of recent field measurements of symbiotic N₂ fixation by annual legumes. *F. Crop Res.* 65, 211–228. [https://doi.org/10.1016/S0378-4290\(99\)00088-X](https://doi.org/10.1016/S0378-4290(99)00088-X)
- Valbuena, D., Tui, S.H.K., Erenstein, O., Teufel, N., Duncan, A., Abdoulaye, T., Swain, B., Mekonnen, K., Germaine, I., Gérard, B., 2015. Identifying determinants, pressures and trade-offs of crop residue use in mixed smallholder farms in Sub-Saharan Africa and South Asia. *Agric. Syst.* 134, 107–118. <https://doi.org/10.1016/j.agsy.2014.05.013>
- Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., Zingore, S., 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *Soil* 1, 491–508. <https://doi.org/10.5194/soil-1-491-2015>

- Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., Six, J., 2011. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil* 339, 35–50.
<https://doi.org/10.1007/s11104-010-0462-7>
- Waddington, S.R., Karigwindi, J., 2001. Productivity and profitability of maize + groundnut rotations compared with continuous maize on smallholder farms in Zimbabwe. *Exp. Agric.* 37, 83–98. <https://doi.org/10.1017/S001447970100103X>
- Wani, S.P., Rupela, O.P., Lee, K.K., 1995. Sustainable agriculture in the semi-arid tropics through biological nitrogen fixation in grain legumes. *Plant Soil* 174, 29–49.
<https://doi.org/10.1007/BF00032240>
- West, T.O., Post, W.M., 2002. Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation. *Soil Sci. Soc. Am. J.* 66, 1930–1946. <https://doi.org/10.2136/sssaj2002.1930>
- World Bank, 2016. Fertilizer consumption (kilograms per hectare of arable land) [WWW Document]. URL <https://data.worldbank.org/indicator/AG.CON.FERT.ZS> (accessed 5.2.17).
- Wortmann, C.S., Kaizzi, C.K., 1998. Nutrient balances and expected effects of alternative practices in farming systems of Uganda. *Agric. Ecosyst. Environ.* 71, 115–129.
[https://doi.org/10.1016/S0167-8809\(98\)00135-2](https://doi.org/10.1016/S0167-8809(98)00135-2)
- Young, A., 1976. Tropical soils and soil survey. *Trop. soils soil Surv.*
<https://doi.org/10.2307/2259206>
- Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007a. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agric. Ecosyst. Environ.* 119, 112–126.
<https://doi.org/10.1016/j.agee.2006.06.019>
- Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007b. Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. *F. Crop. Res.* 101, 296–305.
<https://doi.org/10.1016/j.fcr.2006.12.006>

Chapter 2: Organic resource flows and soil C across smallholder farms in western Uganda

Abstract

Organic inputs are key to building soil organic matter, the primary indicator of soil health. The quantity and quality of organic materials available to smallholder farmers in sub-Saharan Africa is often limited, as is the accessibility, time, and labor needed to transport, manage, or apply organic inputs. Organic resources and labor are often concentrated close to homesteads, while fields farther away, i.e., outfields, receive fewer inputs, a dynamic that can lead to gradients of decreasing soil fertility at increasing distance from the homestead. I used whole-farm surveys to quantify and map organic resource and nitrogen (N) flows within 19 case study farms in western Uganda. I characterized farms by resource endowment and for each resource group, I tracked the fate and cycling of all available, potential organic matter inputs to soil, including household waste, animal manure, and crop residues. Home banana plantations located directly adjacent to homesteads received the majority of organic inputs, and only a few outfields received any additional inputs. A field-scale partial N balance was positive for home banana plantations but negative for outfields, even those receiving potential N benefits from legumes. Although homefields received more SOC and N inputs, they did not have higher values than outfields, and I did not find evidence of a management gradient affecting SOC and N. The inherently fertile, volcanic soils within the study region may obscure management impacts. Farms were highly fragmented, and households accessed fields far from homesteads and village centers, which affected management practices and SOC and N values. Farms with greater resource endowments had higher yields overall and more organic resources, but better-

resourced farms did not fully utilize available resources or have better soil, which indicates the importance of other factors like crop timing, labor, and seed quality. estimated that farms had enough organic materials to generate compost in quantities substantial enough to boost yields, but the logistics of making and applying compost across the farm could be challenging.

Introduction

In areas with high population densities and favorable conditions for crop production, such as the East African Highlands, smallholder farmers are driven to intensify agricultural practices resulting in high rates of nutrient depletion (Nandwa and Bekunda, 1998). Farmers' management options are often limited by the quantity and quality of resources available, e.g., organic inputs, fertilizer, labor, knowledge (Marinus et al., 2021). A farm's resource endowment impacts and is impacted by the farm's characteristics and location within the socioeconomic and agroecological environment, as well as the farm's production orientation (Chikowo et al., 2014). Farmer resource endowment is a major factor affecting the quantity and flow of resources and nutrients within smallholder farms, and it is frequently used to categorize or create a typology of farms (Berre et al., 2017; Falconnier et al., 2015; Gambart et al., 2020; Kamanga, 2011; Mtambanengwe and Mapfumo, 2005; Ncube et al., 2009; Reetsch et al., 2020; Tittonell et al., 2010, 2005a; Zingore et al., 2007b).

Differential farmer resource allocation coupled with inherent soil variability results in soil fertility gradients and heterogenous soil fertility within and across smallholder farms in SSA (Tittonell et al., 2013; Zingore et al., 2007a). Because nutrients and labor are often concentrated close to the homestead while further fields receive fewer inputs, gradients of

decreasing soil fertility can develop in fields located at an increasing distance from the homestead (Tittonell et al., 2013, 2005a; Vanlauwe et al., 2006; Zingore et al., 2007b, 2007a). Depleted soils impact food production and the identification of nutrient imbalances and less fertile fields within an agroecosystem can allow for targeted soil fertility management strategies and sustainable adaptations (Chikowo et al., 2014; Haileslassie et al., 2007).

Resource flow maps and nutrient balances highlight farmer management practices and are effective tools to show soil nutrient gains and losses at the field and farm level, and at larger spatial scales from district up to continental (Bekunda and Manzi, 2003; Briggs and Twomlow, 2002; Cobo et al., 2010; de Jager, 2005; Esilaba et al., 2005; Kanmegne et al., 2006; Lederer et al., 2015; Sheldrick and Lingard, 2004; Stoorvogel and Smaling, 1990; Tittonell et al., 2005a). Resource flow maps track the source, movement and management strategies of organic resources and nutrients around the farm (Briggs and Twomlow, 2002; Bucagu et al., 2014; Esilaba et al., 2005; Ncube et al., 2009; Tittonell et al., 2005b). In conjunction with flow maps, nutrient balances estimate the nutrient fluxes into and out of smallholder fields, and partial nutrient balances are particularly effective at emphasizing management practices through estimation of the visible nutrient fluxes, e.g. crop harvest, crop residue transfer, manure or fertilizer inputs (Bucagu et al., 2014; Esilaba et al., 2005; Haileslassie et al., 2005; Wortmann and Kaizzi, 1998). Generally, in sub-Saharan Africa (SSA) all nutrient balance studies at all scales show negative balances for the key nutrients, nitrogen (N), phosphorus (P), and potassium (K) (Cobo et al., 2010; Kiboi et al., 2019; Smaling et al., 1993; Stoorvogel and Smaling, 1990). At the field scale, there can be a positive nutrient balance exception for fields located close to the homestead where nutrients are often concentrated; however, at the farm scale,

concentration of nutrients at the homestead combined with continual nutrient removal without adequate replenishment in outer fields leads to negative nutrient balances (Baijukya and De Steenhuijsen Piters, 1998; Giller et al., 1997; Tittonell et al., 2005a; Vanlauwe and Giller, 2006).

Here, I document the organic resources available to smallholder farmers and explore soil organic carbon (SOC) and total N in relation to farmer resource allocation, field distance from the homestead, and farmer resource endowment. I present a snapshot of the dynamic and complex resource flows and nutrients fluxes within smallholder, banana-based agroecosystems located along the densely populated western boundary of Kibale National Park in Kabarole District, western Uganda. I detail the socioeconomic and agroecological environments in which the farms are situated and consider the interplay of these factors and their influence on farmer management and decision-making. The study area encompassed inherently fertile soils allowing for a unique examination of the role of farmer management versus the effect of inherent soil properties in relation to within-farm SOC and N gradients. Banana is a main staple and cash crop in Uganda and within banana-based cropping systems, banana is generally grown in 'plantations' encompassing or directly adjacent to smallholder homesteads (Majaliwa et al., 2015; Wairegi and van Asten, 2010). Based on previous work in the region and from prior studies documenting resource use and soil fertility in banana-based agroecosystems in Uganda (Bekunda and Woomer, 1996; Bekunda and Manzi, 2003; Briggs and Twomlow, 2002; Wortmann and Kaizzi, 1998), I hypothesized that (i) farms allocated the majority of their resources to their homefield, i.e., the closest field to the homestead – the home banana plantation (ii) with greater inputs of organic materials, SOC and N would be highest in the homefields, and (iii) that farmer management and decision-making, and thus

resource allocation and any management-induced soil fertility gradients, would vary according to farmer resource endowment. An in-depth understanding of the organic resources available, the allocation of those organic resources, and the impact of resource management on SOC and N will contribute to identification of sustainable practices and adaptations to boost soil fertility management.

Materials and Methods

Study Site

In July 2016, surveys and soil sampling were conducted at 19 farms along the western border of Kibale National Park (KNP) in Kabarole district in western Uganda (Figure 2.1). The surveyed farms were within six villages - Kanyawara, Kyakabuzi, Kyakabale, Rweteera, Kyantambara, and Iruhuura, which fall along a previously established north-south transect that lies within 5 km of the western boundary of KNP.

The study sites are located between latitude 0.56°-0.46° N and longitude 30.35°–30.30° E and at elevations from 1400 to 1550 m above sea level. The climate is tropical with an average daily temperature range of 15 to 23°C (Struhsaker, 1997). The region experiences bimodal rainfall with a shorter rainy season occurring from around early March through mid-to-late May followed by a dry period and then longer rains occurring from September through November followed by another dry period (Hartter et al., 2012). Mean annual rainfall ranges from 1100 to 1700 mm with rainfall decreasing and temperature increasing when moving north to south along the elevational gradient (Struhsaker, 1997). Within the study region, mean annual precipitation from 1981 to 2014 was 1359 mm (Figure 2.2) as calculated from monthly

average precipitation data collected from the Climate Hazards InfraRed Precipitation with Station (CHIRPS) resource (Funk et al., 2015) and attained through the Google Earth Engine platform (Gorelick et al., 2018). Study area soils are classified as ferralitic sandy clay loams and eutrophic volcanic ash.

KNP and the surrounding region lie within the Albertine Rift, a biodiversity hotspot that comprises part of Africa's Rift Valley (Lepp and Holland, 2006). KNP was established to preserve and protect a remnant of transitional moist evergreen forest that is now isolated within a densely populated agricultural landscape (Chapman and Lambert, 2000). Around the park, there is extremely high population density that was estimated to be approximately 300 individuals km⁻² in 2006 (Hartter and Southworth, 2009), and to have an annual growth rate of over 3% (Naughton-Treves et al., 2007).

Bordering KNP, the study site landscape is undulating hills, dominated by the small-scale agriculture that is the focus of this study, as well as by tea plantations, grasslands, and fuelwood plantations (Chapman and Lambert, 2000; Majaliwa et al., 2010). Smallholder farmers maintain banana (*Musa spp.*) plantations and intercrop and/or rotate a large diversity of annual crops, including maize (*Zea mays L.*), common bean (*Phaseolus vulgaris L.*), groundnut (*Arachis hypogaea L.*), 'Irish' potato (*Solanum tuberosum L.*), sweet potato (*Ipomoea batatas L.*), cassava (*Manihot esculenta Crantz*), sorghum (*Sorghum spp.*), and finger millet (*Eleusine coracana L.*). Kabarole district, which encompasses the study site, is characterized as an area of "high agricultural potential" with banana, tea (*Camellia sinensis (L.) Kuntze*), maize, and coffee (*Coffea spp.*) among the main cash crops (de Jager et al., 2004).

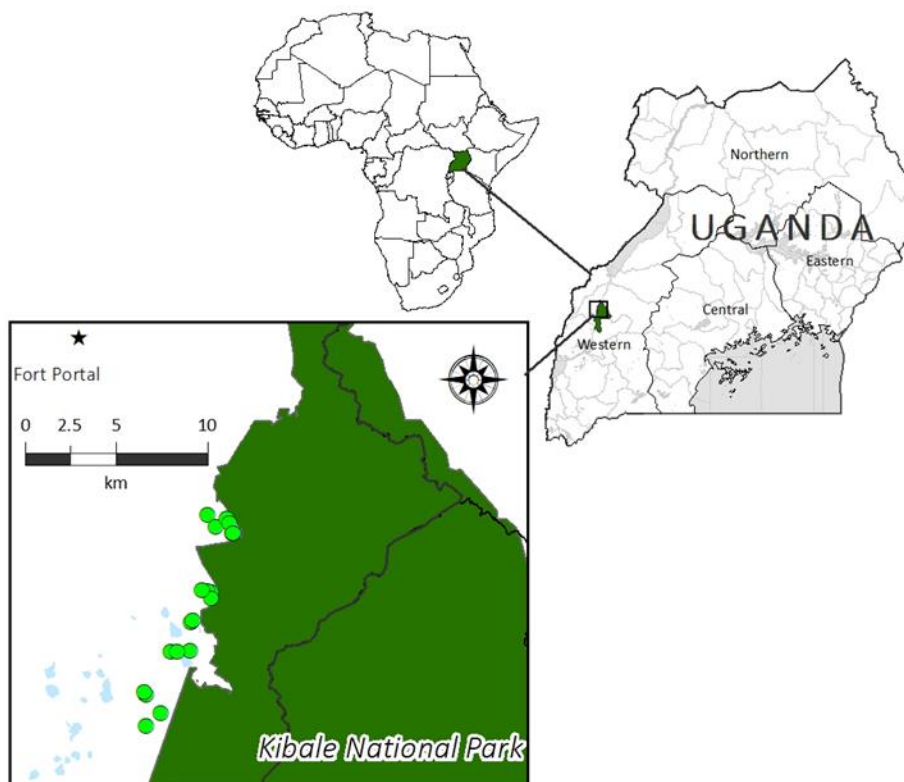


Figure 2.1. The study area lies along the western edge of Kibale National Park (KNP) in western Uganda. Case study farms are denoted by filled circles.

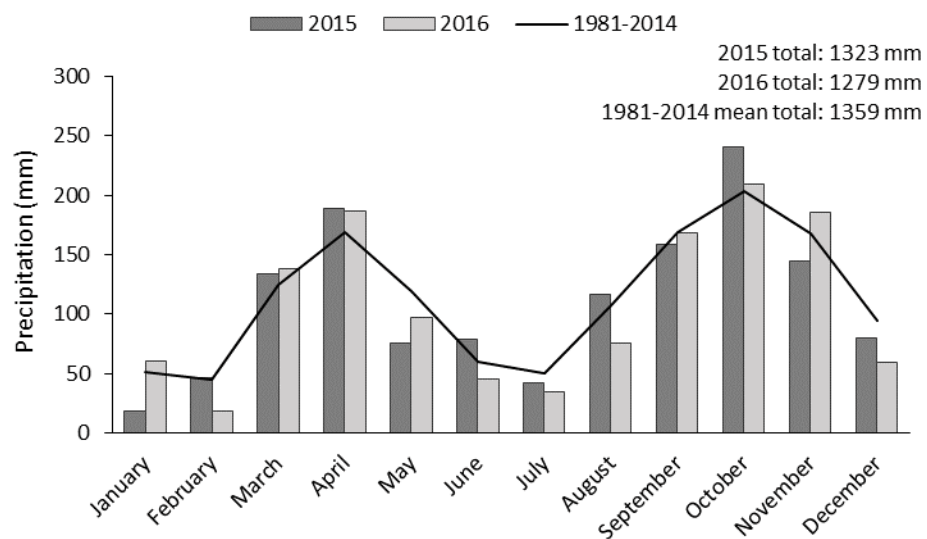


Figure 2.2. Monthly precipitation within the study region in 2015 and 2016 and the average monthly precipitation from 1981 to 2014.

Household surveys and socioeconomic information

A total of 19 households were surveyed in six villages: Kanyawara (n=6), Kyakabuzi (n=4), Kyakabale (n=2), Rweteera (n=3), Kyantambara (n=2), and Iruhuura (n=2). Enumerators translated survey questions and respondent's answers between English and Rutooro or Rukiga, the respective languages of the resident Batooro and Bakiga ethnic groups. Households were approached and asked if they were willing to participate in an extensive survey of their entire growing area, including detailed information on inputs, crop management, and crop residues. Households that had previously participated in surveys conducted by the research team in 2013, 2014, or 2015 were preferred, and two were specifically chosen as known examples of 'wealthy' farms. Of the 19 households surveyed, 12 had previously participated in a survey; five had participated in a 2015 survey on legume fields and management and seven had participated in a one-time survey on maize fields that was conducted during 2013-2015.

Surveys included questions regarding household demographic data (e.g., members, head of household, education level); land use and ownership; crop decisions and income; crop storage; household waste amounts and waste management; livestock and livestock waste management; farmer knowledge sources; general farm management; and primary production unit management. Farmers identified primary production units or fields as land that was usually managed uniformly as a single unit. For each field, I gathered crop information including seed amount, planting and harvesting date, yield, yield use (household needs, saved, sold), crop condition, amount of crop loss, residue management, and the use of any inputs, and their quantity and application. In addition to obtaining the crop yield and management data for the first 2016 cropping season (approximately March to September 2016), I collected yield data and

management history for the two prior primary cropping seasons (August 2015 to February 2016, March 2015 to September 2015 – this latter season was the focus of previous surveys in 2015). Three households were unable to provide complete historical field crops data; one farmer was time limited (the farmer with the most fields (10)), and two households were unable to remember some of the previous yields. All responses were farmer recall.

Farms were classified into three relative resource groups based on socioeconomic factors provided in the surveys: better (RG1), average (RG2), and poorly-resourced (RG3) (Bucagu et al., 2014; Chikowo et al., 2014; Ncube et al., 2009). I assigned a numerical value to assets including homestead dwelling (based on construction type, 1-4 with 4 being concrete), livestock (total livestock units (TLU); cattle=0.7, goats=0.1, pigs=0.2, chickens=0.01 (Jahnke, 1982), and use of hired labor (“1” if they used hired labor and “0” if not); I summed these values with the total farm size in hectares to create a continuous variable used to classify farms based on the interquartile range (Hockett and Richardson, 2018).

Mapping and geographic data

To determine field size and distance from the household, a handheld Garmin GPS 62s unit was used to mark homestead and field locations and to make a track around the perimeter of each field. GPS data was retrieved from each of the units and input into ArcGIS 10.4 to map the household locations, field locations, and field perimeter track. Using ArcGIS, I determined field size by calculating the area within the perimeter track, and I measured the Euclidean distance between the homestead and fields.

I categorized the banana plantation directly adjacent to the homestead as the homefield, fields within 50 m of the homestead as “close” fields, fields between 50 and 100 m as “mid-distance” fields, while those further than 100 m were categorized as “remote” (Zingore et al., 2007a). Close, mid-distance, and remote fields were further grouped for analysis as outer fields in comparison to the homefield. The terrain of the study region and the slope of each field was derived using the NASA Shuttle Radar Topography Mission (SRTM) 30 m digital elevation model (DEM). Field location and accuracy were cross referenced using Google Maps and Google Earth Pro.

Resource flow maps and partial N balances

Resource flows and partial N balances were constructed using farmer-reported yields, inputs, and residue management practices, in conjunction with my own measurements and with values from the literature (Table 2.1). Literature values were primarily drawn from experiments or research conducted in low-to-no input agroecosystems in Uganda or from on-farm or experiment station plots with no added fertilizer; however, if these data points were lacking, I used values from similar agroecosystems within the East African region and then, if necessary, from other tropical agroecosystems (Table 2.1).

Farmers reported fresh weight or air-dried yields/organic matter amounts in kilograms (kg) or local units (bags, basins, baskets, bundles), for which I established standard values. A portable scale was taken to some of the farms to establish weights for yields and residues. Local unit weights for marketed crops were also verified at local markets and with local traders. The time frame for the organic material flows and the nutrient balance covers the first rainy season

of 2016 (March to August). Banana yields were predominantly reported as number of bunches per season or per day/week/month as bananas are largely harvested year-round for household consumption. Based on published bunch weights from unfertilized, low-input banana plantations, I used 15 kg as a standard weight conversion for bunches (Bekunda and Woomer, 1996; Wairegi and van Asten, 2010). The yield ha^{-1} of each individual crop was calculated as the reported yield divided by the GPS-determined field area and multiplied by an estimation of the fraction of total area occupied by the crop (Fermont and Benson, 2011; Tiftonell, 2003). Crop parameters, including dry matter and N content, harvest index (HI), and N fixation values, were taken from the literature and my own measurements (Table 2.1). Crop yields were converted to dry weight and the HI (Table 2.1) was used to calculate residue biomass. I did not estimate banana, coffee, or Irish potato residues as these always remained in the field. Residue biomass was calculated as:

$$\text{Residue (kg ha}^{-1}\text{)} = \text{Harvested yield (kg ha}^{-1}\text{)} / (\text{HI} - \text{Harvested yield (kg ha}^{-1}\text{)}) \text{ (Eq.1)}$$

Using published N values, I calculated the N contained in the harvested dry weight and in the estimated residue dry yield, and for legume crops, I estimated the amount of N derived through biological N fixation (BNF) (Table 2.1). If there was a net N input from legume aboveground biomass after subtracting harvested grain yield, it was classified as an organic N fertilizer input. If legume residues were removed from a field, then only the soil N contained within the residues was considered an N output.

The partial N balance was calculated for each field (kg ha^{-1}) by subtracting the total N removed in the harvested product and crop residues from the total N added to the field through inputs of animal manure, household waste, compost, crop residue, and BNF.

$$\text{N Balance} = \text{INPUTS (animal manure + household waste + compost + crop residues + BNF)} - \text{OUTPUTS (harvested product + crop residues removed or burnt) (Eq.2)}$$

Table 2.1. Nutrient content and values of crops, animal manure, household waste and compost used to construct the organic material and N flows and N balances.

Crop	Dry matter	HI	Product N	Residue N	BNF	Source
	%		%	%	%	
Banana	25	na	0.26	na		Belayneh et al., 2014; Wortmann and Kaizzi, 1998
Beans	88	0.4	3.3	1.04	0.5	Wortmann and Kaizzi, 1998; current study; Ojiem et al., 2007
Groundnut	93	0.2	4.5	2.03	0.7	Nijhof et al., 1987; current study; Stoorvogel & Smaling, 1990; Ojiem et al., 2007
Cassava	35	0.39	0.26	0.93		Fermont et al., 2007
Sorghum	88	0.22	1.63	0.56		Kaizzi et al., 2012
Maize	88	0.24	1.57	1		Kaizzi et al., 2012
Sweet Potato	30	0.5	0.6	1		Tumwegamire et al., 2011; Wortmann and Kaizzi, 1998; Abidin et al., 2017
Irish	25	0.65	3.38	na		Kesiime et al., 2013; van den Bosch et al., 1998; Haverkort and Harris, 1987.
Millet	88	0.2	2.3	0.126		van den Bosch et al., 1998
Coffee	87	na	1.5	na		Cheyne et al., 2006; Wortmann and Kaizzi, 1998

Livestock manure

Farmers reported livestock manure inputs in local units or kg per unit of time (day, week, month, or season), and these values were converted into kg ha⁻¹ season⁻¹ by considering the field area where applied. Several farmers reported manure usage as a percentage of the manure produced over one season by each livestock species. Manure production percentages were similarly converted into kg ha⁻¹ season⁻¹ by multiplying literature values for animal excretion rates by the quantity of livestock; this value was then reduced by 50% to account for incomplete manure collection, losses to grazing areas, and dry matter loss over time when

stored uncovered (Table 2.2)(Rufino et al., 2007; Wortmann and Kaizzi, 1998). I used published N values to determine the N content of the livestock manure for each type of livestock (Table 2.2), and the N content of the manure was similarly reduced by 50% to approximate N loss through processes such as leaching and volatilization.

Table 2.2. Nutrient content and values of animal manure used to construct the organic material and N flows and N balances.

Animal manure	Dry matter production	C	N	Source
	kg/animal/season	%	%	
Cattle manure	300	29.1	1.3	Sileshi et al., 2017; Fernandez-Riviera et al., 1995
Goat manure	45	29.7	1.7	Sileshi et al., 2017; Fernandez-Riviera et al., 1995
Pig manure	165	36.3	1.9	Sileshi et al., 2017; Ngwabie et al., 2018
Chicken manure	4	33.7	1.8	Sileshi et al., 2017; ASAE, 2005

Household waste

Household waste data was calculated using respondents' estimates for waste generation reported in local units for a period of time, e.g., one basin per week. Household waste data included estimates for kitchen peelings and food scraps, cooking ash, and crop residue components that are commonly dealt with at the household, such as banana peels, groundnut shells, maize cobs and husks. For each type of waste, respondents said how and where the waste was applied and most gave a percentage of use, e.g., 100% spread as mulch in the banana plantation. I quantified waste or compost applied to a specific field on an area basis and reported it as kg ha⁻¹. The N content for each type of waste and for compost was computed using values from the literature (Table 2.3).

Table 2.3. Nutrient content and values of household waste and compost used to construct the organic material and N flows and N balances.

Household Waste & Compost	N	Source
	%	
Kitchen peelings & food scraps	1.10	Wortmann & Kaizzi, 1998
Groundnut shells	1.47	Promsakha et al., 2000
Banana peels	1.05	Kalemelawa et al., 2012
Maize cobs	0.6	Barbosa et al., 2016
Maize husks	0.5	Barbosa et al., 2016
Cooking ash	0.15	Wortmann and Kaizzi, 1998
Compost	0.4	Bekunda and Manzi, 2003

Soil and residue samples

Soil samples were collected from each field that was identified and managed by the household. The soil was sampled to a depth of 15 cm using a 2-inch diameter soil probe. Three soil samples were taken at random locations within each field, and the samples were combined to create one composite sample for each surveyed field.

A small number of plant residue samples, maize ($n=3$), groundnut ($n=4$), bean ($n=2$), and elephant/Napier grass ($n=1$), were collected from random fields.

Soil and plant samples were air-dried in Uganda and shipped to Michigan State University in MI, USA for analysis.

Organic C and total N analysis

Soil and plant samples were run on an elemental analyzer (ECS 4010, Costech Analytical Technologies, Inc., Valencia, CA, USA) to determine organic C and total N by dry combustion. Soils were prepared for analysis on the C/N analyzer by first sieving to less than 2 mm and weighing a 5 g subsample of each soil into 20 ml scintillation vials. The air-dried subsamples

were oven-dried at 60°C for 24 hours. Oven-dried soils were ground on a roller mill and subsamples weighing approximately 20 mg were packed into tins that were then loaded into the elemental analyzer. Plant samples were prepared for the elemental analyzer by dividing into stem, leaf, and root components, and then cutting into small pieces that were dried, ground, packed, and analyzed as described above.

Data Analysis

Data were analyzed for descriptive statistics and frequencies using STATA/IC 14.2 statistical software (StataCorp, College Station, TX)

Results

A total of 19 farms and 90 fields were surveyed with 85 fields visited and soils sampled (Table 2.4). I was unable to visit five fields, all identified by farmers as extremely remote; two of the farmers (each with two rented fields) feared that by visiting the fields, the landowners might think they were trying to sell the land, and one respondent did not have time to accompany us to a newly acquired, distant plot. For these fields, I used farmer-estimated field areas and distances. Two of the households that had participated in a previous survey were no longer cultivating fields that had been surveyed one year prior in 2015 (one plot was no longer rented out by the farmer and one plot was being rented to another household), and for these, I used harvest data and field measurements from the 2015 surveys.

Five farms were classified as better resourced (RG1), nine were average (RG2), and five farms were poorly resourced (RG3) (Table 2.5). Farms ranged in size from 0.04 to 1.59 ha with a mean of 0.54 ha and were comprised of one to 10 fields distributed across the hilly landscape

(Table 2.4). Most homesteads were located along or close to roads or thoroughfares following hilltop ridgelines. Fields varied in size from 0.01 to 0.44 ha and were located at varying distances from the homestead (0-1770 m) with a median distance of 67 m and a mean of 253 m (Table 2.4). The number of home, close, mid-distance, and remote fields differed by farm and among resource groups (Table 2.6). All homesteads were directly adjacent to a household banana plantation, except for two RG3 farms, one of which had an inherited banana plantation distant from the homestead and the other did not own or manage a banana plantation. The majority of farms were highly fragmented within the landscape and only one farm had entirely contiguous fields, though it was one of the poorest farms with small fields around the homestead (one household only had one field - a home banana plantation with intercrops). Slightly more than half of the farms owned all their fields, while nine out of the 19 farms managed at least one field that was rented or unowned, and at least one farm in each resource group rented a field (Table 2.4). Banana plantations were solely located on land owned by the household, i.e., with secure land-tenure, as was coffee, a high-value crop. Fields owned by households were located an average 119 m from the homestead, while the average distance for rented fields was 555 m from the homestead.

All farms practiced crop rotation and intercropping with the mean number of crops per field lowest for RG1 and highest for RG3 farm (Table 2.5). On average, RG1 farms were larger, had more fields, and cultivated a greater diversity of crops, though the mean field size of RG2 farms was larger (Table 2.5). Livestock ownership (TLUs) was generally low for all farms (Tables 2.4 and 2.5). RG1 farms owned the most livestock and only RG1 farms owned cattle, but they did so at very low numbers of one, three, and seven cattle, respectively, for three farms. Five

farms, two RG1 and three RG2, kept pigs at a mean of 1.5 pigs per farm. Chickens and goats were more common with 58% and 47% of all farms keeping them, but similarly at low numbers with an average of 6.5 chickens and 5.4 goats. All farms with chickens and goats applied the manure to their fields, but only two of three farms with cattle applied cattle manure, and just two of the five farms with pigs used the pig manure. No animal manure was sold.

Twelve households (63%) hired labor to work on the farm with 100% of RG1, more than three-quarters of RG2, and none of the RG3 farms employing off-farm laborers (Table 2.5). Hired laborers worked in all fields managed by RG1 farms. While this was similar for two RG2 farms, the remaining five RG2 farms only employed laborers in a single field, and for four out of the five RG2 farms it was a remote field containing maize. All fields were worked manually with hand hoes and were rainfed. Fields were typically weeded one to two times each season and weeds were heaped and spread in the field, although one RG2 farm reported removing weeds from outfields to use as mulch in the banana plantation.

Crop yields in the study region were mostly within the range of values reported for Kabarole district, western Uganda, and Uganda as a whole (Table 2.7) (UBOS, 2010). For farms within all resource groups, maize yields were much lower than yields reported for the district, region, or Uganda as a whole (Tables 2.7 & 2.8). More than half of the farms (53%) said that maize yields were fair or poor because of drought. Based on rainfall for the 2016 first rains season, it appears that there was less rainfall prior to the season start in February and then lower than average rainfall in May, June, and July (Figure 2.2). Bean and casava yields were also low compared to district yields and closer to regional and national values.

All households except one reported that they tried to increase their soil fertility. All farmers recognized that crop residues could be beneficial and made statements that crop residues “decompose and turn into soil”, “improve the soil”, “add manure to the soil”, or “add manure to the plants.” The word ‘manure’ was used as an encompassing term for something that adds fertility, and in addition to animal manure, compost was referred to as compost “manure” and decomposing residues were understood to add “manure.”

Table 2.4. Case study farm and household (HH) characteristics.

Resource group ^a	Farm ^b	Mean distance								Mean farm			HH mem-			Farm is main			
		Total farm	Total field	Mean field size	Total crop species	Mean crops field ⁻¹	home to field	Land owned	Mean farm SOC	farm total soil N	Mean farm soil C:N	TLU ^c	bers	HH head gender	Hired Labor	income source	Crops for HH	Crops saved	Crops sold
		ha	n	ha	n	n	m	%	g kg ⁻¹	g kg ⁻¹		#	#				%	%	%
RG1	BL 2	1.59	10	0.16	8	1.6	232	100	65.63	4.47	14.71	3.96	6	man	yes	yes	40	20	40
	IU 1	0.29	5	0.06	11	3.4	28	100	63.26	4.23	15.01	1.76	5	woman	yes	yes	53	10	37
	KZ 1	0.98	7	0.14	10	2.0	89	57	68.55	4.81	14.01	0.52	5	woman	yes	yes	56	10	34
	TM 2	0.73	5	0.15	9	2.2	25	100	53.26	3.44	15.49	5.28	11	man	yes	yes	33	11	56
	YA 3	0.21	6	0.04	9	1.2	57	100	42.64	2.97	14.40	0.27	6	woman	yes	no	92	8	0
RG2	BL 1	0.64	4	0.16	5	1.8	107	75	68.01	4.80	14.29	0.8	3	woman	yes	yes	80	2	18
	IU 2	1.19	4	0.30	9	5.5	972	50	50.95	3.22	15.81	0.16	11	man	yes	yes	40	9	51
	KZ 2	0.59	2	0.29	3	2.0	368	50	74.75	5.30	14.14	0.4	9	man	yes	yes	63	7	30
	KZ 3	0.92	6	0.16	7	1.5	108	100	83.67	5.65	14.79	0	8	woman	yes	yes	50	5	45
	KZ 4	0.28	4	0.07	6	1.5	193	75	71.62	4.68	15.23	0.6	2	man	yes	yes	48	16	36
	RW 1	1.01	7	0.14	8	1.6	264	100	43.78	3.11	14.14	0	13	man	yes	yes	38	17	46
	RW 3	0.27	4	0.07	5	1.5	279	20	46.01	3.52	13.05	0.1	4	man	no	yes	63	3	34
	YA 4	0.23	4	0.06	6	2.5	59	25	40.64	2.93	13.88	0.41	7	man	yes	no	95	0	5
	YA 5	0.35	4	0.09	10	1.8	51	100	36.99	2.57	14.56	2.07	9	man	no	no	94	6	0
RG3	RW 2	0.42	3	0.14	6	2.7	1668	33	75.04	4.48	16.81	0.03	3	man	no	depends	52	13	35
	TM 1	0.25	3	0.07	7	3.0	567	20	39.08	3.25	11.90	0.06	8	man	no	no	73	14	13
	YA 1	0.18	3	0.06	8	2.3	47	100	52.00	3.96	13.12	0	4	woman	no	no	81	9	10
	YA 2	0.04	1	0.04	4	4.0	5	100	39.91	2.95	13.53	0.1	3	woman	no	no	100	0	0
	YA 6	0.10	3	0.03	4	1.3	10	100	40.74	2.79	14.61	0	3	woman	no	no	94	0	6
Total		0.54	4	0.12	7.11	2.28	270	74	55.61	3.85	14.39	0.87	6.32				66	8	26

a RG1 = better resourced; RG2 = average; RG3 = poorly resourced

b Farm ID reflects location by village: Kyakabale (BL), Iruhuura (IU), Kyakabuzi (KZ), Rweteera (RW), Kyantambara (TM), Kanyawara (YA)

c TLU, total livestock units: cattle=0.7, goats=0.1, pigs=0.2, chickens=0.01 (Jahnke, 1982)

Table 2.5. Mean characteristics of the relative farm resource groups: RG1, better resourced; RG2, average; RG3, poorly resourced.

Resource group	Farms RG ⁻¹	Farm size ha	Total fields RG ⁻¹	Field size ha	Fields farm ⁻¹	Crop species	Crops field ⁻¹	Land owned %	Banana plantation (ha)	Land planted to banana %	Distance to home field m	Mean farm SOC %	Mean farm total soil N %	Mean farm C:N %	TLU	Hired labor %	Farm is main income source %	Crops for HH %	Crops saved %	Crops sold %
RG1	5	0.76	34	0.11	6.6	9.4	2.1	97	0.30	25	86	5.96	0.40	14.75	2.36	100	80	55	12	33
RG2	9	0.54	41	0.15	4.3	6.6	2.2	67	0.20	37	267	5.77	0.40	14.36	0.50	78	78	63	7	29
RG3	5	0.19	15	0.07	2.6	5.8	2.7	72	0.06	44	459	5.08	0.36	14.07	0.04	0	0	80	7	13
Total	19	0.54	90	0.12	5	7.1	2.3	74	0.16	34	270	55.61	3.85	14.39	0.87	63	58	66	8	26

Table 2.6. Average field area and distance from the homestead $\pm$ SE, and the most frequent crops by field type, averaged by farm resource group.

	Homefields	Close fields	Mid-distance fields	Remote fields
RG1 (n)	5	13	6	10
Average area (ha)	0.20 $\pm$ 0.06	0.07 $\pm$ 0.02	0.15 $\pm$ 0.06	0.10 $\pm$ 0.03
Average distance (ha)	3.9 $\pm$ 0.9	31 $\pm$ 5.3	101 $\pm$ 12	429 $\pm$ 150
Most frequent crops (%)	Banana 100 Coffee 40	Maize 38 Irish potato/ 23 groundnut	Maize 33 Irish potato 33	Maize 40 Groundnut 30
RG2 (n)	9	10	8	14
Average area (ha)	0.20 $\pm$ 0.04	0.09 $\pm$ 0.02	0.09 $\pm$ 0.02	0.18 $\pm$ 0.04
Average distance (ha)	3.8 $\pm$ 0.4	51 $\pm$ 10	83 $\pm$ 11	229 $\pm$ 56
Most frequent crops (%)	Banana 100 Beans/ 33 cassava/Coc	Maize 60 Sweet potato 40	Maize 63 Beans 25	Maize 64 Beans 43
RG3 (n)	3	4	1	7
Average area (ha)	0.06 $\pm$ 0.03	0.04 $\pm$ 0.004	0.10	0.08 $\pm$ 0.03
Average distance (ha)	5.8 $\pm$ 1.7	21 $\pm$ 7	78	1120 $\pm$ 214
Most frequent crops (%)	Banana 100	Sweet potato 50 Cocoyam 50	na	Maize 72 Beans 43
Total average area (ha)	0.17 $\pm$ 0.03	0.07 $\pm$ 0.01	0.12 $\pm$ 0.03	0.13 $\pm$ 0.02
Total average distance (ha)	4.2 $\pm$ 0.45	37 $\pm$ 5	90 $\pm$ 8	670 $\pm$ 96

Table 2.7. Mean crop product yield and stover yield (fresh weight) with respective product N and stover N (dry weight), percentage of crop product used by the household or sold, N input from legume BNF, and percentage of stover retained, burnt in the field, used as banana mulch, fed to livestock, or burned as firewood. Mean values are reported for all farms. National survey first season mean yields for Kabarole district, western Uganda, and all of Uganda, are included as a comparison (UBOS, 2010).

All farms									National survey seasonal yields		
Crop	Yield			Stover			Legume N				
	count	Mean	Product N	Crop for HH use	Crop for sale	Mean	Stover N	N input	Kabarole district	Western region	Uganda
	<i>n</i>	kg ha ⁻¹	kg ha ⁻¹	%	%	kg ha ⁻¹	kg ha ⁻¹	kg ha ⁻¹	kg ha ⁻¹	kg ha ⁻¹	kg ha ⁻¹
Banana	21	9539 ± 1031	6 ± 0.7	79	17	na			8952	5954	4981
Beans	18	812 ± 133	24 ± 3.9	74	12	1218 ± 199	12 ± 1.8	-5.7 ± 1.1	2117	1703	1505
Cassava	10	2611 ± 354	2 ± 0.3	83	22	4084 ± 553	13 ± 1.8		7032	3352	3321
Coffee	4	1854 ± 636	4 ± 1.4	0	100	na			na	1330	705
Groundnuts	15	1004 ± 187	42 ± 7.8	43	30	4016 ± 746	75 ± 13.9	39.7 ± 7.4	1926	867	709
Irish	11	5763 ± 1021	14 ± 2.6	42	24	na			7322	5181	4714
Maize	33	1322 ± 173	18 ± 2.4	79	21	3994 ± 437	35 ± 3.8		8195	2639	2329
Millet	3	1093 ± 132	22 ± 2.7	41	46	4371 ± 527	5 ± 0.6		5760	1508	1108
Sorghum	3	770 ± 304	11 ± 4.4	100	0	2731 ± 1079	13 ± 5.3		1274	1363	941
Sweet Potato	11	7772 ± 1332	14 ± 2.4	75	17	7772 ± 1332	23 ± 4.0		8101	3010	4131
Cocoyam	6	1625 ± 707	-	100	0	na					
Sugarcane	1	863	-		100	na					
Fallow	3										

Table 2.8. Mean crop product yield and stover yield (fresh weight) with respective product N and stover N (dry weight), percentage of crop product used by the household or sold, N input from legume BNF, and percentage of stover retained, burnt in the field, used as banana plantation mulch, fed to livestock, or burned as firewood. Mean values are reported by resource group: RG1, RG2, and RG3.

RG1													
Crop	Yield			Stover				Legume N	Stover use				
	Fields with crop	Mean	Product N	Crop for		Mean	Stover N	N input	Banana				
				HH use	sale				Retained	Burnt	mulch	Livestock	Firewood
				%	%				kg ha ⁻¹	kg ha ⁻¹	%	%	%
Banana	7	9121 ± 1179	6 ± 0.8	63	18	na			100				
Bean	4	1320 ± 368	38 ± 10.7	61	12	1980 ± 553	20 ± 4.6	-9.4 ± 3.4	25		75		
Cassava	2	1687 ± 90	2 ± 0.1	63	25	2639 ± 141	9 ± 0.5		0				100
Coffee	3	1695 ± 871	4 ± 2.0	0	100	na			100				
Groundnut	7	1404 ± 289	59 ± 12.1	30	41	5616 ± 1154	104 ± 21.5	55.5 ± 11.4	100				
Irish	5	6792 ± 1315	17 ± 3.3	42	35	na			100				
Maize	9	1471 ± 473	20 ± 6.5	78	21	4024 ± 1001	35 ± 8.9		45		55		
Millet	2	999 ± 160	20 ± 3.2	50	33	3515 ± 562	4 ± 0.7		100				
Sorghum	1	1379 ± na	20 ± na	100	0	4302 ± na	24 ± na		0		100		
Sweet Potato	4	10321 ± 2295	19 ± 4.1	70	26	10321 ± 2295	31 ± 6.9		80	20			
Cocoyam	1	459	-	100	0	na			100				
Sugarcane	1	863	-	100	0	na			100				
Fallow	1												
Eucalyptus	1												
RG2													
Crop	Yield			Stover				Legume N	Stover use				
	Fields with crop	Mean	Product N	Crop for		Mean	Stover N	N input	Banana				
				HH use	sale				Retained	Burnt	mulch	Livestock	Firewood
				%	%				kg ha ⁻¹	kg ha ⁻¹	%	%	%
Banana	10	10483 ± 1420	7 ± 0.9	82	19	na			100				
Bean	11	630 ± 133	18 ± 3.9	76	17	945 ± 200	9 ± 1.9	-4.6 ± 1.1	24		75		
Cassava	5	3545 ± 330	3 ± 0.3	83	33	5545 ± 517	18 ± 1.7		80				20
Coffee	1	2331 ± na	5 ± na	0	100	na			100				
Groundnut	6	745 ± 223	31 ± 9.3	55	24	2981 ± 893	55 ± 17	29.5 ± 8.8	83	17			
Irish	4	5946 ± 2186	15 ± 5.5	31	22	na			100				
Maize	19	1201 ± 165	17 ± 2.3	83	22	3802 ± 522	33 ± 5.0		70	5	25		
Millet	1	1281 ± na	26 ± na	23	71	4510 ± na	6 ± na		100				
Sorghum	2	466 ± 14.57	7 ± 0.2	100	0	1454 ± 45	8 ± 0.3		50	50			
Sweet Potato	5	4317 ± 1027	8 ± 1.9	100	0	4317 ± 1027	13 ± 3.1		40		20	40	
Cocoyam	2	1557 ± 964	-		0	na			100				
Fallow	1												
RG3													
Crop	Yield			Stover				Legume N	Stover use				
	Fields with crop	Mean	Product N	Crop for		Mean	Stover N	N input	Banana				
				HH use	sale				Retained	Burnt	mulch	Livestock	Firewood
				%	%				kg ha ⁻¹	kg ha ⁻¹	%	%	%
Banana	4	7909 ± 3934	5 ± 2.6	92	8	na			100				
Bean	3	802 ± 265	23 ± 7.7	100	0	1204 ± 398	14 ± 2.4	-4.7 ± 2.9	75		25		
Cassava	3	1669 ± 238	2 ± 0.2	94	6	2611 ± 372	9 ± 1.2		25				75
Coffee	0												
Groundnut	2	380 ± 98	16 ± 4.1	48	17	1522 ± 391	28 ± 7.3	15 ± 3.9	50	50			
Irish	2	2823 ± 154	7.00 ± 0.4	56	11	na			100				
Maize	5	1527 ± 348	21 ± 4.8	62	33	4835 ± 1106	43 ± 9.7		40	40	20		
Millet	0												
Sorghum	0												
Sweet Potato	2	11312 ± 181	20 ± 0.3	58	30	11312 ± 181	34 ± 0.5		0			100	
Cocoyam	3	2147 ± 1308				na			100				
Fallow	1												

Organic resource and N flows

Flow maps show the seasonal flow of organic materials and N across the farms, highlighting the flow of resources within the farm, the substantial flow of resources out of the farms, and the lack of corresponding flows of resources into the farms. Harvested products from the outfields and homefields comprised the main organic resource flows for all farm types (Figures 2.3, 2.4, 2.5). RG1 farms transferred the highest quantity of organic materials and N off-farm through crop sales, while RG2 and RG3 averaged somewhat similar crop sale N flows. However, RG1 farms sold the highest proportion of their harvested products at 33%, RG2 sold 29% and RG3 farms sold 13% (Table 2.5). Crop residues were transferred from outfields to the home banana plantation within farms of all resource groups, though the average quantity of residues transferred was highest for RG1. Crop residues were applied as mulch to control weeds and add fertility to home banana plantations in 73% of farms; almost all RG1 and RG2 farms applied residues, while only one RG3 farm did (Figures 2.3, 2.4, 2.5). The residues most commonly used as banana mulch, either singly or in combination, were bean (86%) and maize (57%) residues (Table 2.8).

Across resource groups, few farms transported residues to the homestead to use as firewood (Figure 2.6). Several RG2 and RG3 farms burned maize and/or groundnut residues in the field, and for those that did there was significant organic matter and N lost through burning. One RG2 household stated that they burned maize residues because it cost too much money to transport them. Not captured in the flow maps is the fact that 37% of households (one from RG1, five RG2, and one RG3) reported they occasionally burned their fields; approximately half of those farmers resorted to burning to get rid of unwanted grass

(elephant/Napier grass or spreading grasses like couch grass), while half burned maize fields to make field preparation easier.

Banana residues and residues from all crops intercropped with bananas remained in the banana plantation and were used as mulch. The majority of households reported throwing household waste into the home banana plantation, as well as tossing daily yard sweepings containing chicken and goat droppings into the plantation (Figure 2.3). As banana is the staple crop, banana peelings constitute a large percentage of household waste, though these were not considered as an input if they were returned to the banana plantation.

Compost was rarely made and employed. Four farms, one RG1 and three RG2 farms, reported adding household waste to compost and then three used compost on the home banana plantation, with one farm adding it to a close field. Household waste was used to feed livestock on RG1 and RG2 farms, but not on RG3 farms where chickens and goats were fed crop residues, tethered, or were free-range foragers. Groundnut shells and maize cobs were the main components of household waste that were burnt, while cooking ash was a waste that was often heaped in one spot (Figures 2.3, 2.4, 2.5).

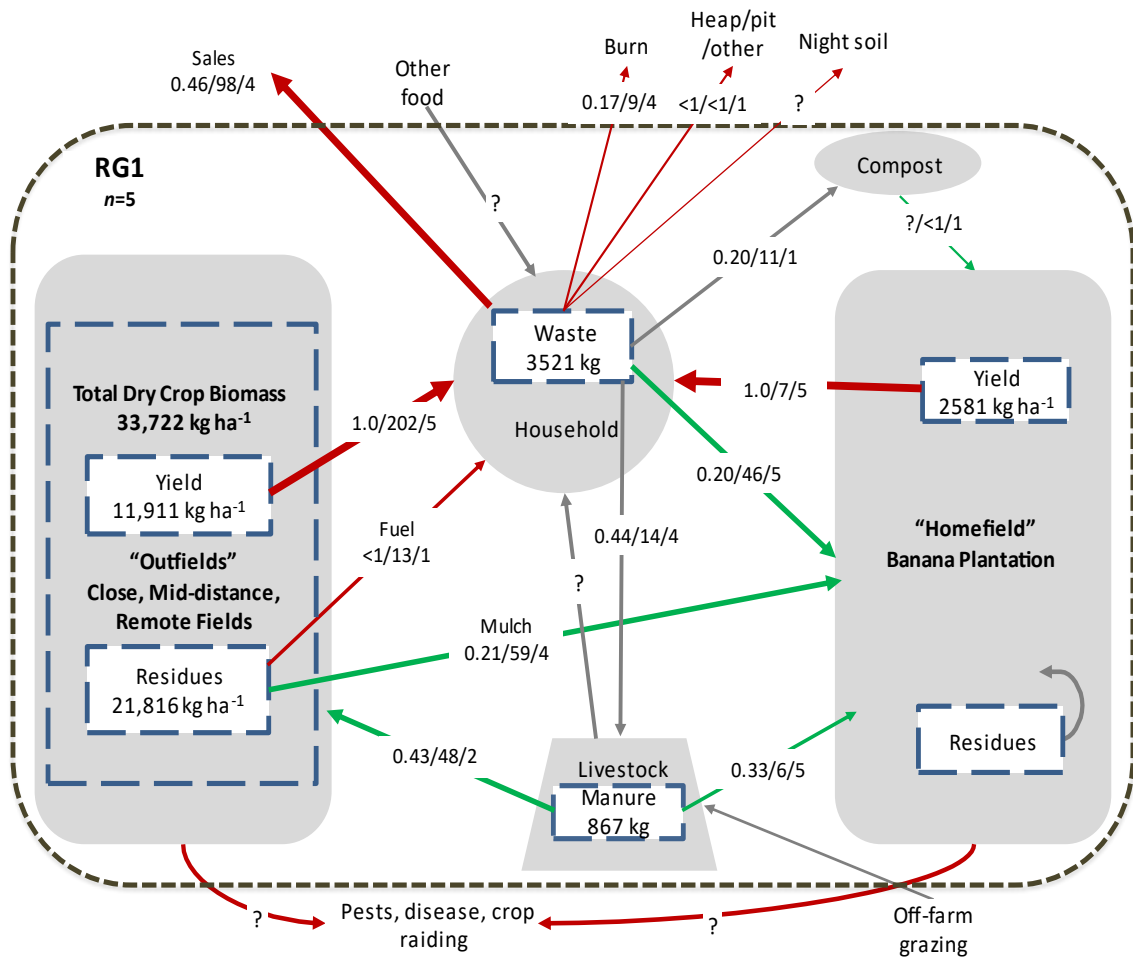


Figure 2.3. Organic resource and N flow maps for better resourced (RG1) smallholder farms located next to Kibale National Park in western Uganda for the first rains season in 2016. The arrow lines indicate the flow direction, and the number values show percent of resource transferred/amount of N transferred/number of farms transferring the resource. The total biomass, yields, residues, and livestock manure are reported on a dry weight basis while household waste is reported as fresh weight. Green arrows represent an input into a field. Red arrows indicate outputs. Gray arrows represent flows that are uncertain as to input status.

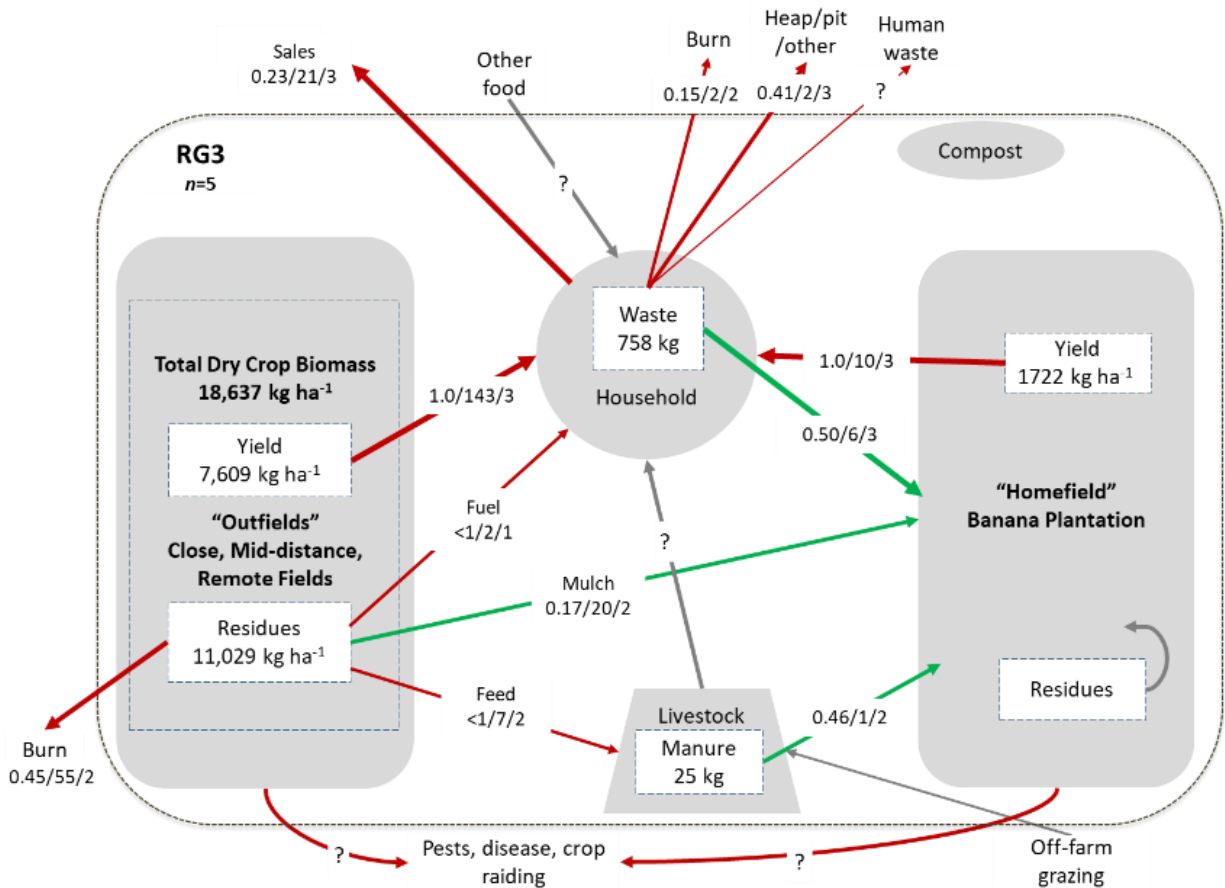


Figure 2.5. Organic resource and N flow maps for poorly resourced (RG3) smallholder farms located next to Kibale National Park in western Uganda for the first rains season in 2016. The arrow lines indicate the flow direction, and the number values show percent of resource transferred/amount of N transferred/number of farms transferring the resource. The total biomass, yields, residues, and livestock manure are reported on a dry weight basis while household waste is reported as fresh weight. Green arrows represent an input into a field. Red arrows indicate outputs. Gray arrows represent flows that are uncertain as to input status.

N Inputs and partial N balances

None of the farms used inorganic fertilizers. N from organic inputs, which included crop residues, animal manure, household waste, and compost, were applied to the home banana plantations for all resource groups and contributed an average of 87, 72, and 35 kg N ha⁻¹ to RG1, RG2, and RG3 home banana plantations, respectively (Figure 2.6A). Two RG1 farms added animal manure and one added compost to close fields (Figure 2.6A). The only remote fields to

receive any organic inputs were two remote banana plantations owned by the largest RG1 farm, and these fields received maize and bean residues from nearby outfields (Figure 2.6B). Outfields, but not homefields, received N input from legume BNF, which specifically reflects the input from groundnut BNF as the estimated 50% N fixation rate for common bean (Table 2.1) resulted in low-level soil N mining rather than N addition once grain removal was factored in (Figure 2.6B and Table 2.8). Despite the N input from groundnut BNF, outfields for all resource groups exhibited negative N balances (Figure 2.6C). Home banana plantations, on the other hand, had positive mean N balances for all resource groups, with the balances for RG1 and RG2 more than two times greater than RG3 (Figure 2.6C). Farm scale N balances would be strongly negative for farms of every resource group, as is made evident by the resource flow maps with their many substantial N flows out of the farms and extremely scarce N inputs into the farms.

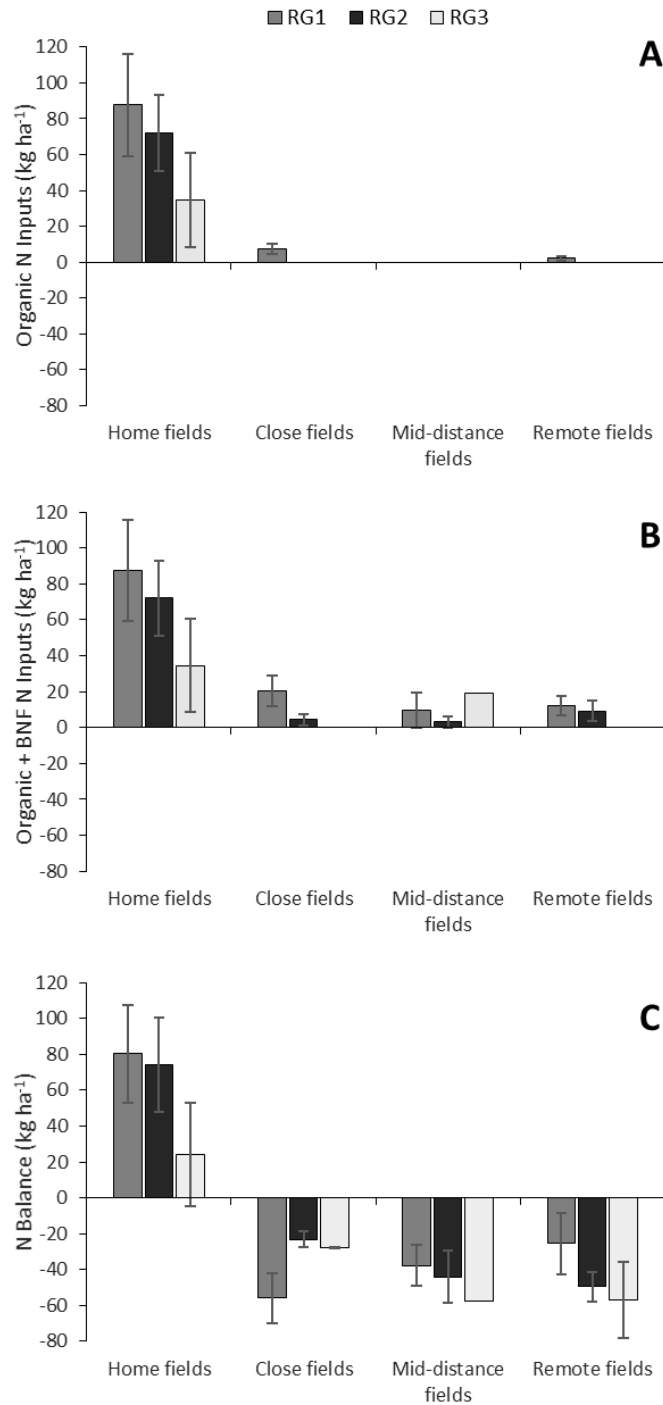


Figure 2.6. (A) Organic N inputs and (B) Organic N and BNF inputs into case study fields categorized according to their distance from the homestead and by farm resource group (RG1, RG2, RG3). Organic inputs included crop residues, household waste, compost, and manure. The (C) N balance is the N inputs (organic + BNF) balanced with the N lost through grain harvest and removal of crop residue (removed from the field or burned). Bars represent means and error bars ± 1 SE.

SOC and N gradients within the farm

SOC and N did not exhibit consistent trends across farms when analyzed by distance from the homestead. SOC and N varied by village location with farms in Kyakabuzi, and Kyakabale having higher SOC and N than farms in Iruhuura, Rweteera, Kyantambara, and Kanyawara (Figure 2.7). SOC and N showed a slight decrease with increasing field distance from the homestead for farms in Iruhuura and Kyantambara. There was also an opposite trend, a slight increase further from the homestead, for farms in Rweteera, Kanyawara, and Kyakabuzi. Farms in Kyakabale had similar SOC and N over distance from the homestead. C:N values trended moderately upward at an increasing distance from the homestead for farms in Iruhuura, while farms in Kyantambara had decreasing C:N in fields further away. There was no obvious SOC and N gradient from homestead to outfields and the trends that were more visible showed the opposite trend – SOC and N increasing in fields further from the homestead.

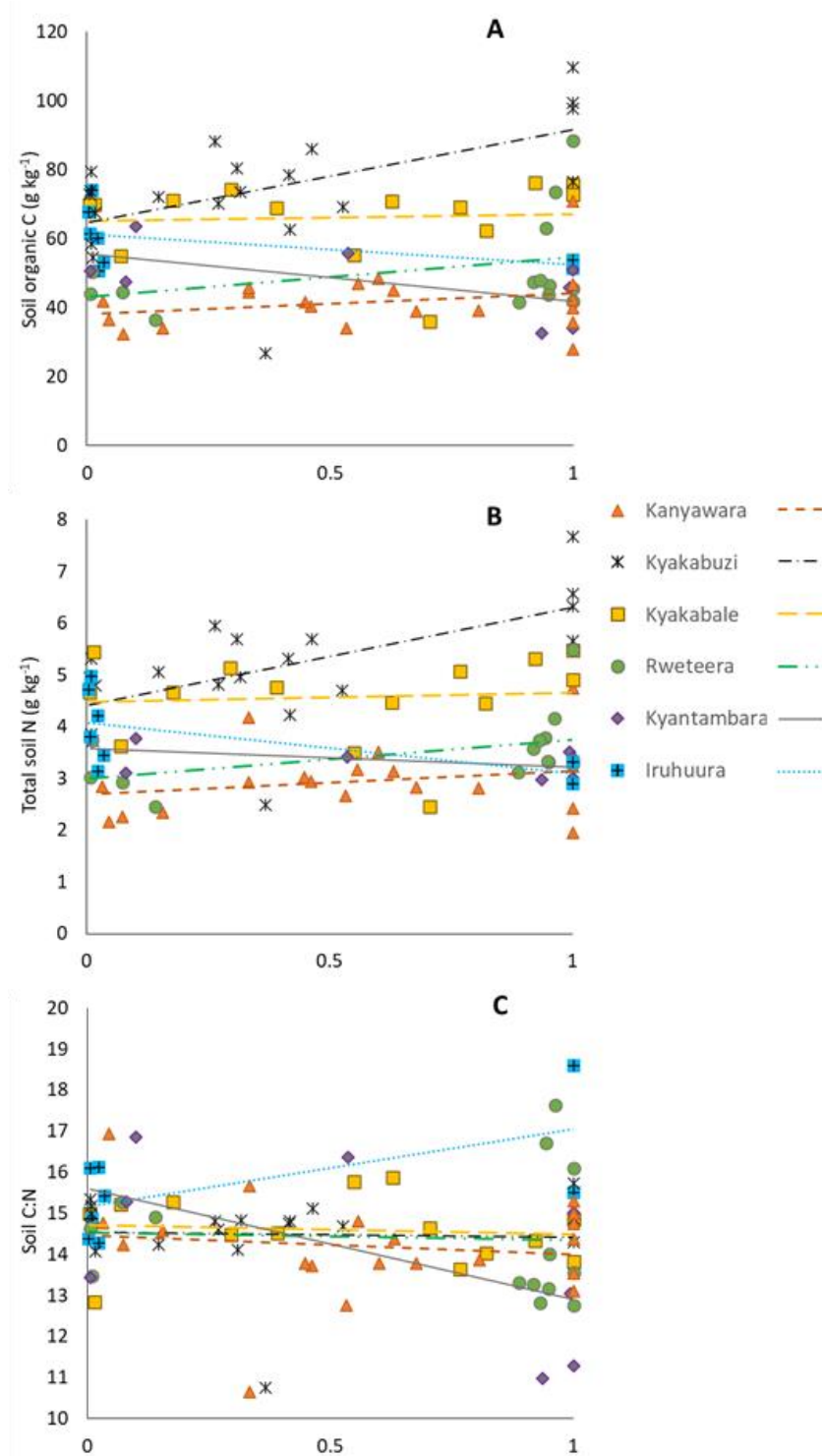


Figure 2.7. (A) Soil organic C, (B) total soil N, and (C) C:N in relation to the absolute distance from each field to the homestead within the six villages along KNP. To standardize the relative field distances from the homestead across farms of different sizes, the absolute distance to a field was divided by the maximum distance from homestead to field within a farm (after Tittonell et al., 2007).

Discussion

I found that farms of all resource endowments allocated the majority of their resources to home banana plantations, but despite the high relative transfer and input of organic resources into the homefields (Figures 2.3, 2.4, 2.5) and their resulting positive nutrient balances (Figure 2.6), home banana plantations did not have higher SOC or N than outfields (Figure 2.7). SOC and N gradients did not appear to be connected to resource endowment or resource flows (Figure 2.7). Within the study region, the inherent soil fertility appears to be the predominant factor affecting soil heterogeneity as there are clear differences in SOC and N based on farm location but unclear variation in soil fertility within farms (Figure 2.7). Though not reflected in SOC and N, resource allocation and crop management varied within farms and according to farm resource endowment.

Organic resource flows and partial N balances: quantity, quality, and limitations

Organic resource flow maps showed that home banana plantations received the most organic matter inputs, while outfields had few input flows coupled with large output flows, indicative of SOM mining (Figures 2.3, 2.4, 2.5). Flow maps highlighted important nutrient inputs from animal manure, household waste, and crop residues, but each of these nutrient flows come with caveats. Animal manure is a valuable resource as it provides organic matter as well as N, P, K and many other elements (Hoffman et al., 2001). However, manure often provides these nutrients in low amounts in SSA, reflecting the generally poor diets of the animals (Eck and Stewart, 1995). Collection and storage of manure greatly impacts manure composition, with large differences between covered and uncovered, composted and

uncomposted manure (Palm et al., 2001). Timing and method of application also affect manure benefits (Giller et al., 1997). As noted previously, goat and chicken manure were often “thrown” into the plantation as yard sweepings, rather than being deliberately applied. Household waste was similarly described as being “thrown” into the plantation, not spread or incorporated.

Conversely, crop residues were purposefully spread as mulch to control weeds and improve soil fertility in the banana plantation. Crop residues contributed greater quantities of organic material but with less concentrated N than manure or household wastes, except at the highest application amounts as seen for RG1 farms (Figure 2.3). However, transferred crop residue inputs come at the expense of another field’s soil fertility and thus are not a sustainable option. All farmers reapplied banana residues, consisting of stalks and leaves, as mulch to the banana plantation, which is a practice that retains important organic materials, but could also increase the prevalence of pests and disease (Bekunda and Woomer, 1996). A study in southern central Uganda found that farmers reported the largest bunch weights (~ 20 kg bunch⁻¹) when they applied a combination of banana residues, field crop residues, and cattle manure to the banana plantation (Bekunda and Woomer, 1996). Notably, in my calculations all organic inputs except for groundnut residues were estimated to have less than 2% N, which means that upon application they may initially cause N immobilization and potentially have a negative effect on crop growth (Palm et al., 2015; Sileshi et al., 2017).

I calculated a positive partial N balance for the home banana plantation for all levels of farm resource endowment. It is important to note that the partial N balance did not account for N loss through volatilization, leaching, or erosion, or N gains from erosion or deposition.

Wortmann and Kaizzi (1998) calculated full nutrient balances for smallholder farms and fields in central and eastern Uganda and determined that the full balance for banana plantations, which similarly received organic inputs, would be close to neutral. However, Wortmann and Kaizzi (1998) assumed that an average household produced 20 and 100 kg year⁻¹ of ash and household waste, respectively; household waste was not defined and no data or measurements were provided to justify this assumption. From farmer-reported values, I estimated a much higher value of 5790 kg year⁻¹ of household waste and ash. My estimates for household waste are closer to the 9200 kg year⁻¹ of household waste reported by Briggs and Twomlow (2002), who assumed that a typical household produced two basins of peelings (1 basin = 15 kg) and one basin of sweepings (1 basin = 10 kg) per day. Differences in classification of household waste may account for these large discrepancies. This highlights the importance of well-defined components for resource flow and nutrient balance calculations in order to fully capture and accurately estimate inputs and outputs.

The flow maps and N balances revealed that within farms of all resource types, there are still underutilized organic resources available. To fully utilize or enhance available resources, households could: refrain from burning any residues; employ all their household waste instead of burning or heaping it on one spot; employ all manure; make nutrient-rich compost; or grow more groundnut or other legume crops that can contribute substantial N. Human waste is another resource that has been considered as a potential input in several studies, but utilizing human waste presents other serious challenges and limitations (Andersson, 2015; Lederer et al., 2015). Fully employing available resources requires altering or adopting management practices, which may be difficult, and even if farms maximize their organic resources, the

conundrum remains of how to manually distribute organic resources across a fragmented farm landscape and to ensure that soil nutrient stores are adequately replenished. As acknowledged above, the nutrient composition of organic resources can be highly variable due to environmental and management factors, making it difficult to know whether organic inputs can meet the nutrient requirements, particularly N, necessary for crop production and maintenance of soil fertility.

Impacts of farm resource endowment on organic resource flows and soil fertility gradients

Farm resource endowment impacted organic resource flows and soil fertility gradients through several interconnected factors: (1) distance from the field to the homestead, (2) land ownership, (3) labor, (4) livestock and manure availability, and (5) quantity of crop biomass. Compared to farms with limited resources (RG3), farms with more resources (RG1 and RG2) had fields located closer to the homestead, had more secure land tenure across their farms, hired labor, owned more livestock and larger livestock like cattle and pigs, and had higher yields and total biomass production (Tables 2.4, 2.5, 2.7, 2.8).

The study region is densely populated and land pressure is high as evidenced by the relatively small farms, small field sizes, farm fragmentation with extremely remote fields, and large number of crops per field (Table 2.4). Cultivating fields distant from the homestead increases the time, effort, and labor required to transport resources, particularly if farm fields are also distant from each other. Yet, fields distant from homesteads and village centers may provide access to better quality soils and larger tracts of land. The slightly positive trend of SOC and N with increasing field distance from the homestead may be partly explained by the ability

and willingness of farmers to access higher quality soil through renting of distant fields.

Approximately 45% of remote fields were rented. One RG2 farmer with remote fields stated that if he experienced seasonal yield decline in one of his fields, he allowed the field to fallow and rented from others.

In this specific study region with its fertile soils, renting fields may provide access to more fertile soil, but renting might also entail fields more distant from the household, insecure land tenure, and fields closer to the KNP boundary that have the added risk of crop raiding by park animals. Historically, the land adjacent to KNP was relegated to poorer and more marginalized farmers, but more recently it has become an appealing investment opportunity for wealthier households and distant landowners (L’Roe and Naughton-Treves, 2017). Similar to L’Roe and Naughton-Treves (2017), I found that poorer, RG3 households near to KNP were entering into precarious land rental agreements. One household was farming two small fields that the respondent identified as “free to use”, but the fields were located on a large parcel owned by a wealthy landowner. The respondent said the fields experienced erosion but that they did not take any preventative measures because the owner “chases [sic] away” and so they were afraid to do anything. Another RG3 household was farming land in extremely distant fields directly adjacent to the KNP boundary that was being offered to poorer farmers in exchange for a part of their harvest. Temporary huts were erected on the land where people would stay in order to protect crops from animal raiding at night. The extreme distance of these fields from the surveyed RG3 homestead meant that crop residues were burnt to reduce time and labor, but at a great loss of potential nutrient inputs.

Nutrient loss was also high for RG1 and RG2 households because greater amounts of organic materials were produced and transported within the farm and more residues were transferred from the outfields to the banana plantations (Figures 2.3 and 2.4). Unlike RG3 farms, RG1 and RG2 farms hired labor, which reflects having more resources available to devote to crop residue transfer, as well as transport of resources like animal manure. Hiring labor did not deter burning as a management practice, as one RG2 farm that hired labor stated that they still burned maize residues because they were too costly to transport, and another said that they burned maize fields for easy preparation. Three more RG2 farms and one RG1 farm that hired labor sometimes burned fields to control spreading grasses, e.g., couch grass. RG1 and RG2 farms kept more livestock and therefore had more animal manure available as an input (Table 2.5). However, as noted above, not all farms with cattle and pigs put this manure to use. As one RG2 household head stated, she was single and did not have the time or energy to transport and spread the pig manure.

Soil fertility and farm gradients

Farm-scale nutrient balances were negatively impacted by farmers' preferential allocation of resources to home banana plantations, which corresponds with previous studies documenting farmer management in banana-based agroecosystems in Uganda (Bekunda and Woome, 1996; Bekunda and Manzi, 2003; Briggs and Twomlow, 2002; Esilaba et al., 2005; Wortmann and Kaizzi, 1998). However, these estimated negative nutrient balances are not yet reflected in SOC and N stocks. Although I did not detect reductions in SOC and N in relation to

decreases nutrient balances, this may be due to my small sample size. Indeed, if these practices continue, it is likely SOC and total N losses will become more pronounced and detectable.

I also did not find decreasing soil fertility (as indicated by SOC and total N) with increasing distance from the homestead, which is likely attributable to the high inherent soil fertility of the study region (Figure 2.7) and/or farmers seeking better soils and moving far from their households as discussed above. Tiftonell et al. (2013) observed that while farmer management effects on soil variability were clearer in densely populated areas and in association with slopes in undulating landscapes, farmer management did not have the same impact in areas with inherently fertile or volcanic soils. Soil variability did not appear to be an effect of farmer management, but rather a factor of the inherent, heterogeneous soil landscape (Figure 2.7).

The high regional soil fertility does not equate to drastically higher yields compared to reported yields for common crops at the district, regional, or national level (Tables 2.7 & 2.8). The fact that yields are still low to suboptimal can be seen as indicative of one or more of the multiple factors that restrict yields within smallholder farms in SSA, including land scarcity, labor and time limitations, access to quality seed, rainfall timing and amount, and extension and market information.

Organic material – is it ‘enough’?

I did not find evidence of increased SOC or total N in farm fields receiving organic material inputs. Quantity, quality, timing and method of application, and other management and environmental factors affect the potential impact of organic material additions.

Composting is a recommended practice that can maximize use of organic resources and concentrate nutrients, allowing farmers to make readily usable organic matter that will promote SOM accrual. I was interested to see if farms produced sufficient organic material to create nutrient-rich compost that would meet the needs of a typical maize crop. Following published on-farm compost-making instructions for smallholder farmers, I constructed compost piles for each farm using the same organic materials data used to create the resource flows and nutrient balances (Bello-Bravo and Pittendrigh, 2021; CTA, 2007; Dalzell et al., 1987; Misra et al., 2003). I made 2.5 x 2 x 1.5 m compost piles with five 30 cm layers composed of: 25 cm (336 kg) crop residues; 4 cm (56 kg) animal manure or legume plant material; 2 cm (28 kg) household waste; and a sprinkling of soil/ash/previous compost (Bello-Bravo and Pittendrigh, 2021; CTA, 2007; Misra et al., 2003). Many compost methodologies recommend an initial foundation layer that allows for air circulation, but I did not include it in my calculations because this layer can be more easily improvised with various materials (e.g., woody maize stems, branches, bricks). The weight of one newly constructed compost heap was 2100 kg. I assumed that the pile would reduce to about one-third of its original height and ultimately yield approximately 315 kg mature compost. I determined the amount of mature compost that could be produced in one season if farmers fully utilized their available crop residues, household waste, and manure. I found that on average, farms across RGs could produce approximately 630 kg of mature compost, which would be enough to meet the recommended 400-600 kg of compost needed to supply one handful of compost per planting hole for one hectare of maize spaced 30 cm x 75 cm (44,444 plants ha⁻¹)(CTA, 2007). Mature compost amounts varied dramatically by resource endowment with RG1 farms capable of producing a mean of 1103 kg per season, while RG2

could produce 648 kg, and RG3 only 158 kg. Overall, these values look promising, particularly when considering that farms ranged from 0.04 to 0.59 ha and mean farm size was 0.54 ha. However, the time, labor, and logistics required to produce and apply compost would be challenging, especially considering the distances between the homestead and fields. Farmers would need to gather and transport the 2100 kgs of organic components needed to construct one compost pile and then transport the mature compost to apply it. It has been estimated to take 2-3 labor days to prepare and apply one ton of compost (Dalzell et al., 1987). Household waste and animal manure are generated daily and would need to be stored, while large quantities of vegetative materials like crop residues or weeds are usually produced in one short time period. Livestock are generally not penned and collecting and transporting manure from grazing locations could also prove challenging. Water is added during compost pile construction, as well as throughout the maturation process, and a pile made to the current dimensions would require an estimated 750 L water (calculated based on values given in Dalzell et al., 1987). Mature compost would also need to be covered and stored until use. My back-of-the-envelope calculations suggest that there is enough organic material for farmers to make compost in an amount that could effectively boost crop yields and possibly contribute to maintaining or increasing SOC and N. Yet, for these smallholder farmers, the realities of collecting, transporting, and adding the compost materials, monitoring piles over time, and then applying compost to fields might present substantial deterrents to widespread use and adoption. Additionally, making a substantial amount of compost would necessitate removing most residues from fields, potentially exposing soils to wind and water erosion and moisture loss.

Conclusion

Home banana plantations received the vast majority of organic resources and had the highest concentration of nutrients compared to fields located further from the homestead. Organic resource flow maps confirmed the concentration of nutrients around the homestead in the home banana plantation. A partial N balance at the field scale was only positive for home banana plantations and negative for all outfields, including close outfields and outfields receiving N inputs from legume BNF. Farmer resource endowment mainly affected resource flows as to the quantity of organic materials and N inputs, but this did not appear to result in any differences in SOC and N. Contrary to my hypothesis, home banana plantations did not have higher SOC and N. Current SOC and N values do not reflect management gradients, and instead confirm the inherent heterogeneity of the soil landscape and that soil fertility varied most among village locations. Slightly larger SOC and N values in the reverse gradient from outfields to homefields may be explained by the ability of households to access land through renting fields further from the homestead and village centers. In comparing my methods, values, and results to similar studies in the literature, it became apparent that without standard definitions or quantifications for specific resources, it is possible to construct very different nutrient balances in the same regions with divergent and variable results. Despite these differences, it is clear that many smallholder farms are mining soil nutrients from the majority of their fields and not providing adequate replenishment. The fragmented nature of most farms, with fields distant from the homestead and from each other, augments the time, labor, and transport challenges of resource-limited smallholder farmers. When making recommendations or promoting new technologies, extension and development agencies need

to consider the logistical and practical challenges of working within a highly fragmented landscape.

REFERENCES

REFERENCES

- Andersson, E., 2015. Turning waste into value : using human urine to enrich soils for sustainable food production in Uganda. *J. Clean. Prod.* 96, 290–298.
<https://doi.org/10.1016/j.jclepro.2014.01.070>
- Baijukya, F.P., De Steenhuijsen Piters, B., 1998. Nutrient balances and their consequences in the banana-based land use systems of Bukoba district, northwest Tanzania. *Agric. Ecosyst. Environ.* 71, 147–158. [https://doi.org/10.1016/S0167-8809\(98\)00137-6](https://doi.org/10.1016/S0167-8809(98)00137-6)
- Bekunda, M. a., Woomer, P.L., 1996. Organic resource management in banana-based cropping systems of the Lake Victoria Basin, Uganda. *Agric. Ecosyst. Environ.* 59, 171–180.
[https://doi.org/10.1016/0167-8809\(96\)01057-2](https://doi.org/10.1016/0167-8809(96)01057-2)
- Bekunda, M., Manzi, G., 2003. Use of the partial nutrient budget as an indicator of nutrient depletion in the highlands of southwestern Uganda. *Nutr. Cycl. Agroecosystems* 67, 187–195. <https://doi.org/10.1023/A:1025509400226>
- Bello-Bravo, J., Pittendrigh, B.R., 2021. Survival Gardening: How to Create Compst (3D) [Language: English (USA)] - SAWBO Video Library. [WWW Document].
- Berre, D., Corbeels, M., Rusinamhodzi, L., Mutenje, M., Thierfelder, C., Lopez-Ridaura, S., 2017. Thinking beyond agronomic yield gap: Smallholder farm efficiency under contrasted livelihood strategies in Malawi. *F. Crop. Res.* 214, 113–122.
<https://doi.org/10.1016/j.fcr.2017.08.026>
- Briggs, L., Twomlow, S.J., 2002. Organic material flows within a smallholder highland farming system of South West Uganda. *Agric. Ecosyst. Environ.* 89, 191–212.
[https://doi.org/10.1016/S0167-8809\(01\)00164-5](https://doi.org/10.1016/S0167-8809(01)00164-5)
- Bucagu, C., Vanlauwe, B., Van Wijk, M.T., Giller, K.E., 2014. Resource use and food self-sufficiency at farm scale within two agro-ecological zones of Rwanda. *Food Secur.*
<https://doi.org/10.1007/s12571-014-0382-0>
- Chapman, C.A., Lambert, J.E., 2000. Habitat alteration and the conservation of African primates: Case study of Kibale National Park, Uganda. *Am. J. Primatol.* 50, 169–185.
[https://doi.org/10.1002/\(SICI\)1098-2345\(200003\)50:3<169::AID-AJP1>3.0.CO;2-P](https://doi.org/10.1002/(SICI)1098-2345(200003)50:3<169::AID-AJP1>3.0.CO;2-P)
- Chikowo, R., Zingore, S., Snapp, S., Johnston, A., 2014. Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa. *Nutr. Cycl. Agroecosystems.* <https://doi.org/10.1007/s10705-014-9632-y>

- Cobo, J.G., Dercon, G., Cadisch, G., 2010. Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. *Agric. Ecosyst. Environ.* 136, 1–15. <https://doi.org/10.1016/j.agee.2009.11.006>
- CTA, 2007. Enriched Compost for Higher Yields. Wageningen, Netherlands.
- Dalzell, H., Biddellstone, A.J., Gray, K.R., Thurairanjan, K., 1987. Soil management: compost production and use in tropical and subtropical environments, *FAO Soils Bulletin*.
- de Jager, A., 2005. Participatory technology, policy and institutional development to address soil fertility degradation in Africa. *Land use policy* 22, 57–66. <https://doi.org/10.1016/j.landusepol.2003.06.002>
- de Jager, A., Onduru, D., Walaga, C., 2004. Facilitated learning in soil fertility management: Assessing potentials of low-external-input technologies in east African farming systems. *Agric. Syst.* 79, 205–223. [https://doi.org/10.1016/S0308-521X\(03\)00071-4](https://doi.org/10.1016/S0308-521X(03)00071-4)
- Esilaba, a. O., Nyende, P., Nalukenge, G., Byalebeka, J.B., Delve, R.J., Ssali, H., 2005. Resource flows and nutrient balances for crop and animal production in smallholder farming systems in eastern Uganda. *Agric. Ecosyst. Environ.* 109, 192–201. <https://doi.org/10.1016/j.agee.2005.03.013>
- Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Sanogo, O.M., Giller, K.E., 2015. Understanding farm trajectories and development pathways: Two decades of change in southern Mali. *Agric. Syst.* <https://doi.org/10.1016/j.agsy.2015.07.005>
- Fermont, A., Benson, T., 2011. Estimating yield of food crops grown by smallholder farmers: A Review in the Uganda Context. IFPRI Discuss. Pap. 01097 1–57.
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. *Sci. Data* 2, 1–21. <https://doi.org/10.1038/sdata.2015.66>
- Gambart, C., Swennen, R., Blomme, G., Groot, J.C.J., Remans, R., Ocimati, W., 2020. Impact and Opportunities of Agroecological Intensification Strategies on Farm Performance: A Case Study of Banana-Based Systems in Central and South-Western Uganda. *Front. Sustain. Food Syst.* 4, 1–13. <https://doi.org/10.3389/fsufs.2020.00087>
- Giller, K.E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W.D., Mafongoya, P.L., 1997. Building Soil Nitrogen Capital in Africa, in: Buresh, R.J., Sanchez, P.A., Calhoun, F. (Eds.), *Replenishing Soil Fertility in Africa*, SSSA Spec. Publ. 51. SSSA and ASA, Madison, WI, pp. 151–192. <https://doi.org/10.2136/sssaspecpub51.c7>

- Hailelassie, A., Priess, J. a., Veldkamp, E., Lesschen, J.P., 2007. Nutrient flows and balances at the field and farm scale: Exploring effects of land-use strategies and access to resources. *Agric. Syst.* 94, 459–470. <https://doi.org/10.1016/j.agsy.2006.11.013>
- Hailelassie, A., Priess, J., Veldkamp, E., Teketay, D., Lesschen, J.P., 2005. Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agric. Ecosyst. Environ.* 108, 1–16. <https://doi.org/10.1016/j.agee.2004.12.010>
- Hartter, J., Southworth, J., 2009. Dwindling resources and fragmentation of landscapes around parks: Wetlands and forest patches around Kibale National Park, Uganda. *Landsc. Ecol.* 24, 643–656. <https://doi.org/10.1007/s10980-009-9339-7>
- Hartter, J., Stampone, M.D., Ryan, S.J., Kirner, K., Chapman, C.A., Goldman, A., 2012. Patterns and perceptions of climate change in a biodiversity conservation hotspot. *PLoS One* 7. <https://doi.org/10.1371/journal.pone.0032408>
- Henao, J., Baanante, C., 1999. Estimating Rates of Nutrient Depletion in Soils of Agricultural Lands of Africa Library of Congress Cataloging-in-Publication Data Estimating rates of nutrient depletion in soils of agricultural lands of Africa.
- Hockett, M., Richardson, R.B., 2018. Examining the drivers of agricultural experimentation among smallholder farmers in Malawi. *Exp. Agric.* 54, 45–65. <https://doi.org/10.1017/S0014479716000673>
- Jahnke, H.E., 1982. Livestock production systems and livestock development in tropical Africa, Wissenschaftsverlag Vauk, Kiel, Germany. [https://doi.org/10.1016/0308-521x\(83\)90080-x](https://doi.org/10.1016/0308-521x(83)90080-x)
- Kanmegne, J., Smaling, E.M.A., Brussaard, L., Gansop-Kouomegne, A., Boukong, A., 2006. Nutrient flows in smallholder production systems in the humid forest zone of southern Cameroon. *Nutr. Cycl. Agroecosystems.* <https://doi.org/10.1007/s10705-005-8312-3>
- Kiboi, M.N., Ngetich, F.K., Mugendi, D.N., 2019. Nitrogen budgets and flows in African smallholder farming systems. *AIMS Agric. Food* 4, 429–446. <https://doi.org/10.3934/AGRFOOD.2019.2.429>
- L'Roe, J., Naughton-Treves, L., 2017. Forest edges in western Uganda: From refuge for the poor to zone of investment. *For. Policy Econ.* 84, 102–111. <https://doi.org/10.1016/j.forpol.2016.12.011>
- Lederer, J., Karungi, J., Ogwang, F., 2015. The potential of wastes to improve nutrient levels in agricultural soils: A material flow analysis case study from Busia District, Uganda. *Agric. Ecosyst. Environ.* 207, 26–39. <https://doi.org/10.1016/j.agee.2015.03.024>

- Lepp, A., Holland, S., 2006. A comparison of attitudes toward state-led conservation and community-based conservation in the village of Bigodi, Uganda. *Soc. Nat. Resour.* 19, 609–623. <https://doi.org/10.1080/08941920600742377>
- Majaliwa, J.G.M., Ratemo, S., Zizinga, A., Mugarura, M., Wafula, S.D., Tunywane, I., Ababo, P., Achom, A., Tweyambe, C., Kyalisima, K., Kaahwa, R., 2015. Suitability of major agricultural land uses around Kibale National Park. *African J. Agric. Res.* 10, 3582–3589. <https://doi.org/10.5897/ajar2014.9197>
- Majaliwa, J.G.M., Twongyirwe, R., Nyenje, R., Oluka, M., Ongom, B., Sirike, J., Mfitumukiza, D., Azanga, E., Natumanya, R., Mwerera, R., Barasa, B., 2010. The Effect of Land Cover Change on Soil Properties around Kibale National Park in South Western Uganda. *Appl. Environ. Soil Sci.* 2010, 1–7. <https://doi.org/10.1155/2010/185689>
- Marinus, W., Descheemaeker, K.K.E., Ven, G.W.J. Van De, Waswa, W., Mukalama, J., Vanlauwe, B., Giller, K.E., 2021. “ That is my farm ” – An integrated co-learning approach for whole-farm sustainable intensification in smallholder farming. *Agric. Syst.* 188, 103041. <https://doi.org/10.1016/j.agry.2020.103041>
- Misra, R., Roy, R.N., Hiraoka, H., 2003. On-farm composting methods.
- Mtambanengwe, F., Mapfumo, P., 2005. Organic matter management as an underlying cause for soil fertility gradients on smallholder farms in Zimbabwe. *Nutr. Cycl. Agroecosystems* 73, 227–243. <https://doi.org/10.1007/s10705-005-2652-x>
- Nandwa, S.M., Bekunda, M.A., 1998. Research on nutrient flows and balances in East and Southern Africa: State-of-the-art. *Agric. Ecosyst. Environ.* 71, 5–18. [https://doi.org/10.1016/S0167-8809\(98\)00128-5](https://doi.org/10.1016/S0167-8809(98)00128-5)
- Naughton-Treves, L., Kammen, D.M., Chapman, C., 2007. Burning biodiversity: Woody biomass use by commercial and subsistence groups in western Uganda’s forests. *Biol. Conserv.* 134, 232–241. <https://doi.org/10.1016/j.biocon.2006.08.020>
- Ncube, B., Twomlow, S.J., Dimes, J.P., Van Wijk, M.T., Giller, K.E., 2009. Resource flows, crops and soil fertility management in smallholder farming systems in semi-arid Zimbabwe. *Soil Use Manag.* 25, 78–90. <https://doi.org/10.1111/j.1475-2743.2009.00193.x>
- Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G., Giller, K.E., 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agric. Ecosyst. Environ.* 83, 27–42.
- Palm, C.A., Myers, R.J.K., Nandwa, S.M., 2015. Combined Use of Organic and Inorganic Nutrient Sources for Soil Fertility Maintenance and Replenishment 193–217.

<https://doi.org/10.2136/sssaspecpub51.c8>

- Reetsch, A., Feger, K.H., Schwärzel, K., Dornack, C., Kapp, G., 2020. Organic farm waste management in degraded banana-coffee-based farming systems in NW Tanzania. *Agric. Syst.* 185, 102915. <https://doi.org/10.1016/j.agsy.2020.102915>
- Rufino, M.C., Tittonell, P., van Wijk, M.T., Castellanos-Navarrete, a., Delve, R.J., de Ridder, N., Giller, K.E., 2007. Manure as a key resource within smallholder farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. *Livest. Sci.* 112, 273–287. <https://doi.org/10.1016/j.livsci.2007.09.011>
- Sheldrick, W.F., Lingard, J., 2004. The use of nutrient audits to determine nutrient balances in Africa. *Food Policy* 29, 61–98. <https://doi.org/10.1016/j.foodpol.2004.01.004>
- Sileshi, G.W., Nhamo, N., Mafongoya, P.L., Tanimu, J., 2017. Stoichiometry of animal manure and implications for nutrient cycling and agriculture in sub-Saharan Africa. *Nutr. Cycl. Agroecosystems* 107, 91–105. <https://doi.org/10.1007/s10705-016-9817-7>
- Smaling, E.M. a, Stoorvogel, J.J., Windmeijer, P.N., 1993. Calculating soil nutrient balances in Africa at different scales - II. District scale. *Fertil. Res.* 35, 237–250. <https://doi.org/10.1007/BF00750642>
- Stoorvogel, J.J., Smaling, E.M.A., 1990. Assessment of soil nutrient depletion in Sub-Saharan Africa: 1983-2000. Winand Staring Centre, Wageningen, Netherlands.
- Struhsaker, T.T., 1997. Ecology of an African rain forest: logging in Kibale and the conflict between conservation and exploitation., University Press of Florida. University Press of Florida.
- Tittonell, P., 2003. Soil fertility gradients in smallholder farms of western Kenya - Their origin, magnitude and importance 234.
- Tittonell, P., Muriuki, a., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., Vanlauwe, B., 2010. The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa - A typology of smallholder farms. *Agric. Syst.* 103, 83–97. <https://doi.org/10.1016/j.agsy.2009.10.001>
- Tittonell, P., Muriuki, a, Klapwijk, C.J., Shepherd, K.D., Coe, R., Vanlauwe, B., 2013. Soil Heterogeneity and Soil Fertility Gradients in Smallholder Farms of the East African Highlands. *Soil Sci. Soc. Am. J.* 77, 525–538. <https://doi.org/10.2136/sssaj2012.0250>
- Tittonell, P., Vanlauwe, B., de Ridder, N., Giller, K.E., 2007. Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: Soil fertility gradients or management intensity gradients? *Agric. Syst.* 94, 376–390.

<https://doi.org/10.1016/j.agsy.2006.10.012>

- Tittonell, P., Vanlauwe, B., Leffelaar, P. a., Shepherd, K.D., Giller, K.E., 2005a. Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. *Agric. Ecosyst. Environ.* 110, 166–184. <https://doi.org/10.1016/j.agee.2005.04.003>
- Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., Giller, K.E., 2005b. Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. *Agric. Ecosyst. Environ.* 110, 149–165. <https://doi.org/10.1016/j.agee.2005.04.001>
- UBOS, 2010. UBOS Census of Agriculture 2008/2009 Volume IV: Crop Area and Production Report. Kampala, Uganda.
- Vanlauwe, B., Giller, K.E., 2006. Popular myths around soil fertility management in sub-Saharan Africa. *Agric. Ecosyst. Environ.* 116, 34–46. <https://doi.org/10.1016/j.agee.2006.03.016>
- Vanlauwe, B., Tittonell, P., Mukalama, J., 2006. Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. *Nutr. Cycl. Agroecosystems* 76, 171–182. <https://doi.org/10.1007/s10705-005-8314-1>
- Wairegi, L.W.I., van Asten, P.J.A., 2010. The agronomic and economic benefits of fertilizer and mulch use in highland banana systems in Uganda. *Agric. Syst.* 103, 543–550. <https://doi.org/10.1016/j.agsy.2010.06.002>
- Wortmann, C.S., Kaizzi, C.K., 1998. Nutrient balances and expected effects of alternative practices in farming systems of Uganda. *Agric. Ecosyst. Environ.* 71, 115–129. [https://doi.org/10.1016/S0167-8809\(98\)00135-2](https://doi.org/10.1016/S0167-8809(98)00135-2)
- Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007a. Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. *F. Crop. Res.* 101, 296–305. <https://doi.org/10.1016/j.fcr.2006.12.006>
- Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007b. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agric. Ecosyst. Environ.* 119, 112–126. <https://doi.org/10.1016/j.agee.2006.06.019>

Chapter 3: Double the legumes, double the carbon?

Abstract

Maize-based cropping systems predominate in east and southern Africa and integration of grain legumes through intercropping and rotations has been advocated as a means to increase agroecological resilience, diversify livelihoods, enhance nutrition, and improve soil fertility. In Malawi, a recommended sustainable intensification practice for smallholder farmers is the doubled-up legume rotation (DLR) system in which two compatible legumes are intercropped and then rotated with a cereal. The impact of the DLR system on SOC has not yet been determined, and little is known about the impact of diversifying with grain legumes on SOC. I address this knowledge gap by evaluating simple to complex legume diversified systems in comparison to continuous sole maize at three on-farm trial sites in central Malawi. I measured SOC in bulk soils and aggregate fractions and in faster cycling C pools that respond more rapidly to management practices, including water extractable organic carbon (WEOC), particulate organic matter carbon (POM-C), potentially mineralizable SOC, and macroaggregate SOC. Cropping treatment differences were not seen in bulk SOC or total N after six years of trial establishment, but they were apparent in SOC pools with a shorter turnover time. Intercropped pigeonpea and groundnut in the DLR system accumulated more SOC than sole pigeonpea or sole groundnut in rotation with maize. This study demonstrates that readily decomposable and biologically active SOC pools like WEOC, POM, soil respiration C, and aggregate-associated SOC and can be early indicators of SOC dynamics and the effects of crop rotation and diversification.

Introduction

Loss of soil organic carbon (SOC) and low soil fertility limit crop productivity and threaten food security in sub-Saharan Africa (SSA) (Tamene et al., 2019). An indicator of soil health, SOC is integral to the soil biological, chemical, and physical properties and processes that sustain productive agricultural soils (Johnston et al., 2009; Lal, 2010). SOC is the primary constituent and a relatively easily measured component of soil organic matter (SOM), which is critical for soil nutrient and water holding capacity, soil structure, and microbial diversity, abundance, and species composition (Powlson et al., 2011). Increasing agroecosystem plant diversity can increase both aboveground and belowground net primary productivity (NPP) and belowground plant C inputs, potentially creating a feedback loop of increased plant biomass and organic inputs into the soil and more efficient microbial nutrient cycling (Bartelt-Ryser et al., 2005; Jing et al., 2017; Jobbágy and Jackson, 2000; Kremen and Miles, 2012; Lange et al., 2015). Belowground root inputs can add more C than shoots and are thought to play a crucial role in SOC stabilization due to their close associations with microbes and mineral surfaces and their contributions to aggregate formation (Jastrow, 1996; Kong and Six, 2010; Puget and Drinkwater, 2001; Schmidt et al., 2011). Crop rotations can boost belowground C inputs and microbial contributions to soil C stocks through biotic and physical changes stimulated by the addition of diverse plant residues, root morphologies, root biomass, rhizodeposition, and root exudates (Tiemann et al., 2015; Soares & Rousk, 2019; Kong and Six, 2010; Rasse et al., 2005; Schmidt et al., 2011). A meta-analysis by McDaniel et al. (2014) demonstrates the positive impacts of increasing crop diversity on soil C stocks across a wide range of systems, but also

highlights the much greater impacts of increased crop diversity when a legume is included in the system.

In sub-Saharan Africa (SSA), SOC loss within smallholder agroecosystems has been largely attributed to the practice of continuous monocropping, particularly of maize, the staple food crop (Beedy et al., 2010). Integration of grain legumes into maize-based cropping systems has been advocated as a means to enhance nutrition and farmer livelihoods through production of nutritious grains and fodder, as well as means to diversify systems with the goal of improving soil fertility and agroecological resilience through increased C and N inputs (Smith et al., 2016; Snapp et al., 1998; Thierfelder et al., 2012). Grain legumes in rotation with cereals have well documented positive effects on yields in SSA, which have been attributed to the extra N availability generated through legumes' capacity for biological nitrogen fixation (BNF) and of the resulting N-rich, low C:N residues, as well as other rotation effects such as the breakup of pest and disease cycles (Franke et al., 2018; Giller, 2001; Peoples et al., 1995). Grain legumes' impacts on SOC are less well-established compared to impacts on N supply as detectable changes in SOC accrual require longer-term experiments, which in SSA are scarce (Franke et al., 2018).

Multi-year studies in SSA that quantified SOC and N in grain legume-cereal crop rotations compared to continuous cereal have mixed results (Anyanzwa et al., 2010; Bado et al., 2006; Yusuf et al., 2009). Over the course of three seasons in western Kenya, Anyanzwa et al., (2010) observed higher SOC and N with application of 2 t ha⁻¹ maize stover compared to a no-residue treatment under three cropping systems – continuous maize, maize/soybean intercrop, and maize-soybean rotation; however, no significant differences were observed in the legume

cropping systems versus continuous maize. A 5-year study in Niger showed that fallow-millet, groundnut-millet, and cowpea-millet rotations yielded more than continuous millet and continuous single legumes, but rotations did not differ from continuous monocultures in maintaining SOC. In fact, organic matter declined under continuous millet and the legume-millet rotations in which, notably, the crop residues were removed each year in accordance with local practices, on the other hand, SOC was maintained in the fallow-millet rotation, in which residues were incorporated (Bationo and Ntare, 2000). Two-year maize-cowpea and maize-soybean rotations in the Nigerian savannah had higher water soluble SOC, total N, and soil microbial biomass C and N, and narrower C:N ratios compared to continuous maize, although total SOC was not different (Yusuf et al., 2009). A similar 2-year study in the Nigerian savannah compared maize-cowpea, maize-soybean rotations, and an herbaceous legume-maize rotation, to a natural fallow-maize rotation and found: highest soil microbial biomass C in the legume rotations but no difference in microbial biomass N relative to fallow; highest total SOC and N in the soybean rotation, and lowest SOC in the cowpea rotation (Adeboye et al., 2006). Interestingly, the highest water soluble SOC was found in the fallow relative to the legume rotations (Adeboye et al., 2006). A 7-year study conducted at two sites in the Nigerian savannah compared 2-year natural fallow-maize rotations to maize rotations with different legume types – green manure, forage, dual purpose (long-duration soybean) and grain (sequentially cropped short-duration cowpea and soybean) – and saw high variability in SOC and N within rotations with no clear differences between systems.

Grain legume and cereal characteristics, e.g., harvest index, maturation time, seasonal leaf fall, and N-partitioning, in combination with management practices, e.g., timing of planting

and harvesting, harvesting methods, and residue retention, can strongly influence C and N inputs to soil and subsequent changes in SOC and N. The mixed results chronicled in these studies reflect the variability of different grain legumes and cereals, the corresponding climatic and edaphic environments, as well as differences in crop system management, length/duration of experiment, and in sampling and measurement methods.

Although few studies in SSA have demonstrated positive impacts of legume-cereal rotations on SOC stocks, this may be due in part to historical soil knowledge frameworks, which have shifted over the past couple of decades. Recent research has shifted the historical framework from a concept of intrinsically recalcitrant plant inputs leading to SOC accrual, towards SOC stabilization as the result of physiochemical protection from microbial degradation (Kleber, 2010; Kleber and Johnson, 2010; Schmidt et al., 2011; Dungait et al., 2012; Marin-Spiotta et al., 2014). That is, SOC can be best understood as existing along a spectrum extending from most bioaccessible, i.e., easily accessed and/or labile, to least bioaccessible, e.g., highly protected from microbial decomposition (Wieder et al., 2013). The more accessible soil C pools are often responsive to management, particularly on short time scales, compared to total SOC. For example, Yusuf et al. (2009) and Adeboye et al., (2006), observed management-induced differences in water soluble C and microbial biomass C. Because changes in total SOC stocks may take decades to detect and with a dearth of long-term studies of SOC under different management practices in SSA, we should turn to assessing these more dynamic and quickly changing functional SOC pools as indicators of longer-term change.

SOC will also impact total soil N and plant N availability as the two are closely linked. With higher overall N availability, microbes become more efficient in the use of C leading to

greater potential for SOC accrual and greater plant N availability. While N deficiency can lead to microbial mining of soil organic matter (SOM) for N with resulting losses of C via mineralization and lower N availability due to microbial immobilization (Buchkowski et al., 2015; Chen et al., 2014; Kallenbach and Grandy, 2011; Murphy et al., 2015). With N inputs, through either N-fertilizer or BNF, the C:N ratio of residues available for microbial decomposition can shift. These shifts can then serve as an indicator for potential microbial activity and SOC stabilization and accrual, with N inputs leading to narrower C:N ratios, higher C use efficiency and greater potential for SOC accrual.

To better assess the impacts of crop diversification on SOC, I measured SOC along the spectrum of bioaccessibility. This includes measuring biologically active and rapid-cycling SOC pools, such as water extractable organic carbon (WEOC), particulate organic matter (POM), and short-term soil respiration C ($\text{CO}_2\text{-C}$). I will also focus on more protected and longer-lived SOC pools within different aggregate size fractions. Water extractable organic carbon (WEOC) is an indicator for dissolved organic carbon (DOC) or the portion of SOC that is readily soluble and transferred to the aqueous phase (Kaiser et al., 2015). DOC is considered the most labile, mobile, and bioavailable C pool, often regarded as the primary C source for decomposers (Marschner and Kalbitz, 2003; von Lützow et al., 2007). DOC also plays an important role in slower cycling SOC pools as it interacts with mineral surfaces and organo-mineral complexes (Sokol et al., 2019). POM consists largely of plant-derived material that can be biochemically accessible, but physically protected in aggregates, and therefore persists in soils, although it is vulnerable to disturbance (Angst et al., 2017; Cotrufo et al., 2019). Measuring soil respiration rates in-situ or in laboratory incubations offers insight into both the amount and the availability

or accessibility of SOC (Franzluebbers et al., 2000; Haney et al., 2008). Total C respired after dry soils are re-wet and from short-term soil incubations in the lab, are functionally relevant SOC pools that are highly sensitive to management and are indicative of nutrient dynamics as well as the potential for SOC accrual (Culman et al., 2013; Franzluebbers et al., 2000; Haney et al., 2008; Schmidt et al., 2011; Wander 2004;). The total C respired in these cases can include SOC from all other measured C pools but is primarily composed of easily accessible C such as WEOC and POM.

Soil aggregation protects SOC from biological and physical degradation and aggregate fractionation separates SOC into pools associated with distinct aggregate sizes and protection mechanisms (Six et al., 2002, 2000b, 2000a; von Lützow et al., 2007). Macroaggregates (>250 μm), or large-sized aggregates, are generally associated with SOC that is more recent and readily decomposable, while SOC associated with microaggregates (250-53 μm) is considered more persistent as it is generally less accessible to microbes, more microbially processed, and/or bound to mineral surfaces (Elliott, 1986; Jastrow et al., 2007; Lützow et al., 2006; Tisdall and Oades, 1982). SOC in macroaggregates is generally more transient and susceptible to mineralization as aggregates are disrupted through cultivation, while micro-aggregates have been shown to harbor SOC that can persist for centuries (von Lützow et al., 2007). .

In Malawi, a recommended sustainable intensification practice for smallholder farmers is the doubled-up legume rotation (DLR) system in which two compatible legumes are intercropped and then rotated with a cereal (Chikowo et al., 2015; Kuyah et al., 2021; Smith et al., 2016). Pigeonpea and groundnut are two widely grown grain legumes with complementary growth habits and plant architectures that have been shown to result in minimal intraspecific

competition for light, water, and nutrients (Chikowo et al., 2020). Slower growing pigeonpea has a vigorous and extensive root system with multiple branches that can extend to depths of 1-2 m and can even break plough pans (Nene et al., 1990). Groundnut has shallower rooting depth and reaches maturity before pigeonpea. Intercropping pigeonpea and groundnut augments both aboveground inputs to soil with the addition of N-rich leaves and residues, and belowground inputs as root density, root inputs, and rhizosphere interactions increase, both temporally and spatially (Chikowo et al., 2020). Importantly, compared to sole fertilized maize, the doubled-up pigeonpea and groundnut system has been shown to increase subsequent maize yields and yield stability across a range of environments in central Malawi (Chikowo et al., 2020; Chimonyo et al., 2019).

The impact of the DLR system on SOC pools has not yet been determined, and little is known about the impact of diversifying with grain legumes on SOC. Initial on-farm studies of DLR showed no effect on SOC pools; however, the short-term nature of the studies and heterogeneity of soils on smallholder fields may well explain this (Snapp et al., 2010). I address this knowledge gap by evaluating simple to complex legume diversified systems in comparison to continuous sole maize at three on-farm trial sites in central Malawi. I measured SOC in bulk soils and aggregate fractions and in faster cycling C pools that respond more rapidly to management practices. I hypothesized that increasing diversity from continuous maize to single legume-maize rotations to a doubled-up legume rotation (DLR) would correspond to SOC and N accumulation and stabilization and lower soil C:N ratios. Further, the extensive vegetation and root system of pigeonpea relative to groundnut I hypothesized would support greater SOC accrual, comparing the pigeonpea-maize rotation to the groundnut-maize rotation. I

hypothesized that there would be positive impacts on soil aggregation with greater macroaggregates and microaggregates in the legume-maize rotations compared to continuous maize. I expected to see strong variation in SOC accumulation and stabilization across sites with differing agroecologies. Finally, after this 6-y experiment, I expected to see significant changes in total N and in relatively fast turn-over and dynamic SOC pools, but not in bulk SOC or SOC associated with microaggregates.

Methods

Study sites

In November of 2012, the Africa RISING (Research in Sustainable Intensification for the Next Generation) project established ‘best bet’ legume variety and mixtures at replicated, on-farm sites as part of participatory action research (Mungai et al., 2016; S. S. Snapp et al., 2018). I focus on soils sampled from trial sites based within three administrative units, or extension planning areas (EPAs), in Central Malawi: (1) Linthipe in Dedza district and (2) Kandeu and (3) Nsipe, which are both in Ntcheu district (Figure 3.1). The EPAs encompass a range of agricultural production potential as follows: Linthipe is a high elevation site with generally well-distributed rainfall and high agricultural potential, while Kandeu and Nsipe are mid-elevation with intermediate rainfall distribution and medium potential (Table 3.1; Mungai et al., 2016; Smith et al., 2016; Snapp et al., 2018). All three sites are sub-humid tropical. Malawi has a unimodal rainfall regime with a rainy season extending from November to April and a dry season from May to October (Table 3.1; Jury and Mwafulirwa, 2002). In central Malawi, annual precipitation ranges from 800 to 1100 mm and exhibits strong inter-annual variability in both

distribution and quantity (Mungai et al., 2016; Snapp et al., 2018). Soils vary by study site. Linthipe is largely dominated by ferric luvisols, and Kandeu and Nsipe have a mix of chromic luvisols and orthic ferralsols (Lowole, 1984).

At each site, three replicate plots per treatment were arranged in a nonrandomized block design. I monitored soil as described below and analyzed samples from four of the treatments (Table 3.2): (1) groundnut-maize rotation (Gnut), (2) “doubled-up legume” rotation (DLR) consisting of a pigeonpea-groundnut intercrop rotated with maize, (3) pigeonpea-maize rotation (PP) and (4) a continuous maize (Maize). All treatments were fertilized according to the government recommended rate of full 69 kg N ha⁻¹ and 9.2 kg P ha⁻¹ applied to continuous maize, or a half rate applied to maize grown in rotation or as an intercrop with a legume (Malawi Guide to Agriculture, 2012; Table 3.2). Each crop was grown according to its respective recommended planting density, in-row spacing, and planting arrangement with 0.75 m between planting ridges and all ridging done by hand-hoe (Snapp et al., 2018). Plots were 5 x 5 m at the site in Linthipe, 6 x 5 m in Kandeu, and 8 x 5 m in Nsipe.

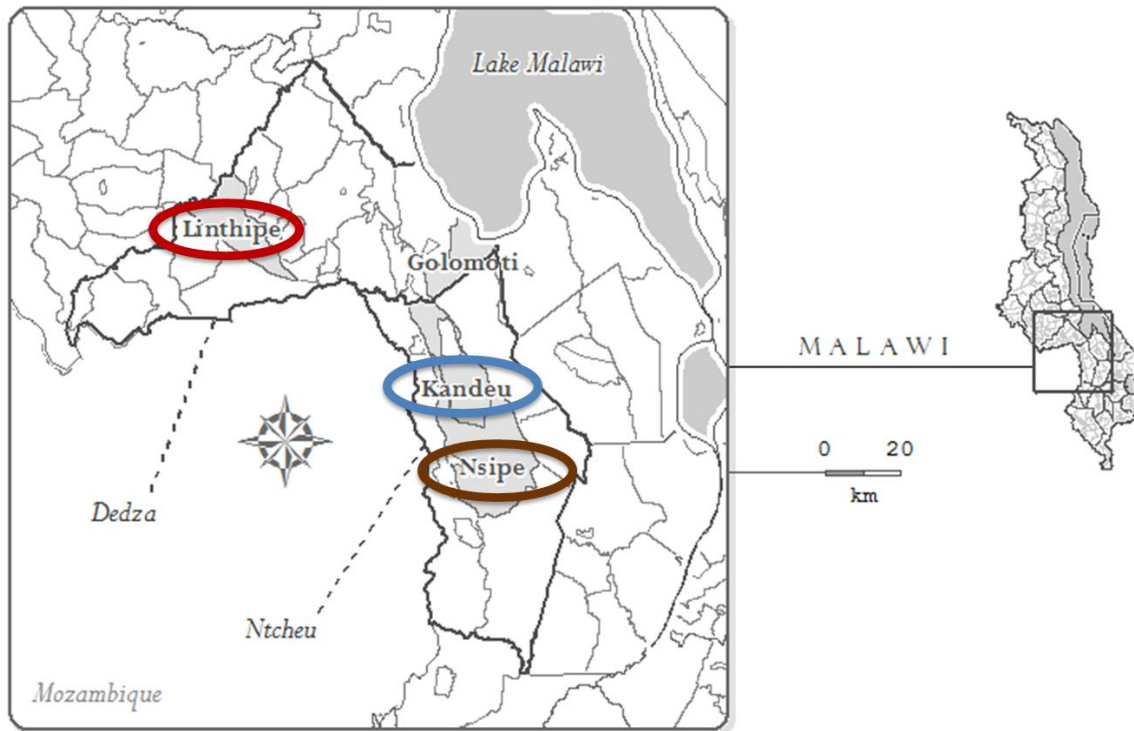


Figure 3.1. Locations of Linthipe, Kandeu, and Nsipe Africa RISING trial sites in central Malawi. Map courtesy of Brad Peter.

Table 3.1. Characteristics of the three Africa RISING trial sites in Central Malawi.

	Linthipe	Kandeu	Nsipe
Latitude/Longitude	-14.20°S/34.11°E	-14.63°S/34.60°E	-14.93°S/34.75°E
Elevation (masl)	1221	921	864
Mean annual rainfall 2012-2018 (mm) ¹	979	969	992
Total rainfall 1/1/2018-June 2018 sampling date ¹	656.8	552.6	562.1

¹ Climate Hazards InfraRed Precipitation with Station (CHIRPS) (Funk et al., 2015) data attained via Google Earth Engine (Gorelick et al., 2018)

Table 3.2. Cropping systems examined in this study with abbreviations and description of management practices.

	Cropping treatment	Fertilizer (kg ha ⁻¹)	Planting density (plants ha ⁻¹)	Plant spacing
Maize	Sole maize, fully fertilized	69 N, 9.2 P	53,000	25 cm within row
Gnut	Groundnut-maize rotation	Gnut= 17.3 N, 2.3 P Maize= 34.5 N, 4.6 P	Gnut= 88,889 Maize= 53,000	Gnut = 10-15 cm within row, 2 rows Gnut per ridge
PP	Pigeonpea-maize rotation	PP= 17.3 N, 2.3 P Maize= 34.5 N, 4.6 P	PP= 44,000 Maize= 53,000	PP = 90 cm within row & 3 plants per station
DLR	Doubled up legume rotation (Pigeonpea/groundnut intercrop rotated with maize)	PP/Gnut= 17.3 N, 2.3 P Maize= 34.5 N, 4.6 P	PP= 44,000 Gnut= 79,000 Maize= 53,000	PP = 90 cm within row & 3 plants per station Gnut = 9 cm within row

In-situ soil respiration and water infiltration

I measured in-situ soil respiration immediately before and approximately two hours after adding 2 L water to a 23.7 cm diameter ring set at least 3 cm into planting ridge soils. I took three respiration measurements per replicate using a portable CO₂ gas analyzer (PP Systems EGM-5, Amesbury, MA). Concurrently, I measured water infiltration as the time taken for the water added to the ring to percolate into the soil with no surficial water remaining (Franzluebbers, 2002).

Soil sampling and handling

I sampled at the conclusion of the sixth growing season after all rotations had been planted to maize; each rotation treatment had completed three full rotations (June 2018). I collected three soil cores to 10 cm depth using a 6.35 cm diameter PVC corer within each of the three replicate plots for the four different cropping treatments for a total of 108 samples. Cores

were sealed in plastic bags with a cushion of air to minimize compression and disruption of aggregates. Field moist samples were transported to a soils lab at University of Malawi's Chancellor College in Zomba, where each core was weighed, analyzed for gravimetric soil moisture, and separated into aggregate size fractions. Bulk density was measured using the core method (Grossman and Reinsch, 2002). The three replicate soil cores from each plot were analyzed individually and not combined for analyses. Field moist cores were gently broken by hand to obtain aggregates smaller than 8 mm diameter. Gravimetric soil moisture was determined by weighing 5 g subsamples into tins, drying the samples for 24 hours at 105°C in a drying oven, then reweighing the dried samples. Upon determining that soils were at maximum friability for dry sieving (Kristiansen et al., 2006), a 200 g subsample was passed through a series of three sieves using a portable sieve shaker (Gilson Wet/Dry Sieve Vibrator SS-23, Lewis Center, Ohio) and separated into four fractions: >2000 μm (large macroaggregates), 2000-250 μm (small macroaggregates), 250-53 μm (microaggregates), and <53 μm (silt and clay). I ran the sieve shaker for 2 min with the full stack of sieves then removed the 2 mm sieve, ran it for 1.5 min and then removed the 250 μm sieve, and finally ran it for 3 min with the remaining 53 μm sieve. Aggregates and remaining whole, i.e., bulk, soils were subsequently air-dried, packed into coolers and shipped to Michigan State University in East Lansing, MI, for further analysis. Prior to analysis, whole soils were passed through a 2000 μm sieve.

Organic carbon and total nitrogen

Soil organic C and total N were determined for bulk soil samples, macroaggregates (2000-250 μm), and microaggregates (250-53 μm). Approximately 5 g subsamples were

weighed into scintillation vials, oven dried at 105°C, and ground to a fine powder on a roller mill. Samples weighing 15-20 mg were packed into tins and analyzed via elemental analyzer (Costech ECS 4010, Costech Analytical Technologies, Valencia, CA). Using bulk density measurements, mean SOC and N stocks were calculated on an area basis to 10 cm depth.

Water-extractable organic carbon

To measure water extractable organic carbon (WEOC), I weighed 4 g of air-dried bulk soils into 50 ml centrifuge tubes and added 40 ml of deionized water. Tubes were capped and shaken for 10 minutes on a reciprocal shaker, after which they were centrifuged for 5 minutes, and the resulting supernatant was filtered through Whatman 2V filter paper (Bustamante and Hartz, 2016). Triplicate 10 ml samples were analyzed with a TOC analyzer (vario TOC cube, Elementar, Ronkonkoma, NY).

Particulate organic matter

Particulate organic matter (POM) was determined by dispersing 10 g of air-dried bulk soil with 30 mL of 5% sodium hexametaphosphate and shaking for 18 hours on a reciprocal shaker at 180 rpm. The material remaining on the 53 µm sieve was classified as POM and sand and was dried at 105°C, ground to a fine powder with a ball mill, and analyzed for organic C and total N concentration by dry combustion in an elemental analyzer (Costech ECS 4010, Costech Analytical Technologies, Valencia, CA).

Laboratory incubation

In preparation for the incubation, water holding capacity (WHC) was determined on a subset of four bulk soils per site, with 5 ± 0.1 g of soil placed into a funnel lined with Whatman #1 filter paper. The weight of the funnel and its contents was recorded, and soils were subsequently fully soaked with water. The funnels were wrapped with plastic wrap and left to drain for 24 hours, after which the weight was again recorded. To obtain the WHC, the initial dry weight was subtracted from the final wet weight of the funnel and soil. An average WHC was calculated for each site and from this the amount of water needed to bring soils to 65% WHC. For the incubation experiment, 5 ± 0.1 g of soil was added to 250 ml jars, soils were brought to 65% WHC, and jars were capped with rubber stoppers. To measure CO₂ respiration, jars were uncapped, flushed with lab air, recapped and a 5 mL gas sample was removed from the headspace using a syringe and injected into an infrared gas analyzer (Li-Cor Inc., Lincoln, NE). After allowing the capped soils to sit and accumulate CO₂ in the headspace, a second sample was collected and analyzed. Soils were sampled on days 1, 2, 3, 6, and 12 with a corresponding increase in time between the first and second gas samples, respectively, 3, 5, 8, 24, and 48 hours. The difference between the two sampling points was calculated as respiration potential over time (Robertson et al., 1999). I determined cumulative CO₂-C by integrating the respiration rates for the total incubation time period.

Statistical Analysis

To compare treatment differences across all three sites and account for the nonrandomized design, I first transformed all variables using a normal quantile transformation,

also known as a normal scores transformation (SAS PROC RANK with Blom option for the normal scores, SAS Institute, Cary, NC) (Conover, 2012; Conover and Iman, 1981; Montgomery, 2005). Transformed variables were analyzed by additive two-way ANOVA with treatment and site as the main effects (SAS PROC MIXED); interaction effects were not significant. Post-hoc testing of differences between means used the pdiff option of the LSMEANS statement in PROC MIXED, and I used the PDMIX800 macro (Saxton 1998) to assign letters for mean separation. For each transformed variable, I checked normality of the residuals and homogeneity of variance.

I determined the sand content of each aggregate fraction by dispersing 4 g subsamples in 0.5% sodium hexametaphosphate solution, shaking on a reciprocal shaker for 18 hours, and washing samples through a 53 μm sieve with deionized water (Elliott et al., 1991; Grandy and Robertson, 2007). The particles remaining on the 53 μm sieve were washed into pre-weighed tins and dried at 60°C for 48 hours. I used the following equations to sand-correct the aggregate distribution:

$$\text{Sand – corrected aggregation (\%)} = \frac{(\text{Weight}_{\text{aggregate size fraction}} - \text{Weight}_{\text{aggregate-sized sand}}) \times 100}{\sum (\text{All fractions})_{\text{sand-corrected weights}}}$$

(1)

and to calculate the sand-free aggregate-associated C and N (Denef and Six, 2005):

$$\text{Sandfree (C or N)fraction} = \frac{(\text{C or N})_{\text{fraction}}}{1 - (\text{sand proportion})_{\text{fraction}}}.$$

(2)

Results

Aggregation and soil physical properties

At all sites, ~40% of soil aggregates were in the 2000-250 μm size fraction (Figure 3. 2). The next highest distribution (~30%) was the 250-53 μm aggregate fraction, and the >2000 and <53 size classes had low aggregate mass. Only the <53 μm fraction exhibited a response to cropping treatment, where these silt and clay sized particles varied as follows PP $\geq$ DLR $\geq$ Maize $\geq$ Gnut (Figure 3. 2). Linthipe and Nsipe soils had a greater proportion of >2000 μm aggregates than Kandeu, though Kandeu had more 250-53 μm and <53 μm aggregates. The proportion of small macroaggregates were similar at each site.

I saw no influence of cropping treatment on the rate of water infiltration. Kandeu had higher infiltration rates than Linthipe, which was greater than Nsipe (Table 3.3).

I did not find cropping system effects on bulk density or aggregate MWD, but both were greater in Nsipe and Linthipe soils than in Kandeu (Table 3.3).

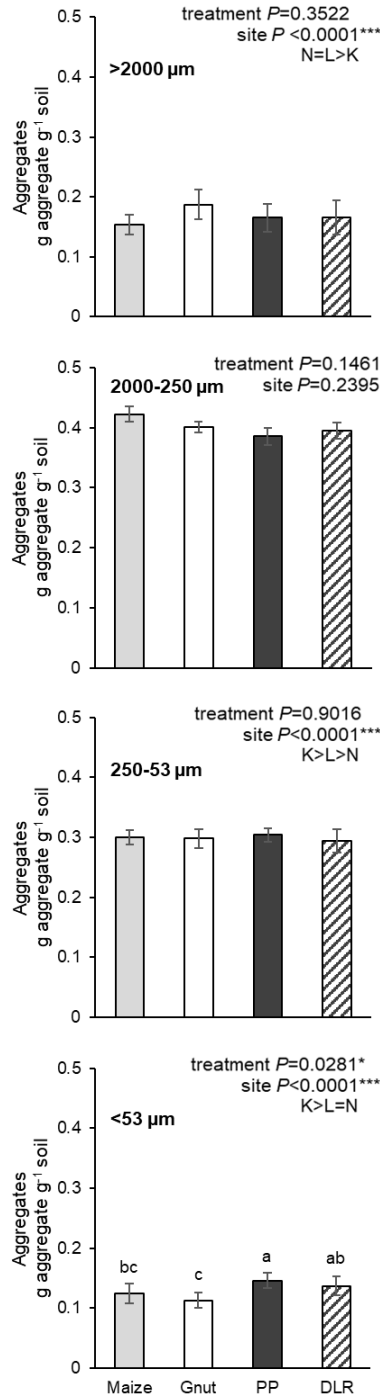


Figure 3.2. Cropping treatment effects on the proportion of dry-sieved soil in different aggregate size classes. Treatments with different lowercase letters are significantly different. P-values represent effects on the proportion of aggregates in each fraction. Treatment effects for continuous maize (Maize), Groundnut-maize rotation (Gnut), pigeonpea-maize rotation (PP) and doubled-up legume rotation (DLR) and site effects for Kandeu (K), Linthipe (L), and Nsipe (N) were assessed using post hoc testing of differences between least-squares means. Bars represent means and error bars ± 1 SE.

Table 3.3. Cropping treatment and site effects on soil C and N and differences in soil properties at Africa RISING trial sites in 2018. Means with SE in parentheses.

Site	Treatment	SOC (%)	Total N (%)	C/N ratio	SOC stock g C m ⁻²	Total N stock g N m ⁻²	Bulk Density g cm ⁻³	MWD mm	Infiltration cm h ⁻¹	Sand %
Linthipe	Maize	1.36 (0.09)	0.09 (0.01)	15.4 (0.16)	1056 (54.18)	68.7 (3.11)	1.32 (0.04)	1.46 (0.06)	42.4 (3.07)	54.8 (0.83)
	Gnut	1.41 (0.09)	0.09 (0.01)	15.5 (0.19)	1036 (58.15)	66.5 (3.42)	1.35 (0.01)	1.66 (0.13)	35.1 (4.12)	54.0 (2.71)
	PP	1.46 (0.06)	0.09 (0.01)	15.7 (0.40)	1045 (42.15)	66.7 (4.22)	1.39 (0.02)	1.38 (0.10)	45.7 (4.51)	62.5 (0.95)
	DLR	1.46 (0.21)	0.09 (0.01)	15.6 (0.05)	1096 (186.4)	70.8 (11.7)	1.37 (0.05)	1.47 (0.02)	39.2 (5.76)	61.4 (0.18)
Kandeu	Maize	1.06 (0.19)	0.08 (0.01)	13.3 (0.15)	850.9 (205.4)	63.9 (15.1)	1.31 (0.06)	1.28 (0.09)	61.4 (9.13)	76.8 (2.15)
	Gnut	1.29 (0.11)	0.10 (0.01)	13.2 (0.03)	1075 (28.87)	81.7 (2.31)	1.25 (0.01)	1.31 (0.06)	61.7 (3.30)	76.7 (1.56)
	PP	1.20 (0.11)	0.09 (0.01)	13.3 (0.53)	929.3 (115.5)	70.6 (11.0)	1.32 (0.04)	1.27 (0.05)	58.5 (7.34)	77.4 (1.31)
	DLR	1.27 (0.10)	0.10 (0.01)	12.8 (0.35)	1036 (53.95)	82.1 (5.71)	1.22 (0.02)	1.15 (0.07)	57.0 (6.47)	75.6 (3.44)
Nsipe	Maize	0.69 (0.05)	0.06 (0.00)	13.2 (0.37)	503.7 (32.99)	39.2 (2.83)	1.36 (0.03)	1.42 (0.05)	29.4 (1.65)	60.6 (0.75)
	Gnut	0.78 (0.04)	0.06 (0.01)	14.1 (0.93)	569.6 (37.05)	41.0 (3.54)	1.38 (0.03)	1.57 (0.13)	30.7 (2.86)	59.8 (1.19)
	PP	0.73 (0.04)	0.06 (0.01)	12.9 (1.33)	467.5 (51.10)	35.8 (2.29)	1.43 (0.02)	1.55 (0.14)	27.5 (0.84)	59.6 (3.70)
	DLR	0.83 (0.07)	0.07 (0.00)	11.9 (0.76)	584.5 (21.56)	49.30 (1.71)	1.46 (0.02)	1.64 (0.10)	28.1 (2.05)	60.8 (1.53)
Two-way Additive Anova										
Treatment	<i>P</i> value	0.5287	0.2550	0.3900	0.5636	0.0913	0.2575	0.3609	0.4828	0.1957
Site	<i>P</i> value	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	<.0001***	0.0002***	<.0001***	<.0001***
Site differences		L>K>N	K=L>N	L>K=N	K=L>N	K=L>N	L=N>K	L=N>K	K>L>N	K>L=N
*Significant at <i>P</i> <0.05										
**Significant at <i>P</i> <0.01										
***Significant at <i>P</i> <0.001										

Total SOC and N

I did not see a treatment influence on bulk SOC, total N, SOC stocks, or soil C:N ratios, but there were significant differences by site and total soil N was marginally significant by treatment ($P<0.1$) (Table 3.3). Bulk SOC was highest in Linthipe, followed by Kandeu, and lowest in Nsipe. Kandeu and Linthipe were higher in total N, SOC stocks, and total N stocks than Nsipe. Linthipe had the widest C:N ratio, while Kandeu and Nsipe had narrower C:N values (Table 3.3).

WEOC

WEOC was significantly higher in DLR compared to all other treatments (Figure 3. 3, Table 3.4), and significantly greater at Linthipe than Kandeu and Nsipe. Rotations containing pigeonpea were higher in WEOC compared to the rotations without pigeonpea, i.e., DLR and continuous maize (Table 3.4.) Relative to bulk SOC, I saw no treatment differences in WEOC,

and Nsipe had significantly more WEOC than Linthipe, which had more than Kandeu. WEOC was approximately 0.83 to 0.97% of bulk SOC.

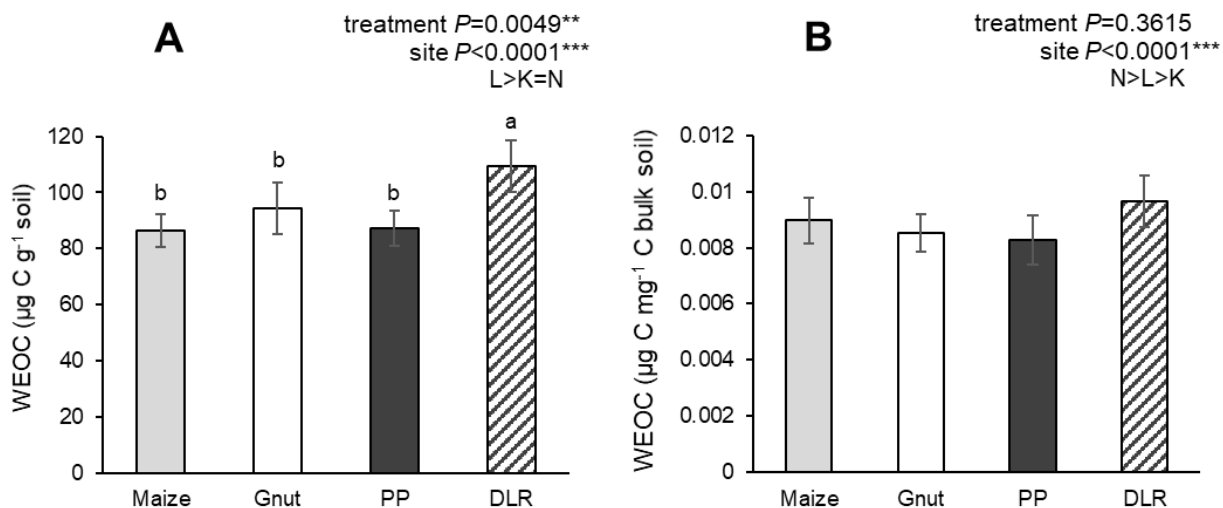


Figure 3.3. Cropping system effects on water extractable organic carbon (WEOC) on a whole soil basis (A) and relative to the bulk SOC (B). Treatments with different lowercase letters are significantly different. Site effects for Kandeu (K), Linthipe (L), and Nsipe (N) were assessed using post hoc testing of differences among least-squares means. Bars represent means and error bars ± 1 SE.

POM-C

POM-C was higher in the DLR and the single-legume rotations compared to maize (Figure 3. 4A, Table 3.4), but differences were not apparent for POM-C relative to bulk SOC (Figure 3.4B). POM-C comprised approximately 25-29% of total SOC. Linthipe and Kandeu had significantly more POM-C relative to bulk soil than Nsipe, but relative to bulk SOC, Kandeu soils had significantly more than Linthipe and Nsipe.

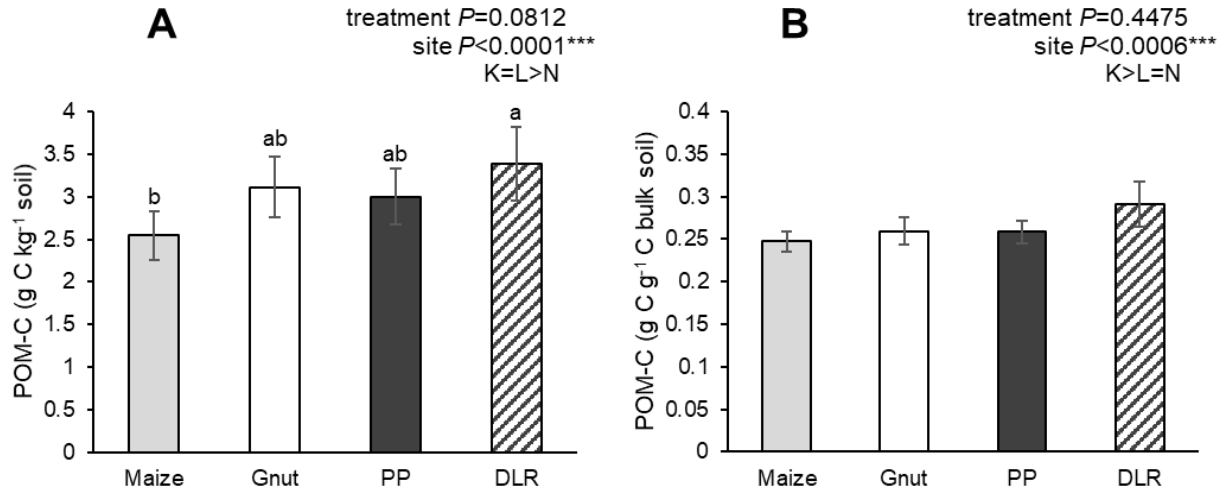


Figure 3.4. Cropping system effects on POM-C concentrations in bulk soil (A) and relative to bulk SOC (B). Treatments with different lowercase letters are significantly different. Site effects for Kandeu (K), Linthipe (L), and Nsipe (N) were assessed using post hoc testing of differences among least-squares means. Bars represent means and error bars ± 1 SE.

In-situ respiration and infiltration

In-situ respiration rates were not significantly different among treatments (Figure 3. 5A). The percent change from respiration rate prior to water addition to post water addition was also not significantly different by treatment (Figure 3. 5B). However, rates were significantly different among trial sites. Nsipe had the highest in-situ respiration rates and the greatest changes in respiration rate after water addition, Linthipe followed, and lastly Kandeu exhibited the lowest respiration rates and differences in the rate of CO₂ respired pre- and post-water addition.

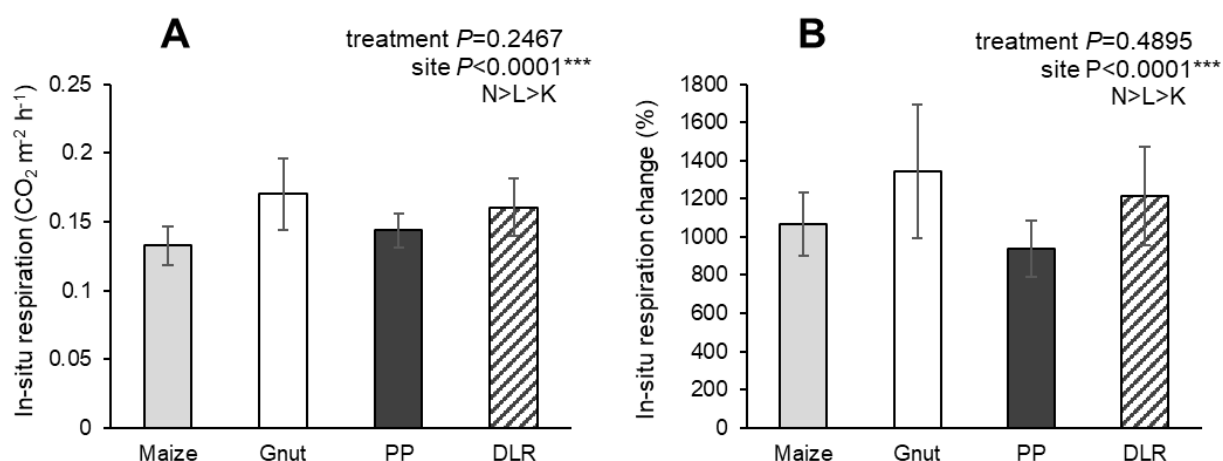


Figure 3.5. Treatment effects on the in-situ respiration rate after water addition (A) and the percent change in respiration rate following water addition (B). Treatments with different lowercase letters are significantly different. Site effects for Kandeu (K), Linthipe (L), and Nsipe (N) were assessed using post hoc testing of differences among least-squares means. Bars represent means and error bars ± 1 SE.

Potential mineralizable C – laboratory incubation

I observed significant effects of treatment on total C respired during a 12-day incubation with highest total C respired in DLR soils, followed by PP, Gnut, and lowest in maize soils (Figure 3. 6A, Table 3.4). Kandeu and Linthipe had significantly greater total C respired compared to Nsipe. In contrast, total C respired relative to bulk SOC exhibited no significant treatment differences, and Nsipe and Kandeu soils respired greater total C per bulk SOC than Linthipe soils (Figure 3. 6B).

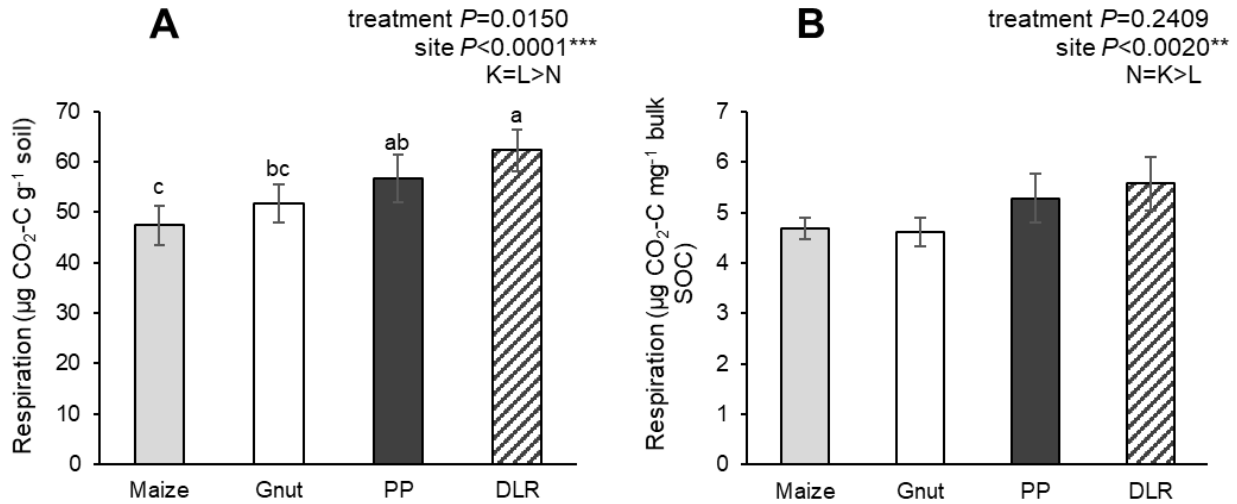


Figure 3.6. Cropping treatment effects on the cumulative $\text{CO}_2\text{-C}$ respired over 12-day incubations on a bulk soil basis (A) and relative to the bulk SOC (B). Treatments with different lowercase letters are significantly different. Site effects for Kandeu (K), Linthipe (L), and Nsipe (N) were assessed using post hoc testing of differences among least-squares means. Bars represent means and error bars ± 1 SE.

Aggregate C and N

SOC within small macroaggregates (2000-250 μm) and microaggregates (250-53 μm) was significantly impacted by treatment (Figure 3. 7A & D) and significantly different among sites. For both size classes, the highest concentrations of soil C were found in the DLR and the lowest in maize (Figure 3. 7A & D, Table 3.4). Within the small macroaggregates, total N was significantly lower in the continuous maize treatment compared to the rotations containing legumes (Figure 3. 7B); however, I did not find treatment effects on total N within the microaggregates (Figure 3. 7E). Small macroaggregate and microaggregate SOC and total N were all highest in Kandeu, next highest in Linthipe, and lowest in Nsipe. C/N values within small macroaggregates and microaggregates showed no treatment impact, and sites followed different patterns than the SOC and total N; Linthipe soils had the widest C/N ratios in both fractions (Figure 3.7C & F).

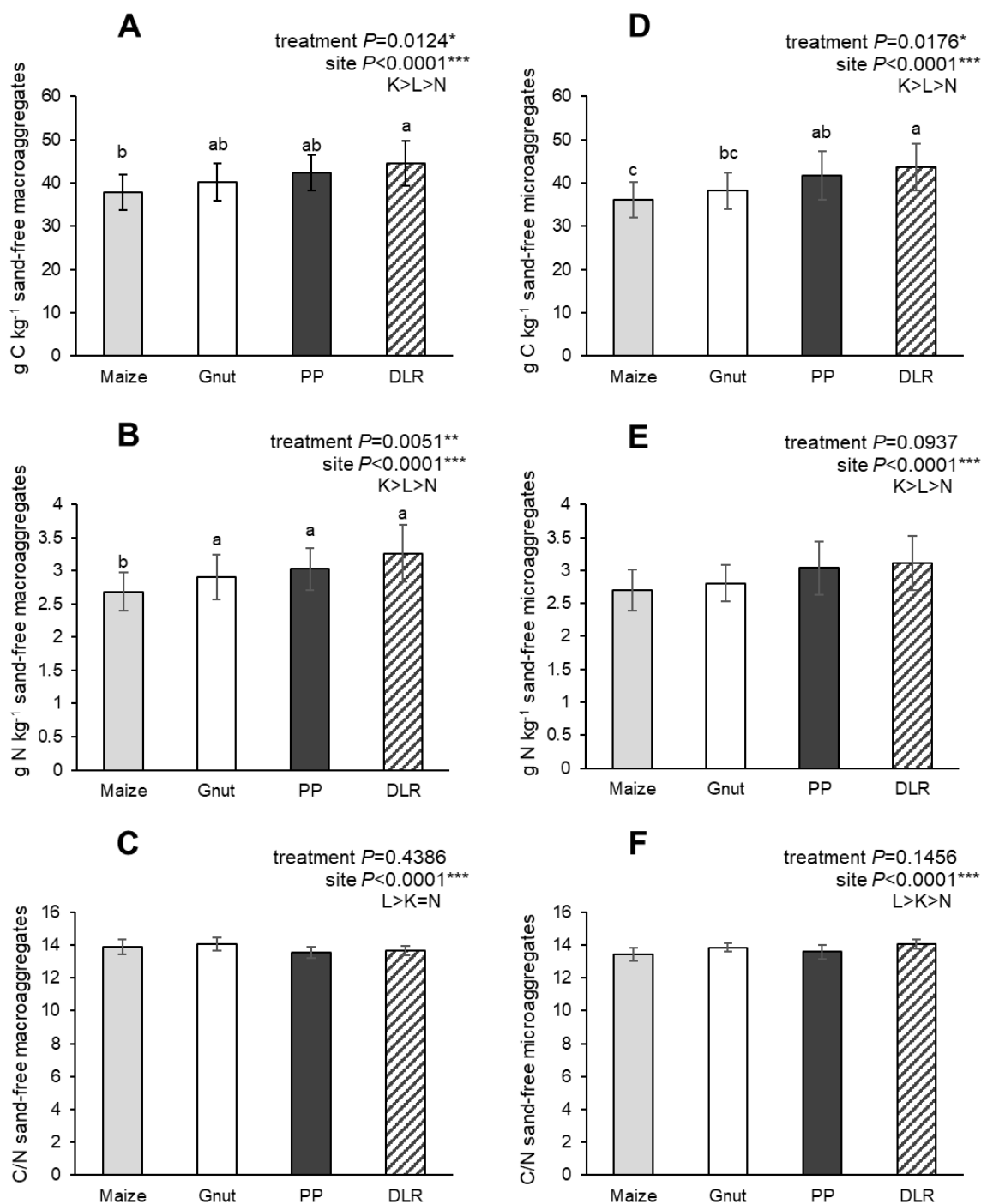


Figure 3.7. Treatment effects on total sand-free C and N concentrations and C/N ratio in the small macroaggregates (2000-250 μm) and microaggregate (250-53 μm) fractions. Treatments with different lowercase letters are significantly different. Site effects for Kandeu (K), Linthipe (L), and Nsipe (N) were assessed using post hoc testing of differences among least-squares means. Bars represent means and error bars ± 1 SE.

Table 3.4. Planned contrasts to differentiate effects of maize vs legume rotations, DLR vs. single legume rotations, and rotations containing pigeonpea vs. rotations without pigeonpea, on SOC pools – WEOC, POM-C, cumulative respiration, small macroaggregate, and microaggregate C.

Planned Contrasts		WEOC g C kg ⁻¹ soil	POM-C g C kg ⁻¹ soil	Cumulative respiration µg CO ₂ -C g ⁻¹ soil	2000-250 µm C g C kg ⁻¹ aggregate	250-53 µm C g C kg ⁻¹ aggregate
Continuous maize vs. maize-legume rotations	<i>P</i>	0.0998	0.0286*	0.0195*	0.0069**	0.0108*
DLR vs single legume rotations (Gnut and PP)	<i>P</i>	0.0018**	0.159	0.0442*	0.0456*	0.0621
Treatments with pigeonpea vs no-pigeonpea treatments	<i>P</i>	0.0129*	0.3954	0.9174	0.4514	0.7919

*Significant at $P < 0.05$

**Significant at $P < 0.01$

Discussion

I show that DLR and the single legume-maize rotations had positive impacts on SOC across three agroecologies in central Malawi. Compared to continuous maize, DLR and the single legume rotations had significantly greater SOC within labile C pools - POM, WEOC, mineralizable SOC, and macroaggregates, as well as in the more stable microaggregates. Supporting my hypothesis that increasing diversity and duration of legume presence would be associated with SOC status, DLR accrued significantly more SOC than the single legume rotations which accrued more SOC than the sole maize. This is consistent with the idea that diversifying crop rotations with grain legumes will have the potential to enhance SOC stabilization and is one of the first reports to show this effect on smallholder farm sites. Of the single legume rotations, SOC in PP was generally not different than Gnut, but PP had more microaggregate associated SOC than Gnut. Rotational diversity did not impact aggregate distribution, but it did affect aggregate associated SOC and N. As expected, there were differences by site in almost all variables measured.

Bulk SOC and related soil physical characteristics

Across all sites, treatment differences were not apparent in bulk SOC and total N concentrations or stocks or C:N ratios suggesting that changes seen in the other C pools are too small or incremental to be captured at the larger, bulk soil scale (Table 3.3). These results are consistent with other studies in SSA that did not detect changes when comparing bulk SOC and total N in legume-maize rotations to continuous sole maize (Anyanzwa et al., 2010; Bationo and Ntare, 2000; Franke et al., 2008; Yusuf et al., 2009). Substantial changes in SOC stocks are required to impact soil physical properties like bulk density, MWD, and infiltration, and with little change in total SOC, I also did not see impacts of legumes on these parameters (Table 3.3). Although it has been theorized that decomposition of pigeonpea's large coarse roots could create deep channels that enhance rainfall infiltration (Chikowo et al., 2020), I did not see evidence of increased water infiltration rates in PP or DLR after three rotation cycles. Overall, I did not find changes in bulk or total pools of C and N with legumes after three rotation cycles, but I would expect to begin to see changes in these pools over time if observed changes in more dynamic C pools continue.

Aggregation and SOC stabilization

Aggregation did not vary by treatment for the $>53\ \mu\text{m}$ size classes (Figure 3. 2), likely because all treatments and sites were intensively tilled with hand hoes and ridged on an annual basis. Tillage reduces the number and stability of soil aggregates and promotes rapid mineralization of SOC (Six et al., 2000a). Aggregate disturbance is often greater in coarse-textured, sandy soils (Feller and Beare, 1997). Sandier soils at Kandeu may have contributed to

lower numbers of large macroaggregates (>2000) compared to Linthipe and Nsipe. However, Kandeu had a larger proportion of microaggregates and <53 size fraction, which are size classes that are less susceptible to tillage disturbance.

DLR had the highest SOC in both small macroaggregates and microaggregates, PP and Gnut followed, and maize had the lowest SOC, demonstrating the potential for legumes to accrue and stabilize SOC in aggregates versus fertilized maize (Figure 3. 7A & D). While all treatments received some amount of N-fertilizer, the greatest inputs were to the maize treatment, and N-fertilizer has been shown to increase C mineralization and macroaggregate turnover, resulting in lower SOC (Chivenge et al., 2011). More N-fertilizer was added to the maize, but the rotations with legumes had significantly more accumulated N in macroaggregates, perhaps due to N-rich litter and root inputs from legumes contributing to macroaggregate formation. Like the SOC, the N in macroaggregates is more easily mineralized, and therefore it is not surprising that the total N within microaggregates was not higher for legume treatments as the N was mineralized before reaching that stage of stabilization.

Active C pools

The POM fraction exhibited the same pattern of treatment differences as the macroaggregates (DLR>PP=Gnut>Maize). POM can act as a “seed” in macroaggregate formation, and can be indicative of macroaggregate generation and C concentration (Six et al., 2000a). POM is understood to be largely plant-derived, thus larger amounts of POM are linked to changes in the quantity or quality of plant matter inputs. N-rich, low C:N legume residues are expected to decompose faster than high C:N maize residues. It is possible that the higher POM

content in the DLR and single legume rotations is actually associated with maize residue inputs, but with maize being only present in one year out of two, it is also equally likely that POM-C may be associated with legumes residues.

Partially in-line with my hypotheses, I found higher WEOC to be associated with DLR but not single legume rotations, relative to continuous maize. In contrast, another study in SSA did find water soluble carbon, i.e., WEOC, to be higher in single legume-maize rotations compared to continuous maize (Yusuf et al., 2009). The range of WEOC values (Figure 3. 3) are lower than those obtained by Yusuf et al. (2009) but comparable to other values reported in the literature (Rochette and Gregorich, 1998; Schiedung et al., 2017). WEOC concentrations can vary based on the season, duration of extraction, soil-to-water ratio, and air-drying of soils (Chantigny, 2003; Kaiser et al., 2015; Schiedung et al., 2017). I sampled at one time point during the dry season, after maize harvest, and values may be affected by seasonal fluctuations, soil handling, and measurement methods.

I explored whether measuring respiration before and after wetting soils *in situ* could effectively capture a CO₂ burst, but no treatment differences were seen (Figure 3. 5). At all sites, the soils were extremely dry and there had been no rainfall for over one month prior to adding the water for the burst tests at Linthipe and Nsipe, with one 5 mm rainfall event recorded at Kandeu more than two weeks prior to sampling (Climate Hazards InfraRed Precipitation with Station (CHIRPS) (Funk et al., 2015)). Due to logistical time and equipment constraints, I was limited to measuring respiration two hours after water addition. There were dramatic flushes of CO₂ after soil rewetting (Figure 3. 5B), but due to the short time frame, it is unlikely that I captured a flush indicative of longer-term C mineralization (Canarini et al., 2017;

Franzluebbers, 2002). Multiple measurements over a longer time period post-wetting could be more effective. Nsipe, which had the lowest total SOC and lowest SOC in all other measurements relative to the other sites, had the highest in-situ soil respiration rates and change in soil respiration post-water addition, suggesting that at Nsipe SOC exists in fragile, rapidly mineralized pools.

Although treatment differences were not discernable in the field-based respiration test in the 12-day laboratory incubation, cumulative respiration was highest for DLR followed by PP, Gnut, and maize on a bulk soil basis. These data support other analyses of bioaccessible soil C accrual with legumes and also highlight that at least some of the SOC accumulated in the DLR and the single legume treatments was not stabilized and easily mineralizable. However, when quantifying cumulative respiration relative to bulk SOC as opposed to bulk soil, there were no treatment differences, which is consistent with there being both more SOC and more stable SOC in the DLR and legume-maize rotations than in the continuous maize.

Site Effects

As expected, the impact of cropping system treatment on SOC and N pools varied by site. An Agricultural Production Systems Simulator (APSIM) modeling study that examined SOC and N changes at Africa RISING trial sites in Linthipe, Kandeu, and Golomoti, predicted slightly negative bulk SOC and N trends in DLR and a strongly negative trend in Gnut and Maize at Linthipe, while at Kandeu it predicted a positive trend for SOC and N in the DLR and fairly constant values in Gnut and Maize (Smith et al., 2016). I did not see treatment differences in bulk SOC and total N concentrations or stocks across trial sites in Kandeu, Linthipe, and Nsipe,

but I observed that Kandeu had higher SOC and N in the more rapid-cycling macroaggregate, microaggregate, and POM-C pools (Figures 3.7, 3.4), which appears to support the APSIM predictions. In these same pools DLR had the highest values and PP and Gnut fluctuated as close seconds, which lends some support to Smith et al.'s (2016) observation that the addition of pigeonpea to the cropping system model caused SOC and N to increase at Kandeu and remain constant at Linthipe. Nsipe had the lowest bulk SOC and N values (Table 3.3), but the highest *in situ* respiration rates (Figure 3.5), lab incubation cumulative respiration relative to bulk SOC (Figure 3.6B), and WEOC relative to bulk SOC (Figure 3.3B), which suggests that the low concentration of SOC at Nsipe was also easily mineralized and unstable. Based on soil and environmental indicators, Mungai et al. (2016) classified the agricultural land potential at Linthipe as highly suitable, while Kandeu and Nsipe were marginally suitable, but the current findings and those of Smith et al. (2016) highlight the potential for Kandeu to achieve higher SOC and N gains, relative to Linthipe and Nsipe.

Conclusion

Integration of grain legume rotations into continuous maize has the potential to increase and stabilize SOC compared to sole maize. This is the first evidence for soil health services being associated with doubled-up grain legume diversified maize system under smallholder farm conditions. Intercropped pigeonpea and groundnut in the DLR system accumulated more SOC than sole pigeonpea or sole groundnut in rotation with maize. Cropping treatment differences were not seen in bulk SOC or total N after six years of trial establishment, but they were apparent in SOC pools with a shorter turnover time. This study demonstrates

that readily decomposable and biologically active SOC pools like aggregate-associated SOC, POM, WEOC, and soil respiration can be early indicators of SOC dynamics and the effects of crop rotation and diversification. I recommend that in addition to measuring bulk SOC and total N, future studies examining the impacts of management practices on SOC or soil health, measure these or other rapid-cycling, active SOC pools.

REFERENCES

REFERENCES

- Adeboye, M.K.A., Iwuafor, E.N.O., Agbenin, J.O., 2006. The effects of crop rotation and nitrogen fertilization on soil chemical and microbial properties in a Guinea Savanna Alfisol of Nigeria. *Plant Soil* 281, 97–107. <https://doi.org/10.1007/s11104-005-3828-5>
- Angst, G., Mueller, K.E., Kögel-Knabner, I., Freeman, K.H., Mueller, C.W., 2017. Aggregation controls the stability of lignin and lipids in clay-sized particulate and mineral associated organic matter. *Biogeochemistry*. <https://doi.org/10.1007/s10533-017-0304-2>
- Anyanzwa, H., Okalebo, J.R., Othieno, C.O., Bationo, A., Waswa, B.S., Kihara, J., 2010. Effects of conservation tillage, crop residue and cropping systems on changes in soil organic matter and maize-legume production: A case study in Teso District. *Nutr. Cycl. Agroecosystems* 88, 39–47. <https://doi.org/10.1007/s10705-008-9210-2>
- Bado, B. V., Bationo, A., Cescas, M.P., 2006. Assessment of cowpea and groundnut contributions to soil fertility and succeeding sorghum yields in the Guinean savannah zone of Burkina Faso (West Africa). *Biol. Fertil. Soils* 43, 171–176. <https://doi.org/10.1007/s00374-006-0076-7>
- Bartelt-Ryser, J., Joshi, J., Schmid, B., Brandl, H., Balser, T., 2005. Soil feedbacks of plant diversity on soil microbial communities and subsequent plant growth. *Perspect. Plant Ecol. Evol. Syst.* 7, 27–49. <https://doi.org/10.1016/j.ppees.2004.11.002>
- Bationo, A., Ntare, B.R., 2000. Rotation and nitrogen fertilizer effects on pearl millet, cowpea and groundnut yield and soil chemical properties in a sandy soil in the semi-arid tropics, West Africa. *J. Agric. Sci.* 134, 277–284. <https://doi.org/10.1017/S0021859699007650>
- Beedy, T.L., Snapp, S.S., Akinnifesi, F.K., Sileshi, G.W., 2010. Impact of *Gliricidia sepium* intercropping on soil organic matter fractions in a maize-based cropping system. *Agric. Ecosyst. Environ.* 138, 139–146. <https://doi.org/10.1016/j.agee.2010.04.008>
- Buchkowski, R.W., Schmitz, O.J., Bradford, M.A., 2015. Microbial stoichiometry overrides biomass as a regulator of soil carbon and nitrogen cycling. *Ecology* 96, 1139–1149. <https://doi.org/10.1890/14-1327.1.sm>
- Bustamante, S.J.C., Hartz, T.K., 2016. Carbon Mineralization and Water-Extractable Organic Carbon and Nitrogen as Predictors of Soil Health and Nitrogen Mineralization Potential Carbon Mineralization and Water-Extractable Organic Carbon and Potential. *Commun. Soil Sci. Plant Anal.* 47, 46–53. <https://doi.org/10.1080/00103624.2016.1232095>

- Canarini, A., Kiær, L.P., Dijkstra, F.A., 2017. Soil carbon loss regulated by drought intensity and available substrate: A meta-analysis. *Soil Biol. Biochem.* 112, 90–99.
<https://doi.org/10.1016/j.soilbio.2017.04.020>
- Chantigny, M.H., 2003. Dissolved and water-extractable organic matter in soils: A review on the influence of land use and management practices. *Geoderma* 113, 357–380.
[https://doi.org/10.1016/S0016-7061\(02\)00370-1](https://doi.org/10.1016/S0016-7061(02)00370-1)
- Chen, R., Senbayram, M., Blagodatsky, S., Myachina, O., Dittert, K., Lin, X., Blagodatskaya, E., Kuzyakov, Y., 2014. Soil C and N availability determine the priming effect: Microbial N mining and stoichiometric decomposition theories. *Glob. Chang. Biol.* 20, 2356–2367.
<https://doi.org/10.1111/gcb.12475>
- Chikowo, R., Chimonyo, V., Gwenambira, C., Snapp, S., 2020. Ecosystem services in doubled-up legume systems, in: *The Role of Ecosystem Services in Sustainable Food Systems*. Elsevier Inc., pp. 171–180. <https://doi.org/10.1016/B978-0-12-816436-5.00009-3>
- Chikowo, R., Zingore, S., Nyamangara, J., Bekunda, M., Messina, J., Snapp, S., 2015. Approaches to Reinforce Crop Productivity Under Rain-fed Conditions in Sub-humid Environments in Sub-Saharan Africa, in: *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa*. <https://doi.org/10.1007/978-3-319-09360-4>
- Chimonyo, V.G.P., Snapp, S.S., Chikowo, R., 2019. Grain Legumes Increase Yield Stability in Maize Based Cropping Systems. *Crop Sci.* 0, 0.
<https://doi.org/10.2135/cropsci2018.09.0532>
- Chivenge, P., Vanlauwe, B., Gentile, R., Six, J., 2011. Comparison of organic versus mineral resource effects on short-term aggregate carbon and nitrogen dynamics in a sandy soil versus a fine textured soil. *Agric. Ecosyst. Environ.* 140, 361–371.
<https://doi.org/10.1016/j.agee.2010.12.004>
- Conover, W.J., 2012. The rank transformation — an easy and intuitive way to connect many nonparametric methods to their parametric counterparts for seamless teaching introductory statistics courses 4. <https://doi.org/10.1002/wics.1216>
- Conover, W.J., Iman, R.L., 1981. Rank Transformations as a Bridge Between Parametric and Nonparametric Statistics Author (s): W . J . Conover and Ronald L . Iman Published by : Taylor & Francis , Ltd . on behalf of the American Statistical Association Stable URL : <https://www.jstor.org/35,124-129>.
- Cotrufo, M.F., Ranalli, M.G., Haddix, M.L., Six, J., Lugato, E., 2019. Soil carbon storage informed by particulate and mineral-associated organic matter. *Nat. Geosci.* 12, 989–994.
<https://doi.org/10.1038/s41561-019-0484-6>

- Culman, S.W., Snapp, S.S., Green, J.M., Gentry, L.E., 2013. Short- and long-term labile soil carbon and nitrogen dynamics reflect management and predict corn agronomic performance. *Agron. J.* 105, 493–502. <https://doi.org/10.2134/agronj2012.0382>
- Denef, K., Six, J., 2005. Clay mineralogy determines the importance of biological versus abiotic processes for macroaggregate formation and stabilization. *Eur. J. Soil Sci.* 56, 469–479. <https://doi.org/10.1111/j.1365-2389.2004.00682.x>
- Elliott, E.T., 1986. Aggregate Structure and Carbon, Nitrogen, and Phosphorus in Native and Cultivated Soils. *Soil Sci. Soc. Am. J.* 50, 627–633. <https://doi.org/10.2136/sssaj1986.03615995005000030017x>
- Elliott, E.T., Palm, C.A., Reuss, D.E., Monz, C.A., 1991. Organic matter contained in soil aggregates from a tropical chronosequence: correction for sand and light fraction. *Agric. Ecosyst. Environ.* 34, 443–451. [https://doi.org/10.1016/0167-8809\(91\)90127-J](https://doi.org/10.1016/0167-8809(91)90127-J)
- Feller, C., Beare, M.H., 1997. Physical control of soil organic matter dynamics in the tropics. *Geoderma* 79, 69–116. [https://doi.org/10.1016/S0016-7061\(97\)00039-6](https://doi.org/10.1016/S0016-7061(97)00039-6)
- Franke, A.C., van den Brand, G.J., Vanlauwe, B., Giller, K.E., 2018. Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. *Agric. , Ecosyst. Environ.* 261, 172–185. <https://doi.org/10.1016/j.agee.2017.09.029>
- Franzluebbers, A.J., 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil Tillage Res.* 66, 197–205. [https://doi.org/10.1016/S0167-1987\(02\)00027-2](https://doi.org/10.1016/S0167-1987(02)00027-2)
- Franzluebbers, A.J., Haney, R.L., Honeycutt, C.W., Schomberg, H.H., Hons, F.M., 2000. Rush of Carbon Dioxide following Rewetting of Dried Soil Relates to Active Organic Pools 64, 613–623.
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. *Sci. Data* 2, 1–21. <https://doi.org/10.1038/sdata.2015.66>
- Giller, K.E., 2001. *Nitrogen Fixation in Tropical Cropping Systems*, CABI. Wallingford, UK.
- Grandy, A.S., Robertson, G.P., 2007. Land-use intensity effects on soil organic carbon accumulation rates and mechanisms. *Ecosystems* 10, 58–73. <https://doi.org/10.1007/s10021-006-9010-y>
- Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility, in: Dane, J. H. & Topp, G.C. (Ed.), *Methods of Soil Analysis. Part 4. Physical Methods*. Soil Science Society of

- America Inc., Madison, WI, pp. 201–228.
- Haney, R.L., Brinton, W.H., Evans, E., 2008. Estimating soil carbon, nitrogen, and phosphorus mineralization from short-term carbon dioxide respiration. *Commun. Soil Sci. Plant Anal.* 39, 2706–2720. <https://doi.org/10.1080/00103620802358862>
- Jastrow, J.D., 1996. Soil aggregate formation and the accrual of particulate and mineral-associated organic matter. *Soil Biol. Biochem.* 28, 665–676. [https://doi.org/10.1016/0038-0717\(95\)00159-X](https://doi.org/10.1016/0038-0717(95)00159-X)
- Jastrow, J. D., Amonette, J. E., Bailey, V. L., 2007. Mechanisms controlling soil carbon turnover and their potential application for enhancing carbon sequestration. *Clim. Change* 80, 5–23. <https://doi.org/10.1007/s10584-006-9178-3>
- Jing, Z., Chen, R., Wei, S., Feng, Y., Zhang, J., Lin, X., 2017. Response and feedback of C mineralization to P availability driven by soil microorganisms. *Soil Biol. Biochem.* 105, 111–120. <https://doi.org/10.1016/j.soilbio.2016.11.014>
- Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.* 10, 423–436. [https://doi.org/10.1890/1051-0761\(2000\)010\[0423:TVDOSO\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2)
- Jury, M.R., Mwafulirwa, N.D., 2002. Climate variability in Malawi, Part 1: Dry summers, statistical associations and predictability. *Int. J. Climatol.* <https://doi.org/10.1002/joc.771>
- Kaiser, M., Kleber, M., Berhe, A.A., 2015. How air-drying and rewetting modify soil organic matter characteristics: An assessment to improve data interpretation and inference. *Soil Biol. Biochem.* <https://doi.org/10.1016/j.soilbio.2014.10.018>
- Kallenbach, C., Grandy, A. S., 2011. Controls over soil microbial biomass responses to carbon amendments in agricultural systems: A meta-analysis. *Agric. Ecosyst. Environ.* 144, 241–252. <https://doi.org/10.1016/j.agee.2011.08.020>
- Kong, A.Y.Y., Six, J., 2010. Tracing Root vs. Residue Carbon into Soils from Conventional and Alternative Cropping Systems. *Soil Sci. Soc. Am. J.* 74, 1201. <https://doi.org/10.2136/sssaj2009.0346>
- Kremen, C., Miles, A., 2012. Ecosystem services in biologically diversified versus conventional farming systems: Benefits, externalities, and trade-offs. *Ecol. Soc.* 17. <https://doi.org/10.5751/ES-05035-170440>
- Kristiansen, S.M., Schjøning, P., Thomsen, I.K., Olesen, J.E., Kristensen, K., Christensen, B.T., 2006. Similarity of differently sized macro-aggregates in arable soils of different texture. *Geoderma* 137, 147–154. <https://doi.org/10.1016/j.geoderma.2006.08.005>

- Kuyah, S., Sileshi, G.W., Nkurunziza, L., Chirinda, N., Ndayisaba, P.C., Dimobe, K., Öborn, I., 2021. Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review. *Agron. Sustain. Dev.* <https://doi.org/10.1007/s13593-021-00673-4>
- Lange, M., Eisenhauer, N., Sierra, C.A., Bessler, H., Engels, C., Griffiths, R.I., Mellado-Vázquez, P.G., Malik, A.A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B.C., Trumbore, S.E., Gleixner, G., 2015. Plant diversity increases soil microbial activity and soil carbon storage. *Nat. Commun.* 6. <https://doi.org/10.1038/ncomms7707>
- Lützow, M. v., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions - A review. *Eur. J. Soil Sci.* 57, 426–445. <https://doi.org/10.1111/j.1365-2389.2006.00809.x>
- Marschner, B., Kalbitz, K., 2003. Controls of bioavailability and biodegradability of dissolved organic matter in soils. *Geoderma* 113, 211–235. [https://doi.org/10.1016/S0016-7061\(02\)00362-2](https://doi.org/10.1016/S0016-7061(02)00362-2)
- Montgomery, D.C., 2005. *Design and Analysis of Experiments*, Sixth. ed. John Wiley and Sons, Inc. <https://doi.org/10.1080/00224065.2005.11980315>
- Mungai, L.M., Snapp, S., Messina, J.P., Chikowo, R., Smith, A., Anders, E., Richardson, R.B., Li, G., 2016. Smallholder Farms and the Potential for Sustainable Intensification. *Front. Plant Sci.* 7, 1–17. <https://doi.org/10.3389/fpls.2016.01720>
- Murphy, C.J., Baggs, E.M., Morley, N., Wall, D.P., Paterson, E., 2015. Rhizosphere priming can promote mobilisation of N-rich compounds from soil organic matter. *Soil Biol. Biochem.* 81, 236–243. <https://doi.org/10.1016/j.soilbio.2014.11.027>
- Peoples, M.B., Herridge, D.F., Ladha, J.K., 1995. Biological Nitrogen-Fixation - an Efficient Source of Nitrogen for Sustainable Agricultural Production. *Plant Soil* 174, 3–28. <https://doi.org/10.1007/BF00032239>
- Powlson, D.S., Whitmore, A.P., Goulding, K.W.T., 2011. Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. *Eur. J. Soil Sci.* 62, 42–55. <https://doi.org/10.1111/j.1365-2389.2010.01342.x>
- Puget, P., Drinkwater, L.E., 2001. Short-Term Dynamics of Root- and Shoot-Derived Carbon from a Leguminous Green Manure. *Soil Sci. Soc. Am. J.* 65, 771–779. <https://doi.org/10.2136/sssaj2001.653771x>
- Rasse, D.P., Rumpel, C., Dignac, M.F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant Soil* 269, 341–356. <https://doi.org/10.1007/s11104-004-0907-y>

- Rochette, P., Gregorich, E.G., 1998. Dynamics of soil microbial biomass C, soluble organic C and CO₂ evolution after three years of manure application. *Can. J. Soil Sci.* 78, 283–290. <https://doi.org/10.4141/S97-066>
- Schiedung, H., Bornemann, L., Welp, G., 2017. Seasonal Variability of Soil Organic Carbon Fractions Under Arable Land. *Pedosphere* 27, 380–386. [https://doi.org/10.1016/S1002-0160\(17\)60326-6](https://doi.org/10.1016/S1002-0160(17)60326-6)
- Schmidt, M.W.I.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. a., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D.A.C.C., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478, 49–56. <https://doi.org/10.1038/nature10386>
- Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* 241, 155–176.
- Six, J., Elliott, E.T., Paustian, K., 2000a. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biol. Biochem.* 32, 2099–2103. [https://doi.org/10.1016/S0038-0717\(00\)00179-6](https://doi.org/10.1016/S0038-0717(00)00179-6)
- Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000b. Soil Structure and Organic Matter I. Distribution of Aggregate-Size Classes and Aggregate-Associated Carbon. *Soil Sci. Soc. Am. J.* 64, 681–689. <https://doi.org/10.2136/sssaj2000.642681x>
- Smith, A., Snapp, S., Dimes, J., Gwenambira, C., Chikowo, R., 2016. Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi. *Agric. Syst.* 145, 139–149. <https://doi.org/10.1016/j.agsy.2016.03.008>
- Snapp, S.S., Mafongoya, P.L., Waddington, S., 1998. Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. *Agric. Ecosyst. Environ.* 71, 185–200. [https://doi.org/10.1016/S0167-8809\(98\)00140-6](https://doi.org/10.1016/S0167-8809(98)00140-6)
- Snapp, S.S., Blackie, M.J., Gilbert, R.A., Bezner-Kerr, R., Kanyama-Phiri, G.Y., 2010. Biodiversity can support a greener revolution in Africa. *Proc. Natl. Acad. Sci.* 107, 20840–20845. <https://doi.org/10.1073/pnas.1007199107>
- Snapp, S.S., Grabowski, P., Chikowo, R., Smith, A., Anders, E., Sirrine, D., Chimonyo, V., Bekunda, M., 2018. Maize yield and profitability tradeoffs with social, human and environmental performance: Is sustainable intensification feasible? *Agric. Syst.* 162, 77–88. <https://doi.org/10.1016/j.agsy.2018.01.012>
- Sokol, N.W., Sanderman, J., Bradford, M.A., 2019. Pathways of mineral-associated soil organic

- matter formation: Integrating the role of plant carbon source, chemistry, and point of entry. *Glob. Chang. Biol.* 25, 12–24. <https://doi.org/10.1111/gcb.14482>
- Tamene, L., Sileshi, G.W., Ndengu, G., Mponela, P., Kihara, J., Sila, A., Tondoh, J., 2019. Soil structural degradation and nutrient limitations across land use categories and climatic zones in Southern Africa. *L. Degrad. Dev.* 30, 1288–1299. <https://doi.org/10.1002/ldr.3302>
- Thierfelder, C., Cheesman, S., Rusinamhodzi, L., 2012. A comparative analysis of conservation agriculture systems: Benefits and challenges of rotations and intercropping in Zimbabwe. *F. Crop. Res.* 137, 237–250. <https://doi.org/10.1016/j.fcr.2012.08.017>
- Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. *J. Soil Sci.* 33, 141–163. <https://doi.org/10.1111/j.1365-2389.1982.tb01755.x>
- von Lützow, M., Kögel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., Marschner, B., 2007. SOM fractionation methods: Relevance to functional pools and to stabilization mechanisms. *Soil Biol. Biochem.* 39, 2183–2207. <https://doi.org/10.1016/j.soilbio.2007.03.007>
- Wander, M., 2004. Soil Organic Matter Fractions and Their Relevance to Soil Function. <https://doi.org/10.1201/9780203496374.ch3>
- Wieder, W.R., Bonan, G.B., Allison, S.D., 2013. Global soil carbon projections are improved by modelling microbial processes. *Nat. Clim. Chang.* <https://doi.org/10.1038/nclimate1951>
- Yusuf, A.A., Abaidoo, R.C., Iwuafor, E.N.O., Olufajo, O.O., Sanginga, N., 2009. Rotation effects of grain legumes and fallow on maize yield, microbial biomass and chemical properties of an Alfisol in the Nigerian savanna. *Agric. Ecosyst. Environ.* 129, 325–331. <https://doi.org/10.1016/j.agee.2008.10.007>