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Assessing Consumer Demand, Producer Profitability, and the Environmental Impacts of Conservation Agriculture Adoption in Sub-Saharan Africa

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by

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ABSTRACT

This dissertation explores three aspects of conservation agriculture (CA) in the Sub-Saharan African region (SSA). The first article examines the demand side of CA and explores whether urban maize (*Zea mays* L.) consumers in the Democratic Republic of the Congo (DRC) would be willing to pay a premium for CA-produced maize flour. The second article estimates the effects CA provides to adopters and their farms in smallholder farming systems in the DRC, focusing on changes in soil properties and cowpea (*Vigna unguiculata*) yields. The final article uses a Life Cycle Assessment (LCA) approach to monetize the environmental impacts of adopting CA in South African wheat (*Triticum aestivum* L.) commercial farming. The following findings emerge from this dissertation: (1) With few exceptions, urban DRC consumers were not willing to pay a premium for white maize flour produced with CA technique; (2) CA was shown to improve soil health, via increasing earthworms populations, soil quality via greater concentrations in soil available P and K, and cowpea yields when compared to conventional farming in the DRC; and (3) CA was more profitable and had a greater environmental efficiency (yield output per dollar of environmental damage) than conventional wheat production in South Africa. The results of this CA adoption research illustrated the production side benefits of adopting sustainable agricultural production but also showed a gap in the consumer demand side of the food systems equation for CA in SSA.

Keywords: *Conservation agriculture, Adoption, Sub-Saharan Africa, Ecosystem, Sustainable agricultural production, Environmental impact, Environmental efficiency*

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DEDICATION

Xavier Phemba Phezo, mentor and friend,

and

Those who tirelessly do good, believe in the power of goodness and will keep focusing on releasing goodness to others and carrying for mother earth.

TABLE OF CONTENTS

LIST OF PUBLISHED PAPERS

Chapter 2

Mulimbi, W., Nalley, L., Nayga Jr., R.M., & Gaduh, A. (forthcoming). Are Consumers Willing to Pay for Conservation Agriculture in Low-Income Countries? The Case of White Maize in the Democratic Republic of the Congo. Status: Accepted to *Natural Resources Forum*, a United Nations Sustainable Development peer-reviewed journal.

CHAPTER 1: INTRODUCTION

The present dissertation aims to advance the literature related to the impacts of adopting conservation agriculture (CA) and help facilitate its promotion in Sub-Saharan Africa (SSA). The introductory chapter briefly defines CA, presents its benefits and factors which hinder its adoption in SSA, and describes the overall framework of this dissertation. This chapter attempts to articulate how three CA-related questions were approached to help fill the CA knowledge gap in SSA. The following three chapters, which are the core of this dissertation research, examine an aspect of CA more in-depth. These core chapters are of varying sides of the food security equation (supply and demand), but together they intersect in assessing social, environmental, and economic dynamics surrounding CA adoption and impacts in SSA. To this end, these three articles on CA in SSA explore: (1) the demand for CA, looking at if urban consumers in Bukavu are willing to pay for CA-produced commodities in the Democratic Republic of the Congo (DRC), (2) the effects of CA on soils properties and crop yields in the agroecosystems of smallholder farming in Maniema province, DRC, and (3) the holistic (economic and environmental) impacts of CA in commercial wheat farming in Western Cape province, South Africa.

The first article is based on a consumer survey study conducted in Bukavu, a large urban city in the Eastern DRC. This study set out to estimate if there was a demand-pull aspect to CA in DRC. That is, would urban consumers be willing to pay (WTP) a premium for CA if producers could supply white maize (*Zea mays* L.) meal produced using CA methods? If consumers are WTP a premium for CA white maize meal, this could act as a market incentive which could enhance CA adoption by smallholder producers. Understanding the demand for CA agriculture is important given that most agricultural technology promotions in the DRC occurred under short-term projects implemented mainly through national and international non-governmental initiatives focusing solely on production and not consumption. Increased adoption of CA, either through demand-pull (consumers) or supply-push (producers), could help mitigate deforestation and empower rural women producers who are the core of DRC food security.

In the second article, a dataset from on-farm demonstration research is used to analyze CA and conventional farming in the province of Maniema, DRC. The primary goal of this analysis is to examine the effects of CA on soil chemical properties, soil biodiversity, and cowpea (*Vigna unguiculata*) yields in smallholder farming conditions. This study is an agronomy field experiment assessing agricultural production and where the experimental design was a split-split-plot involving the ecosystem, practice, and temporal components. A statistical mixed method was utilized to detect factorial effects and potential interactions. This way, it was possible to better understand and link the CA and conventional farming practices to soil nutrients concentrations and other soil chemicals properties, earthworms' populations, and cowpea yields in savannah and forest, the two main ecosystems in the DRC. This study is the first of its kind in the DRC, as it involved the ecosystems present in smallholder farming in the DRC. Another relevant aspect of this study for smallholder farming in the DRC is the consideration of local reality, such as the lack of agrochemicals that CA literature indicates to be imperative for the success of CA in other countries. This study demonstrates that CA is possible in Central Africa, which holds 18% of the world's rainforests, and should be counted among sustainable agricultural farming options.

In the final article, a 19-year long-term trials dataset on CA in Langgewens and Tygerhoek research stations in the Western Cape of South Africa allows the comparison of the economic and environmental impacts of CA adoption. This analysis combines traditional economic comparisons (profitability per hectare) with a Life Cycle Assessment (LCA) method to estimate CA's economic and environmental impacts when compared to conventional tillage in wheat (*Triticum aestivum* L.) production in South Africa. Profitability analysis is used to examine the performance of CA systems and compare them to conventional wheat production. This study examines holistically the benefits of switching to CA systems for humans and the environment. More importantly, this study invites agricultural scientists to rethink agricultural total factor productivity (TFP) by bringing more insights on accounting for environmental damage efficiency in commercial wheat production in South Africa. This research is unique as it helps internalize the environmental impacts of sustainable agricultural production that most agricultural stakeholders acknowledge but fail to quantify.

1.1. Conservation agriculture

Conservation agriculture (CA) is an agricultural technology combining a set of three interrelated principles: (1) the absence of soil disturbance or at least just a minimum soil disruption, (2) the maintenance of a permanent soil cover, and (3) the integration of crop rotation to diversify plant species (Food and Agriculture Organization of the United Nations [FAO], 2019). These three individual CA principles must be applied together to comply with the definition of a CA system. As a sustainable agricultural practice, CA enhances productivity and maintains natural base resources (Food and Agriculture Organization of the United Nations [FAO], 2019). CA is a practice that seeks to increase profits while preserving the environment (FAO, 2020; Kassam et al., 2019; Kassam et al., 2009).

According to FAO (2020), CA delivers economic, agronomic, and environmental benefits. Studies conducted in SSA have demonstrated that the economic benefits of CA are mainly illustrated by production efficiency improvements, cost and labor requirement reductions, time-saving, and increased yields (Bunderson et al., 2017; Lalani et al., 2017; Micheni et al., 2016; Thierfelder, Bunderson, et al., 2015). Reviews and trials-based CA studies have disclosed agronomic benefits such as enhanced soil productivity, increased level of organic matter, water conservation, reduced soil erosion, and improved soil structure (Brouder & Gomez-Macpherson, 2014; Eze et al., 2020; Page et al., 2020; Thierfelder, Rusinamhodzi, et al., 2015). Research has presented CA's environmental benefits in the form of water and air quality improvements, increasing biodiversity, and carbon sequestration (Briones & Schmidt, 2017; Lal, 2015; Pisante et al., 2015; Wall et al., 2014). Several social benefits associated with CA arise from its economic, agronomic, and environmental benefits. For instance, better soil management through CA benefits farmers through additional incomes gained from farming on slopes (Misiko, 2017). CA empowers women farmers by shortening their trips to the farms (Mulimbi et al., 2019). The knowledge-intensive nature of CA reinforces farmers' skills and working strategies (Giller et al., 2009). CA can act as a productive social safety net by reducing household risks associated with climate change and food insecurity (Gonzalez-Sanchez et al., 2019; Mango et al., 2017; Rust-Smith, 2015; Smith et al., 2017). Together, most of these research studies have been instrumental in highlighting the sustainable merit of CA in SSA.

Previous research has shown that for both humans and the environment, CA benefits are heterogeneous as they are affected by local socio-economic and agroecological conditions (Corbeels et al., 2014; Mafongoya et al., 2016; Swanepoel et al., 2018). Accounting for local conditions is then a pragmatic approach to promoting CA (Giller et al., 2009). SSA has a geographical CA learning gap regarding "where and under what conditions" CA works. Thus, studies like the core articles of this dissertation contribute to CA literature growth by supplying CA lessons from both smallholder and commercial farming in two different locations of SSA.

For these two forms of farming (smallholder and commercial), this dissertation seeks to demonstrate specific impacts that would be expected from implementing CA in SSA.

1.2. CA adoption in SSA

Like in the rest of the world, CA is implemented on farms of any size with annual and perennial crops in diverse agroecological zones of SSA (Kassam et al., 2009). The SSA region, which accounts for 1.5% of the global CA cropland, has the lowest continental adoption rate, and the top five CA-leading nations in SSA are South Africa, Zimbabwe, Mozambique, Ghana, and Malawi, respectively (Kassam et al., 2022).

Multiple reasons are traditionally given for the low implementation of CA in SSA. The widespread of CA has been essentially hindered in SSA by a weak understanding of the CA system by both researchers and farmers, competition found in crop residues management, weed control, lack of adequate tools and operating skills, and shortage of specific research and policies (Andersson & D'Souza, 2014; Basch & González-Sánchez, 2022; Findlater et al., 2019). Another disappointment sometimes encountered by farmers is related to crop yields. It has been shown that CA crop yields benefits are usually well-expressed in the long-term (Corbeels et al., 2020). Finally, changing community cultural norms, such as the traditional plowing, is another impediment to consider in SSA (Lee & Gambiza, 2022; Wall, 2007).

Furthermore, CA adoption rates in SSA tend to be questioned due to a top-down CA-promotional approach (Andersson & Giller, 2012). In many cases, especially in smallholder farming, CA was initiated and promoted by international research and development organizations (Mkomwa et al., 2017). Studies in SSA have demonstrated that some promotional projects failed to engage the community in technology transfer, leading to CA dis-adoption after the project (Chinseu et al., 2019; Razafimahatratra et al., 2021). Typically, the introduction of CA, like most agricultural technologies and innovations brought to SSA, raises the question of incentive to adopt. Therefore, this dissertation, in addition to highlighting CA's positive effects, delves into two alternative incentive pathways. On the one hand, I look downstream in the maize value chain to assess whether white maize flour consumers could support CA adoption. On the other hand, I monetize the ecosystem services CA provides relative to conventional farming to contribute to their quantification and provide policymakers with figures that can possibly serve to motivate CA adoption.

1.3. Questions examined in this dissertation

This dissertation proposes to address the following questions to advance the understanding and dissemination of CA in SSA. These questions are specific to each of the core studies conducted in the present dissertation.

1.3.1. Demand for CA in the DRC

1. Are urban maize consumers in DRC willing to pay a premium for CA-produced white maize flour?
2. Are DRC urban maize consumers aware of the issues of deforestation and domestic violence faced by rural women producers in the DRC agricultural production?
3. Does urban maize consumers' awareness of the socio-environmental concerns in agricultural production drive their willingness-to-pay for sustainable agricultural practices such as CA?

1.3.2. CA adaptability in smallholder farming of Maniema, DRC

1. What are CA effects on soil chemical properties such as soil pH, cation exchange capacity, nutrients (available N, P, K, Ca, Na, and Mg), organic carbon, organic matter, and C/N ratio?
2. What are CA effects on soil biodiversity represented by earthworms' populations?
3. Does CA affect cowpea yields per hectare?
4. Are the effects of CA affected by temporal and ecosystem factors?

1.3.3. Impacts of CA adoption in commercial farming of Western Cape, South Africa

1. Does adopting CA wheat production in Western Cape lead to enhanced profits, environmental benefits, or both?
2. What is the monetized environmental value of adopting CA per hectare in commercial wheat production?
3. What effect does treating the monetized environmental damage of CA and conventional tillage have on their relative profitability?

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CHAPTER 2: ARE CONSUMERS WILLING TO PAY FOR CONSERVATION AGRICULTURE? THE CASE OF WHITE MAIZE IN THE DEMOCRATIC REPUBLIC OF THE CONGO

Abstract

Throughout the low-income world, agricultural producers have a motivation to slash-and-burn rainforests as they cannot afford inorganic fertilizer. Farmers in the Democratic Republic of the Congo (DRC), who are predominantly women, often are forced to walk long distances to cultivate more productive lands in the forest when fertility is reduced near their village. As women work and walk further distances to cultivate new agricultural land, they find themselves a target for rape. Adopting conservation agriculture (CA) could help mitigate deforestation and potentially create a safer environment for women. Knowledge across Sub-Saharan African countries about the benefits of CA is limited and has hindered CA's adoption. Given the impediments to CA adoption, we estimate if consumers in the DRC are willing to pay (WTP) a premium for CA using maize flour as our medium. Using a double-bounded dichotomous choice valuation method, 600 consumers in Bukavu, DRC, were surveyed about their willingness-to-pay for CA-produced maize. Our study finds that only those consumers who self-identify as farmers are WTP a premium. This study indicates that, if CA adoption is to increase in the DRC, it will likely need to come via increased yields or reduced costs before the farm gate and not premiums after the farm gate.

Keywords: *Conservation agriculture, Willingness-to-pay, Democratic Republic of the Congo, Rural women, Deforestation*

2.1. Introduction

Deforestation has been instrumental in accelerating global climate change (Bala et al., 2007; Fearnside, 2000; Intergovernmental Panel on Climate Change [IPCC], 2013). Annually, a forested area of the size of Austria is lost globally via deforestation (Seymour & Busch, 2016). In the Democratic Republic of the Congo (DRC), which accounts for 62% of the Congo Basin rainforest in Africa (approximately 167 million hectares), the deforestation rate doubled between 1990 and 2005 (Tchatchou et al., 2015). The expansion of small-scale forest clearing in search of productive agricultural land is among the largest deforestation drivers in the DRC (Turubanova et al., 2018; Tyukavina et al., 2018). Throughout the low-income world, agricultural producers often have a motivation to slash and burn old-growth rainforests as they often cannot afford inorganic fertilizer, cannot find it when needed, or a combination of both. Once they harvest the rent of organic fertilizer from one area, they often search for alternative productive land, usually at the expense of rainforests (Cannon, 2018).

Farmers' safety, specifically for women farmers, is an additional burden in the agricultural sector in rural DRC (Mulimbi et al., 2019). Safety in the DRC, or the lack of it, is associated with social strife, civil conflicts, and political instability beginning in the 1990s (World Food Programme [WFP], 2020). As a consequence of this destabilization, one out of six people living in extreme poverty in Sub-Saharan Africa (SSA) is located in the DRC, despite the country's immense endowments in natural resources (World Bank, 2018). Millions of Congolese women have encountered rape or sexual violence due to these civil conflicts, which has resulted in massive population displacements in search of safety and fertile agricultural land (Peterman et al., 2011). DRC farmers, who are predominantly women (58%) (Ministère du Plan et Suivi de la Mise en Oeuvre de la Révolution de la Modernité [MPSMRM] et al., 2014), often are forced to walk long distances away from their home/village to cultivate more productive lands in the forest when agricultural fertility is reduced in fields near their home/village (Mulimbi et al., 2019). This not only is a larger opportunity cost, as walking further cuts into productive work hours, but as women work and walk to/from home to these further distances, they find themselves a target for violence and rape.

The adoption of conservation agriculture (CA) can mitigate deforestation (environmental benefits) and potentially create a safer working environment for rural women in the DRC (social benefits). If female producers were to adopt CA (such as in white maize production), it would reduce the longer distance they have to travel to tend to their crops, potentially reducing deforestation (land expansion) and could improve the safety of female producers who have fallen victim to domestic and sexual violence as they travel to their fields. These social and environmental issues are likely to escalate in the DRC due to a growing population, continued regional conflicts, increased demand for food, and the pressure on natural resources. As the population expands and arable land becomes scarcer across the majority of low-income countries (LICs) (including the DRC), an increased number of farmers may choose to slash and burn fragile rainforest lands in search of more fertile ground (Sunderlin et al., 2005).

In this study (following the United Nations definition), CA is a farming system that promotes a permanent soil cover, minimum soil disturbance (i.e., no-tillage), and diversification of plant species that enhances soil quality and promotes soil health (Food and Agriculture Organization of the United Nations [FAO], 2019; Mkomwa et al., 2017; Pisante et al., 2015). Such soil improvements induce increased crop yields (Ares et al., 2015) and make CA an economically viable alternative to slash-and-burn agriculture in forested areas like the DRC (Legoupil et al., 2015). As farmers in the DRC harvest the nutrients from a cleared forest floor, they practice slash-and-burn agriculture to harvest new organic rents. Problematically, they have to move further away from their village each year. A substitute to slash-and-burn such as CA can accommodate these farmers' old farmlands and prevent them from walking further to establish new farmlands in the forest. Previous research (Angelsen, 2009; Landers et al., 2006; Rudel et al., 2009) has shown how conservation agriculture can reduce deforestation, sustaining old-growth forests.

However, knowledge amongst agricultural producers across SSA countries, including the DRC, about the benefits of CA, which include reduced tillage and production costs, improved soil quality, better crop water balance, the potential for enhanced yield, and potential for reduced yield variability, is limited, hindering its widespread adoption (Wall, 2007; Wall et al., 2014). The lack of information on CA throughout farming communities, combined with a poor understanding of its principles, limited access to inputs and crop residues, and resistance to change, impedes large-scale CA adoption (Bunderson et al., 2017). Agricultural producers in the DRC often have multiple objectives, hence a need for multi-disciplinary approach, but rarely have access to people and information (such as best management practices for CA) that can help them work out appropriate solutions. CA production has a learning curve as it requires new management skills and can result in reduced yields if not conducted under best management practices, thus making knowledge of its implementation crucial (Knowler & Bradshaw, 2007; Rusinamhodzi et al., 2011). Given that the poor agricultural extension service plagues most SSA countries, alternative avenues need to be explored to increase CA's adoption.

This paper examines whether CA's adoption by rural producers could be driven by consumers' willingness to pay (WTP) a premium for goods produced with CA. We test the effect of different types of information related to CA's benefits in the DRC on consumers' WTP a premium for a good (in our study, white maize flour) produced under CA. The information sets are related to CA's environmental (potential reduced deforestation) and social (potential reduced violence against women as they are not forced to walk long distances to cultivate new ground) benefits. While simple production of white maize flour does not constitute CA, if CA principles are followed in cultivating white maize, the large amount of cultivated land dedicated to its production could have considerable social and environmental impacts. Given the challenge of obtaining reliable data in the DRC (Thontwa et al., 2017), little research has been conducted to assess sustainable agricultural technologies' demand amongst consumers. To date, no study has explored whether DRC's consumers would be willing to pay to reduce socio-environmental concerns (farmers' safety and deforestation). The existing literature on WTP for CA is either producer or policy-focused (Amusa et al., 2015; Asrat et al., 2004; Baffoe et al., 2021; Johnston & Duke, 2007), leaving a large gap in consumers' WTP for CA.

Given the impediments to CA's adoption across the DRC, this study seeks to estimate if urban consumers in the DRC are willing to pay for white maize flour produced sustainably via CA. While white maize flour is a staple in this part of the DRC, our study focuses on the WTP for CA (through an explanation of its social and environmental benefits) and only uses white maize flour as our testable medium. While many LICs and the DRC consumers simply focus on price minimization regarding dietary needs, rural sexual violence and deforestation are issues that many Congolese consumers are aware of due to years of civil unrest and evident widespread deforestation. Thus, this study aims to be the first to estimate if consumers in the DRC are willing to pay a premium for CA-produced agricultural goods in an effort to help alleviate deforestation and domestic violence against women using white maize flour as our medium. The results of this study are important as they provide valuable information to the DRC government, commodity producers, agricultural scientists, policymakers, and non-governmental organizations (NGOs) about the potential for consumers to pull (via demand) the adoption of CA via premiums instead of policies and extension programs that try to push (via supply) its adoption. If it is found that consumers are willing to pay a premium for CA-produced goods, producers should be more likely to adopt CA, which ultimately has the potential to reduce violence against rural women and deforestation. Further, this study is unique in the literature because it addresses the consumer demand side of CA. After all, while CA has been proven to provide environmental benefits in a meta-analysis of 933 locations across 16 different countries in SSA, the average yield was only found to be 3.7% higher for six major crop species and 4.0% for maize under CA compared to conventional agricultural (including slash and burn) practices (Corbeels et al., 2020). Thus, studies such as this, which analyze consumer demand for CA, could be pivotal for providing information, such as estimated premiums associated with CA, for its widespread adoption across SSA.

2.2. Small-scale agriculture in the DRC

2.2.1. Female agricultural workers in the DRC

While women are the backbone of the agricultural workforce in the DRC, representing 60% of agricultural labor and 73% of the farmers, producing 80% of the food crops for household consumption, they are some of the most vulnerable members of the agriculture sector (UNDP, 2021; International Monetary Fund [IMF], 2013; USAID, 2014; World Bank, 2018). According to the Demographic and Health Survey [DHS] (MPSMRM et al., 2014), agriculture has been the primary occupation for 58% of all DRC women. This occupation rate increases to 66% for women between 45 and 49 years old with more than five children and 77% for women in rural settings (MPSMRM et al., 2014). According to the United Nations entity dedicated to gender equality and women’s empowerment [UN Women] (2016), despite their high representation in agriculture, DRC women are discriminated against within the sector regarding access to arable land, financing, and technologies. Less than 10% of women are landowners; only 2% of women have access to credit from financial institutions, and because of this, 42% of women take loans from family and friends at exorbitant interest rates (UN WOMEN, 2016). Women in agriculture in the DRC are not just victims of economic inequality but also civil inequality.

DRC women are also among the primary victims of the country’s socio-political instability (Ministère de l’Agriculture et du Développement Rural [MINAGRI], 2010). According to Herderschee, Kaiser, and Samba (2011), the government efforts to reduce inequality, exacerbated by civil conflicts and their consequence, are still not leveling the playing field. Women face many types of discrimination, exploitation, and exclusion in their communities throughout the DRC (USAID, 2014). More particularly, rural women in the DRC are more disadvantaged and exposed to higher poverty, food insecurity, and sexual violence. Sexual and gender-based violence (GBV) has spread into a wider social disease and represents a significant barrier to women’s full engagement in social and economic life (World Bank, 2018). Millions of DRC women have faced sexual violence (Peterman et al., 2011). According to Fourati et al. (2021), sexual violence on rural women is a “weapon of war” used by armed groups and, in the DRC, it is mainly associated with the presence of artisanal mining activities. Regardless of these high vulnerability levels, the DRC still does not have a national social protection mechanism to assist its most impoverished communities (World Bank, 2018).

2.2.2. Slash-and-burn practice in the DRC

Slash-and-burn agriculture is a farming practice that is still widely implemented in the DRC agroecological zones today. The increase in slash-and-burn is one of the primary current and future threats to the Central African rainforest (Torbay & Vantomme, 2017). It used to be a sustainable practice, with farmlands being left fallow while soil fertility was restored after the cropping cycle; however, beyond a certain threshold, the forest no longer has time to regenerate between cropping cycles (Torbay & Vantomme, 2017). In the DRC, a study by Nsombo et al. (2016) has shown that the yield increases through slash-and-burn agriculture do not last as soil organic matter drastically decreases over the next cropping cycle, making this practice unsustainable from food security and environmental standpoints.

The rural population in the DRC conducts slash-and-burn agriculture to address their subsistence or financial needs (Ministère de l'Environement Conservation de la Nature et Tourisme [MECNT], 2012). Slash-and-burn is an activity that has been encouraged by a challenging economic environment and a weak institutional framework – political decisions, civil wars, poor governance, crisis, unemployment, and poverty (MECNT, 2012). Subsistence agriculture is a primary livelihood for DRC rural citizens even though between 1960 to 2006, productivity has decreased by 60% due to political instability and farmers abandoning production because of civil strife (IMF, 2013). Additionally, the decline of the agriculture extension system throughout the country hampered the dissemination of best management practices, leading to reduced agricultural productivity, decreased earnings, and increased food insecurity (World Bank, 2013). In 2009 in the province of Maniema, in the Eastern DRC, it was reported that women were at increased risk of sexual violence due to slash-and-burn as this farming practice continuously forces them to walk farther from their homes (Catholic Relief Services [CRS], 2009).

2.2.3. Consumers' WTP for maize in Sub-Saharan Africa

Maize-WTP studies in SSA have traditionally gravitated around six central themes: biofortification, genetic modification, food preparation, seed system security, tolerance to weather shocks, and aflatoxin. Consumers' WTP for biofortified maize has been studied extensively in SSA (Banerji et al., 2018; Diro et al., 2016; Hamukwala et al., 2019). For example, Meenakshi et al. (2012) investigated the impact of nutrition information on WTP for biofortified-provitamin-A orange maize in rural Zambia. Their results suggested that orange maize (traditionally used for livestock feed) could compete with white maize (traditionally used for human consumption). Rural Zambian consumers would be willing to pay a 19% premium over non-fortified maize when they learned about orange maize from the community leaders at home and 23% when they heard about orange maize from the radio outside their homes. Simelane et al. (2016) examined the use of genetically modified (GM) maize in eSwatini, where GM maize is currently outlawed for production. Their results indicate that Emaswati consumers require an 8% discount for GM maize compared to non-GM maize due to health and ethical concerns. A study in Kenya (Kimenju & De Groote, 2008) demonstrated that urban consumers in Nairobi were willing to pay a 13.8% premium for GM maize food mainly due to their trust in their government's ability to control and regulate the food industry.

2.2.4. CA-produced maize in the DRC

CA maize in the DRC is unique in that it is a staple crop that could both have the environmental benefit (slowing deforestation) and social benefit (potentially lowering violence amongst women). Thus, this study sets out to estimate if consumers in the DRC, who typically focus on price minimization, would be willing to pay a premium for CA-produced maize.

The survey for this study was conducted in the city of Bukavu in the Democratic Republic of the Congo. Bukavu, the South Kivu province's capital, is a large city of 1,078,002 people (United Nations Department of Economic and Social Affairs [UNDESA], 2019) located in the eastern part of the country. Maize, specifically maize flour, was chosen for this study as it is the most traded and consumed cereal and ranked second only to cassava (*Manihot esculenta*) as a staple crop in the DRC (Famine Early Warning Systems Network [FEWS NET], 2015). Maize is the largest cereal produced in the DRC (Institut National de la Statistique [INS], 2017). CAID et al. (2018) report that, on average, 55% of locally harvested maize is consumed, and 45% taken to the market, making maize not only an important crop but a crop with which most consumers are familiar with purchasing. In 2018, South Kivu province was ranked second for DRC maize production (CAID et al., 2018).

2.3. Experimental design

An electronic survey questionnaire was designed using *Qualtrics* survey software and uploaded to tablets for use by four surveyors in the summer of 2019. The survey was created to estimate the WTP of consumers in the DRC for white maize flour produced with CA. The survey consisted of three sections. The first section provided participants with an overview of the survey and CA. In the second section, participants were randomly assigned to a treatment group. They were then administered a "cheap talk" script before answering the double-bounded dichotomous choice valuation (DBDC) questions (Cummings & Taylor, 1999) to reduce potential hypothetical bias, given the stated preference nature of the study. The cheap talk script asked participants to behave as if they were actually shopping in a white maize flour market and make the decisions that best met their white maize flour needs. Cheap talk scripts are often incorporated into hypothetical studies to potentially reduce hypothetical bias (Carlsson et al., 2005; Silva et al., 2011). The third section contained a series of questions collecting demographic and socio-environmental views.

The WTP analysis using DBDC in this study is consistent with Hanemann et al. (1991), who provided empirical evidence of increased statistical efficiency of this approach. Similarly described by Holmquist et al. (2012), McLeod and Bergland (1999), and Patterson (1993), in a study applying the DBDC model, two prices are revealed to each subject. The second price option level is contingent upon the first price choice response, which is randomly chosen from a set of prices for each subject. When the subject's answer is "yes," meaning that they are willing to pay the amount of the initial price (B_i), they are presented with a second but higher price (B_h). As a matter of choice, if the subject's answer is " no," meaning that they are not willing to pay the initial price amount, they are presented with a second but lower bid (B_l).

The subsequent questions attempting to elicit upper or lower bounds of the WTP lead to four possible outcomes: (i) both answers are "no," meaning the participant's WTP is lower than B_l; (ii) a "no" followed by a "yes, "meaning the participant's WTP is lower than B_i but greater than or equal to the accepted B_l amount; (iii) a "yes" followed by a "no" meaning the participant's WTP is greater than or equal to B_i but lower than the rejected B_h amount, and (iv) both answers are "yes" meaning the participant's WTP is greater than or equal to B_h. By denoting the WTP for individual i as WTP_i, we describe the following discrete outcomes in the bidding procedure:

$$y_i = \begin{cases} 1 & if\ \ WTP_i < B_l & (no,no) & (1a) \\ 2 & if\ B_l\ \leq WTP_i < B_i & (no,yes) & (1b) \\ 3 & if\ B_i\ \leq WTP_i < B_h & (yes,no) & (1c) \\ 4 & if\ \ WTP_i\ \geq B_h & (yes,yes) & (1d) \end{cases}$$

In a WTP analysis related to a commodity's characteristics, the objective is to examine the maximum an individual consumer would pay for the commodity in question and how the commodity's properties influence this amount. The contingent valuation (CV) methodology is commonly used to estimate WTP.

Accordingly, based on Carson and Hanemann (2005), the response probabilities for the outcomes in the set of equations (1) will be given by :

$$\Pr(no,no) = \Pr(B_l\ >\ WTP_i^*) =\ G_{WTP}(B_l), \qquad (2a)$$

$$\Pr(no,yes) = \Pr(B_i\ >\ WTP_i^* \geq B_l) =\ G_{WTP}(B_i) -\ G_{WTP}(B_l), \qquad (2b)$$

$$\Pr(yes,no) = \Pr(B_l\ \geq\ WTP_i^* \geq B_l) = G_{WTP}(B_h)\ - G_{WTP}(B_i), \qquad (2c)$$

$$\Pr(yes,yes) = \Pr(B_h\ \leq\ WTP_i^*) =\ 1 -\ G_{WTP}(B_h). \qquad (2d)$$

where G_{WTP} is the WTP cumulative distribution function.

The DBDC design generates interval-censored data on WTP. Following several applications of DBDC (Basu, 2013; Lang, 2010; Nosratnejad et al., 2014), the interval regression method is used in this study. As the latent value of WTP could be effectively observed by analyzing respondents' stated information, and there is a probability that the latent value is located within an interval, interval regression is a suitable method for assessing consumers' WTP for white maize flour (Alberini, 1995; Cameron, 1991). Basu (2013) argues that other discrete choice models such as ordered logit or ordered probit models, even though appropriate, could rank the WTP as an ordinal model and ignore the boundary point values.

The participant's WTP for white maize flour produced under CA is then determined in the linear form of its function as follows:

$$WTP_i^* = \alpha + \tau \cdot W_i + \beta' X_i + \varepsilon_i \qquad (3)$$

where WTP_i^* is the subject i's unobserved true WTP, W is the treatment indicator, X the vector of covariates associated with participant i, α, τ and β are the coefficients representing the parameters to be estimated, and ε denotes the error term following a normal distribution with mean 0 and variance σ^2. Here, the vector X covariates include gender, age, education, household size, and being-a-farmer. These covariates help to test the internal validity of the WTP (Alberini et al., 2005). This study extended the specification in equation (3), allowing for the following specification (equation 4) with a set of interactions to check for potential heterogeneity (Barrett & Carter, 2010).

$$WTP_i^* = \alpha + \tau \cdot W_i + \beta' X_i + \gamma' X_i \cdot W_i + \varepsilon_i \qquad (4)$$

where γ is the coefficient estimated for the interaction term. Groups' WTP variation can be found in a study involving people's environmental attitudes, and accounting for unobservable heterogeneity leads to better model fit (Aldrich et al., 2007). Moreover, field experiments in developing nations have established that individuals' subjective perceptions of new markets and technologies in heterogeneous.

Given that initial, lower, and upper bounds are used to figure different bids within the sample of respondents, the likelihood function for the interval regression model takes the form (Bettin & Lucchetti, 2012; Lu & Shon, 2012):

$$L = \sum_i \left[\Phi\left(\frac{U_i - \beta' x_i}{\sigma}\right) - \Phi\left(\frac{V_i - \beta' x_i}{\sigma}\right) \right] \quad (5)$$

where U_i and V_i are respectively the upper bound and lower bound of the interval in which WTP_i^* falls and ϕ is a standard normal cumulative distribution function. Notice that, as illustrated in Table 2.1, for respondents who gave two “yes” responses, U_i is infinity, and for respondents who gave two “no” responses, V_i is negative infinity (Alberini & Cooper, 2000).

A between-subject design was used by randomly assigning respondents to either a control group or one of the three informational treatments. Participants randomly assigned to the control group were simply shown a picture of a one-kg package of white maize flour commonly purchased throughout eastern DRC. There was no brand name or identification on the package itself to mitigate consumer preference for branding.

Participants in the first information group, i.e., the United Nations’ FAO-Definition (treatment 1), had the FAO’s definition of CA in addition to a picture of a one-kg package of white maize flour. Participants in treatment 1 (*Def*) were given the following information:

> *According to the United Nations, Conservation Agriculture (CA) is a farming system that promotes maintenance of a permanent soil cover, minimum soil disturbance (i.e., no-tillage), and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, which contribute to increased water and nutrient use efficiency and to improved and sustained crop production*.

Participants in treatment 1 were told that the one-kg package of white maize flour was produced following the FAO guidelines on CA as described above.

Participants in treatment 2, i.e., the potential Social benefits of CA treatment (*Soc*), had the FAO’s definition of CA plus a short paragraph stating how CA could help to reduce female farmers’ burdens, vulnerability, and risk of violence in rural areas, and help farmers (especially women) to save more time and energy; in addition to a picture of a one-kg package of white maize flour. The social (treatment 2) information stated that:

In the Maniema province of DRC, CA has been applied through farming practices involving crop rotation, no-tillage, and mulching. CA has the potential to reduce or will reduce farmers' workload burdens and vulnerability in the DRC. For female farmers, CA allows them to farm closer to their homes, which can (or has been shown to) reduce the incidence of harassment and risk of violent assaults (Mulimbi et al., 2019). Further, CA has the potential to save time and energy as labor requirements decrease (Catholic Relief Services [CRS], 2015).

Participants in treatment 3, i.e., the Environmental benefits of CA treatment (*Env*), had the FAO's definition of CA plus a short paragraph stating how CA could improve soil quality and could help to reduce deforestation; in addition to a picture of a one-kg package of white maize flour. The environmental information, treatment 3, stated that:

In the Maniema province, CA has been applied through farming practices involving crop rotation, no-tillage (or at least minimum tillage), and mulching. CA can enhance soil quality and has the potential to reduce deforestation in the DRC (CRS, 2015). In 2017, the DRC lost 1.46 million ha of forest cover through deforestation (Weisse & Goldman, 2018).

The second section of the survey questionnaire incorporated a double-bounded dichotomous choice (DBDC) contingent valuation, the CV method used to determine consumers' WTP for white maize flour produced under CA. The DBDC can mimic the reality of urban open markets in the DRC, where customers are exposed to multiple prices and attributes for the same commodity (Alberini & Cooper, 2000). The DBDC approximates how consumers make choices in a market as they choose to buy or not (Loomis, 2011). DBDC demands little explanation because respondents are asked to state their purchasing preferences in reaction to predetermined prices (Durand-Morat et al., 2016). While other methods use predetermined prices, Domonko et al. (2018) used both a DBDC as well as a choice experiment. We chose the DBDC due to its ease of explanation in a market setting.

In an attempt to mitigate potential hypothetical bias, this study integrated a cheap talk script into the second section of the survey questionnaire and administered it prior to the DBDC. A similar technique has been used in Aprile et al. (2012), Van Loo et al. (2011), Sanjuan et al. (2012), and Lee et al. (2015).

Table 2.1. Bounded prices for one kilogram of white maize flour (in CDF)

Prices		**Responses**			
Starting (B_i)	Bounded	Yes – Yes	Yes – No	No – Yes	No – No
1,100	Lower (B_l)	1,300	1,100	900	-
	Higher (B_h)	-	1,300	1,100	900
1,300	Lower (B_l)	1,500	1,300	1,100	-
	Higher (B_h)	-	1,500	1300	1,100
1,500	Lower (B_l)	1,700	1,500	1,300	-
	Higher (B_h)	-	1,700	1,500	1,300
1,700	Lower (B_l)	1,900	1,700	1,500	-
	Higher (B_h)	-	1,900	1,700	1,500
1,900	Lower (B_l)	2,100	1,900	1,700	-
	Higher (B_h)	-	2,100	1,900	1,700

Note: 1 US Dollar (USD) = 1,646 Congolese Franc (CDF) at the time of the field survey in Bukavu, DRC (Banque Centrale du Congo [BCC], 2019).

In the DBDC, each subject was asked if he/she would be willing to pay a randomized price (Table 2.1) for white maize flour. Then, a follow-up bid was asked, and here the follow-up bid was lower if the person answered “No,” to the starting bid and higher if the person answered “Yes” (Patterson, 1993). The prices for white maize flour used in the DBDC were built around the average market price for one kg flour in Bukavu at the time of the survey, 1,500 Congolese Francs (CDF) [about USD 0.91] found from the *Cellule d’Analyses des Indicateurs de Développement* database (Cellule d’Analyses des Indicateurs de Développement [CAID], 2018). Prices were increased and decreased by 200 CDF twice over. The resulting options provided five starting prices (1,100 CDF, 1,300 CDF, 1,500 CDF, 1,700 CDF, and 1,900 CDF) with the starting bid price randomized for each participant in the DBDC. Table 2.1 illustrates the configuration of bounded prices based on bid responses.

Surveyors recruited participants from six different local open markets in Bukavu, DRC. Participants were recruited using convenience sampling within each market. Although convenience sampling has limitations, selecting consumers who were actively shopping for food was the justification for having chosen a convenience sample. Although this survey was not a random sample whereby each member of the population had an equal probability of being selected, most of the markets surveyed consist of consumers who are pretty representative of the Bukavu population. The authors recognize the limitations of convenience sampling, but given the difficulty of recruiting a randomized representative sample in a low-income country, it was the method that was implemented. Convenience samples can provide useful information regarding preliminary trends for novel studies such as this one. The team of four surveyors recruited 638 participants over four weeks in June 2019. After cleaning (for incomplete and survey pretest responses), the analysis dataset included 599 participants. Participation in the survey was voluntary, and, in the beginning, the instructions clearly stated that there was no compensation. Participants were informed about the study's implications, and their consent to participate was collected. Individuals who participated were required to be at least 18 years old and consume white maize flour at least once per week. Participants were randomly assigned to treatment groups that varied the type of information they read about CA following the introductory survey instructions. The survey was designed to collect quantitative responses elicited from the DBDC and qualitative responses (converted to quantitative responses through the use of binary or other numeric scaling) elicited from questions after the DBDC regarding demographic and occupational data and questions about deforestation and the role of women in agriculture.

This study explains the participants' WTP using the randomly assigned informational treatments, integrates a series of independent demographics as covariates, and runs a group analysis. The demographic variables are listed in Table 2.2 The inclusion of covariates in WTP analysis meets policymakers' frequent need to know potential WTP differences in the targeted population (Carson & Hanemann, 2005).

Table 2.2. Study participants' characteristics

Explanatory variables	**Description**	**Hypothesized signs for WTP**
College	Participant has a university education, = 1 if Yes, = 0 if No	+
Woman	Female participant, = 1 if Yes, = 0 if No	+
Male	Male participant, = 1 if Yes, = 0 if No	+/-
Farmer	Involved in farming, = 1 if Yes, = 0 if No	+
Non-Farmer	Not involved in farming, = 1 if Yes, = 0 if No	+/-
Household size	Household size = total number of family members living in the participant's home	+ / -
Age	Participant's age groups: less than 25 years, 25 – 34 years, and 35 years and more	+ / -

This study used the *Survival* package (Therneau, 2015; Therneau & Grambsch, 2013) in R Studio (R version 3.5.1) to perform the interval regression modeling with robust error estimation.

2.4. Results and Discussion

Approximately half of the respondents were between 25 and 34 years old, 41% were 35 years and above, while 12% were under 25. This sample selection process is consistent with the last country's Demographic Health Survey, indicating that in 2013 the large majority of DRC's urban population was 25 years and older (MPSMRM et al., 2014). Our sample consisted of 75% female respondents. This unbalanced gender figure makes intuitive sense in the DRC since women conduct the majority of food shopping. Among the respondents, 11% stated their primary occupation to be farming. Agriculture is the activity of 70.7% of women and 45.6% of men in South Kivu province (MPSMRM et al., 2014), and it is possible to find urban citizens who are still farming in rural areas. Additionally, 24% of respondents had a college degree. Table 2.3 describes the sample's characteristics in numbers and disaggregates for each of the study treatments. Table 2.3 illustrates that the four treatment groups were similar in demographic characteristics. The chi-square test and analysis of variance yielded no statistical difference amongst participants across the four experimental groups (P > 0.10) in Table 2.3.

Table 2.3. Descriptive statistics aggregated by treatment

Variable	**Categories**	**Control**	***Def* *Treatment 1***	***Env* *Treatment 2***	***Soc* *Treatment 3***	**Full sample**
College[a]	% of Yes	21.7%	24.7%	27.2%	22.3%	24%
Woman[a]	% of Yes	78.3%	73.5%	77.6%	69.6%	75%
Farmer[a]	% of Yes	8.0%	11.4%	10.2%	14.9%	11%
Household size[b]	Average	7.0	6.7	6.9	6.6	6.8
Age[a]	Between 25–34	47.1%	49.4%	46.9%	46.6%	47%
	35 and over	37.0%	42.2%	42.9%	40.5%	41%
	Less than 25	15.9%	8.4%	10.2%	12.8%	12%
Observations		138	166	147	148	599

Notes:
- Chi-square test reported no statistical difference for this variable across treatments (p > 0.1)
- Analysis of variance reported no statistical difference across treatments (p > 0.1)

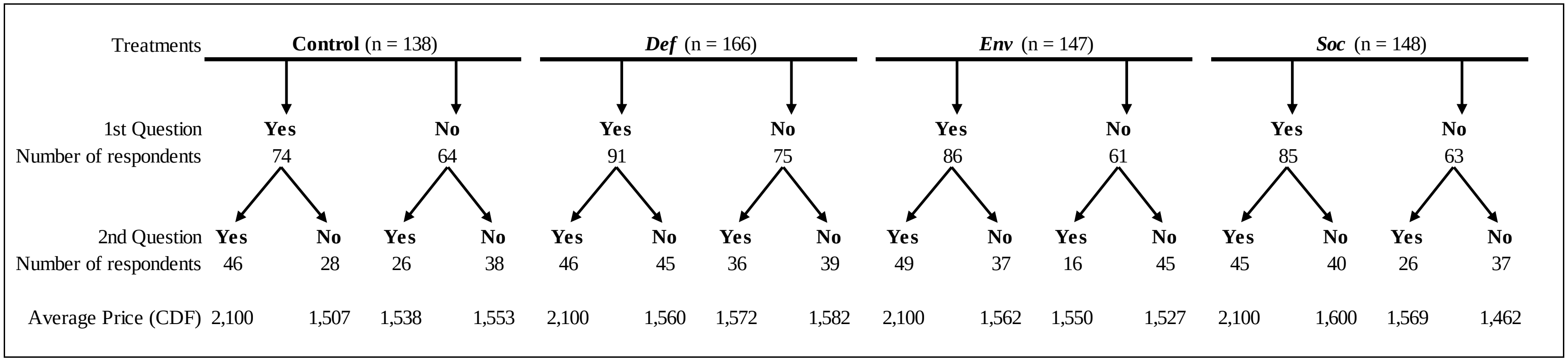

Figure 2.1. Responses to double-bounded dichotomous-choice contingent valuation

Figure 2.1 shows the responses to the DBDC model. The majority of respondents chose the initial higher price for each treatment (CA definition, environmental benefits, and social benefits). Further, after being presented with a higher price in the follow-up question, more than half of the sample continued to choose the higher price for the white maize flour produced with CA. These results would seem to imply that consumers are open to the idea of CA.

A series of questions asked at the end of each survey found the following: 24% of participants had already heard about CA, 86% are aware of deforestation in the DRC, 94% are aware of violence against rural women in the DRC, and 72% are aware of the contribution of women to agricultural labor in the DRC. These results would seem to indicate that maize consumers in Bukavu were at least aware of the social (women in agriculture and violence against women) and environmental (deforestation) issues in the DRC.

Table 2.4 reports the results of nine interval regression models, starting with estimating consumers' WTP on the full sample in the first column (Model 1), followed by subsets of the full sample by gender and occupation. The estimations reported in Table 2.4 focus on the informational treatments (*Def*, *Soc*, *Env*, and the control). Model 1 was estimated on the full study sample and yielded non-significant treatment effects ($P > 0.1$), as shown in Table 2.4. Thus, there was no significant effect of any information set on WTP from a WTP standpoint. Models 2 to 9 in Table 2.4 examine subsets of the data: *farmer*s, non-*farmer*s, *female, male, female farmers*, male *farmers*, female non-*farmers*, and male non-*farmers*, respectively.

Looking at individual subsets, Model 2 (those participants who identified as farmers) in Table 2.4 suggests that when provided information about the social benefits of CA (*Soc, treatment 2*), a participant who self-identified as a farmer is willing to pay 206 CDF ($P < 0.05$) more for CA-produced white maize flour compared to farmers who received no information about CA. This result suggests that farmers are willing to pay a 15.3% premium for CA-produced white maize flour when exposed to CA's social benefits.[1] Similar to the Chen et al. (2019) study, we report actual WTP (in Congolese Francs) for each treatment and subgroup in Table A.2.3. These findings indicate that rural women's safety raised by this study appears to be something that farmers are willing to pay to mitigate. Even though the general public is aware of the issue (94% of those surveyed said they were aware of the issue), this social issue is prioritized only by farmers among the urban white maize consumers, as Model 3 (non-farmers) in Table 2.4 indicates non-farmers are not willing to pay a premium under any information sets.

Table 2.4 also estimates how male and female farmers differ when valuing CA. Model 6 (female farmers) in Table 2.4 suggests that providing the technical definition of CA (*Def, treatment 1*) and the social benefits of CA (*Soc, treatment 2*) to female farmers increases their WTP for CA-produced maize flour. The premiums estimated for each *Def* (232 CDF) and *Soc* (382 CDF) are statistically significant (P > 0.05) within each subgroup. Hence, these results suggest that female farmers are willing to pay a 30.7% premium for CA-produced white maize flour when exposed to CA's social benefits and an 18.7% when informed about CA's FAO definition. These findings are intuitive as female farmers are the most likely to benefit from CA as they are the largest percentage of agricultural workers and have the largest social benefits to gain through CA adoption. Interestingly, there was no significance (P > 0.1) for CA's

[1] Given the small sample size for some subsets a Minimum Detectable Effects (MDE) test was conducted for each subset. Specifically, we acknowledge that the small size of our subsamples of farmers, female farmers, and male farmers for our results in columns (2), (6), and (7) in Table 2.4 could lead to Type-II errors. These MDEs were calculated conservatively based on the sample size of the control group and the smallest of the treated groups for each subsample. Our calculation assumed 80% power for a 90% confidence interval using a one-sided hypothesis test with an unbalanced proportion of treated and control groups. The results were 202.14 CDF, 220.14 CDF, and 53.9 CDF, respectively, for farmers, female farmers, and male farmers' subgroups. As percentages of control group WTPs, these ex-post calculations suggest that these samples were not designed to detect impacts of less than 14.9%, 17.7%, and 3% of the farmers', female farmers', and male farmers' WTP, respectively

environmental benefit amongst female farmers. The seemingly odd results of Model 7 (male farmers) in Table 2.4 suggest that providing information on CA's environmental benefits (*Env*) to male farmers negatively affects their WTP for CA-produced maize flour. This obtuse result is likely the result of a small subset of the total sample identifying as male farmers. The subsets of male farmers have only three male farmers in the control group, seven in the *Def* group, eight in the *Soc* group, and five in the *Env* group, and thus, the results need to be interpreted with caution. Alternative specifications were estimated and presented in Table A.2.1 with similar effects to those reported in Table 2.4; thus, Table 2.4 contains our preferred models.

Given the number of sub-sample analyses presented in Table 2.4, this study's approach accounted for multiple hypothesis testing issues usually illustrated through a higher chance for false positives (Type-I error). Specifically, p-value adjustment was performed on our model specification in Table 2.4 using Benjamini – Hochberg (BH) procedure. The results of p-value adjustments for the informational treatment *Soc* in Model 6 and *Env* in Model 7 did not change their statistical significance under the BH method, while *Soc* in Model 2 statistical significance changed to a 10% level (Table A.2.2). However, alternative adjustments using Bonferroni and Benjamini – Yekutieli (BY) methods were consistent with BH for the first two models, while the latter became insignificant (Table A.2.2).

Taken together, the findings in Table 2.4 suggest the following. First, CA matters to only participants who identify as farmers and only with specific information sets (*Soc* and *Def*). White maize flour consumers who self-identified as farmers are willing to pay a premium for CA-produced maize when presented with CA's social benefits (reduced sexual violence against women). Second, female farmers were estimated to pay a premium for CA's definition and CA's social benefits but not the CA's environmental benefits. Third, CA's social aspect (sexual violence against women) appears to be more of a WTP driver for consumers than CA's environmental benefits (deforestation). Finally, non-farmers appear to be indifferent regarding the WTP associated with CA's benefits, regardless of the information they have been provided.

Table 2.4. Interval regression modeling results

	Dependent variable: WTP								
		Occupation		Gender		Occupation by Gender			
	All	Farmer	Non-Farmer	Female	Male	Female farmers	Male farmers	Female non-farmers	Male non-farmers
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Def treatment 1	13.490	159.111	1.694	-11.389	89.969	231.970**	-46.323	-29.950	108.630
	(35.648)	(96.650)	(37.182)	(39.698)	(79.839)	(114.283)	(86.624)	(40.159)	(88.907)
Env treatment 2	7.923	-6.328	11.756	-17.552	99.071	93.290	-270.846***	-27.286	157.767
	(40.831)	(121.019)	(42.031)	(43.905)	(100.139)	(164.135)	(86.578)	(43.835)	(110.508)
Soc treatment 3	-0.836	206.060**	-21.578	-8.206	27.569	381.785***	-185.555	-47.227	61.659
	(40.390)	(103.643)	(42.809)	(45.207)	(87.991)	(119.278)	(125.863)	(47.320)	(96.872)
Constant	1,546.637***	1,352.603***	1,564.876***	1,556.645***	1,514.218***	1,243.092***	1,615.779***	1,583.608***	1,500.571***
	(28.327)	(70.689)	(29.525)	(30.455)	(67.232)	(74.730)	(18.434)	(30.720)	(74.894)
Observations	599	67	532	447	152	44	23	403	129
Log Likelihood	-679.511	-76.484	-597.327	-488.238	-188.997	-50.542	-22.559	-430.297	-163.196
Chi^2 (df = 3)	0.200	5.270	0.726	0.174	1.896	7.580*	3.151	1.140	2.851

Notes:

- Model (1) is the pooled Model using the whole data sample, while Models (2) to (9) are based on sub-samples.
- *p < 0.1; **p < 0.05; ***p < 0.01

2.5. Summary and Conclusions

Conservation agriculture could help alleviate deforestation, a major environmental threat in the DRC, through increased soil health of existing agricultural land, reducing the need for slash and burn. Further, CA has the potential to lower domestic violence against women, as there would be a reduced need to farm further away from home if existing agricultural lands were made more fertile. While the overwhelming majority of the participants in this study thought deforestation was an important issue in the DRC (86%) and that women in agriculture were at greater risk of assault than those in urban areas (94%), this *a priori* knowledge did little in the way of eliciting premiums for CA and its potential to reduce both issues. This study's key finding seems to confirm that most consumers in LICs are likely more concerned with the price of a commodity rather than attributes associated with its production. However, our study is unique in that an additional key finding is that people believe both violence against women in agriculture and deforestation are issues plaguing the DRC but still are not willing to pay a premium for its potential reduction.

The only premiums identified for CA maize were for participants who presented themselves as farmers. Having a positive reaction from farmers in urban DRC has two likely explanations. First, it is possible that farmers wanted to highlight that CA should be worth a premium. This scenario is unlikely, though, as the only information which elicited a premium was the social aspect (reducing violence against women). If farmers were simply trying to highlight that CA should garner a premium regardless, we should have detected significance for CA attributes. Most likely, those who identified as agricultural producers (specifically female farmers) were intimately aware of the dangers that farming far from home poses and thus saw the social value associated with CA. Interestingly no subgroups of participants were willing to pay a premium for CA and its potential ability to reduce deforestation. Even those participants who were given the environmental information set (of which 83% recognized deforestation to be an issue in DRC) were not willing to pay a premium for CA. One caveat about the results of this study is that they are drawn from a relatively small sample size that used convenience sampling. Future research on WTP for CA in the DRC should focus on a more robust sampling technique that ensures a representative sample which could mitigate the unbalanced and small sample size of subsets present in this study.

While our results seem to indicate that agricultural producers are willing to pay a premium for CA to reduce the potential violence against female agricultural workers, the issue becomes that producers are the least likely (albeit for semi-subsistence farmers) group to be market consumers for agricultural goods produced with CA. This study would seem to indicate that if groups (NGOs, universities, local and federal governments) want to increase CA adoption in the DRC, it will likely need to come via increased yields or reduced costs before the farm gate and not premiums beyond the farm gate. Crop yields are problematic as, in their meta-analysis of CA in SSA, Corbeels et al. (2020) conclude that the practice of CA is not a technology that allows smallholder farmers to overcome low crop productivity and food insecurity in the short term. Such a conclusion (Corbeels et al., 2020), coupled with the lack of WTP, would indicate that policy should be focused on increasing funding to enhance CA productivity such that CA becomes more profitable (and thus result in higher adoption) for agricultural producers. Further, this study's results can signal to stakeholders that if the global community is serious about mitigating climate change and preserving rainforests, the international community may fund the reduction of deforestation in LICs, as their citizens are often more worried about short-run issues like food security. This study shows that consumers in the DRC are informed of the issues (deforestation and violence against women) and believe that these issues pose a threat but do not want to pay to reduce them. The international community can use this study to help reduce, ideally eliminate, violence against women and deforestation by informing global stakeholders that they need to play a role and not only look for domestic solutions to international problems.

This study has highlighted that urban consumers in Bukavu DRC are not likely to pay a premium for agricultural goods produced with CA, although they can internalize the benefits CA would bring. This research is a first attempt at eliciting consumer demand for agricultural commodities produced under CA in the DRC. Given the sample size (both in observations and geographical distribution), additional research is needed to draw large-scale policy conclusions for the DRC in its entirety. Future research needs to focus on the potential supply-side benefits of CA agriculture in the DRC. That is, what are the potential economic benefits to producers via CA adoption, and can these benefits offset any increased costs. Further research needs to be conducted with female agricultural producers in the DRC and assess what/if any barriers to the adoption of CA exist. Future surveys should focus on relevant farm, institutional and locational characteristics. Issues like deforestation and sexual violence against women are complex with many layers, and a single solution like CA is unlikely to alleviate them. If research shows that producers can increase profitability through CA adoption, CA could be a tool that has the positive externality of reducing two of the most important issues in the DRC today.

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Appendices

Table A.2.1. WTP analysis involving treatments, covariates, and gender subgroups samples.

	Dependent variable: *WTP*				
	(1)	(1a)	(1b)	(1c)	(1d)
Def	13.490	16.227	-0.004	-39.832	120.781
	(35.648)	(35.777)	(37.901)	(40.012)	(90.492)
Env	7.923	8.816	9.351	-40.644	170.372
	(40.831)	(40.391)	(42.241)	(43.670)	(106.759)
Soc	-0.836	3.341	-25.120	-54.736	70.478
	(40.390)	(40.515)	(43.276)	(47.142)	(95.594)
College	-	-43.034	-43.813	-33.450	-57.420
		(37.640)	(37.325)	(48.586)	(61.411)
Woman	-	-34.876	-36.327	-	-
		(32.972)	(32.834)		
Farmer	-	-108.390^{**}	-237.990^{***}	-372.631^{***}	110.528
		(43.462)	(73.202)	(73.787)	(95.698)
Household size	-	5.599	5.435	4.241	6.281
		(4.837)	(4.816)	(5.569)	(9.134)
Age ≥ 35	-	38.591	40.628	49.449	25.259
		(28.753)	(28.645)	(31.020)	(63.421)
Age < 25	-	-4.447	-0.234	-39.539	20.659
		(41.088)	(41.082)	(48.451)	(78.617)
Farmer x ***Def***	-	-	171.728^{*}	282.373^{**}	-130.955
			(101.063)	(116.698)	(140.174)
Farmer x ***Env***	-	-	9.457	147.846	-382.797^{**}
			(126.340)	(159.760)	(168.055)
Farmer x ***Soc***	-	-	246.578^{**}	443.741^{***}	-226.931
			(108.289)	(116.175)	(182.090)
Constant	$1{,}546.637^{***}$	$1{,}539.883^{***}$	$1{,}552.058^{***}$	$1{,}554.580^{***}$	$1{,}459.805^{***}$
	(28.327)	(60.002)	(60.270)	(49.661)	(117.320)
Observations	599	599	599	447	152
Log Likelihood	-679.511	-673.346	-670.231	-477.615	-185.966
chi^2	0.200	12.529	18.760^{*}	21.420^{**}	7.957
	(df = 3)	(df = 9)	(df = 12)	(df = 11)	(df = 11)

Note: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$

Table A.2.2. Multiple Treatments Evaluation outcomes.

Subgroups	**Informational treatments**	**p-value**	**adjusted p-values**		
			Bonferroni	BY	BH
All	*Def*	0.705	1	1	0.983
(Model 1)	*Env*	0.846	1	1	0.983
	Soc	0.983	1	1	0.983
Farmers	*Def*	0.1	0.499	0.285	0.125
(Model 2)	*Env*	0.958	1	1	0.958
	Soc	0.047**	0.234	0.178	0.078*
Female Farmers	*Def*	0.042**	0.212	0.121	0.053*
(Model 6)	*Env*	0.57	1	1	0.57
	Soc	0.001***	0.007***	0.005***	0.002***
Male Farmers	*Def*	0.593	1	1	0.593
(Model 7)	*Env*	0.002***	0.009***	0.007***	0.003***
	Soc	0.14	0.702	0.401	0.176

Notes:

- BY = Benjamini – Yekutieli method, BH = Benjamini – Hochberg method.
- p > 0.1; *p < 0.1; **p < 0.05; ***p < 0.01

Table A.2.3. Estimated WTP per respondents' subgroups and treatment groups (in Congolese Francs)

Subgroup	Control	*Def* Treatment 1	*Env* Treatment 2	*Soc* Treatment 3
Pooled data	1,546.6	1,560.0	1,554.6	1,545.8
Farmer	1,352.6	1,511.7	1,346.3	1,558.7**
Non-farmer	1,564.9	1,566.6	1,576.6	1,543.3
Female	1,556.6	1,545.3	1,539.1	1,548.4
Male	1,514.2	1,604.2	1,613.3	1,541.8
Female farmers	1,243.1	1,475.1**	1,336.4	1,624.9***
Male farmers	1,615.8	1,569.5	1,344.9***	1,430.2
Female non-farmers	1,583.6	1,553.7	1,556.3	1,536.4
Male non-farmers	1,500.6	1,609.2	1,658.4	1,562.2

Notes:

- Estimates derived from interval regression results in Table 2.4
- *p < 0.1; **p < 0.05; ***p < 0.01

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To:	Willy Byamungu Mulimbi
From:	Douglas James Adams, Chair IRB Committee
Date:	05/21/2019
Action:	**Exemption Granted**
Action Date:	05/21/2019
Protocol #:	1905196605
Study Title:	Assessing the willingness to pay for maize flour produced using conservation agriculture.

The above-referenced protocol has been determined to be exempt.

If you wish to make any modifications in the approved protocol that may affect the level of risk to your participants, you must seek approval prior to implementing those changes. All modifications must provide sufficient detail to assess the impact of the change.

If you have any questions or need any assistance from the IRB, please contact the IRB Coordinator at 109 MLKG Building, 5-2208, or irb@uark.edu.

cc: Lawton Lanier Nalley, Investigator
Grant Howard West, Investigator

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The IRB protocol number 1905196605 (https://research.uark.streamlyne.org/kew/DocHandler.do?command=displayDocSearchView&docId=135192), Principal Investigator Willy Byamungu Mulimbi , has had the action "Protocol Exempt Approval" performed on it.
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FYI (DismissMessage.form?messageDeliveryId=39625&notifId=7486&command=displayActionListInlineView&action=fyi&standaloneWi

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CHAPTER 3: CONSERVATION AGRICULTURE ASSISTS SMALLHOLDER FARMERS AND THEIR ECOSYSTEM IN THE DEMOCRATIC REPUBLIC OF THE CONGO

Abstract

Conservation agriculture (CA), a sustainable farming practice combining no or minimum soil disturbance, crop diversification, and soil cover, can benefit humans and the biophysical environment. However, less than half of Sub-Saharan African countries implement CA. The adoption of conservation agriculture in Sub-Saharan Africa (SSA) is primarily challenged by the location-specific nature of CA's outcomes, such as crop yields, and the variability of such outcomes in magnitude and direction. Research and field trials on CA adaptation to soils and agroecological conditions are vital for disseminating CA in SSA. This study investigated variation in CA effects in smallholder farming in the province of Maniema in the Democratic Republic of the Congo (DRC). A mixed-effects modeling framework was used to examine soil chemical characteristics, biodiversity, and crop yields in Maniema, DRC's savannah and forest ecosystems, where CA was implemented and compared to conventional agriculture. Results suggest that CA increases earthworms' population, soil available P and K concentrations, and cowpea (*Vigna unguiculata*) yields. Soils under CA had 6.5 times more earthworms ($p < 0.001$), 23 and 10% greater concentrations of soil P and K ($p < 0.05$), respectively, and 100% greater cowpea yield ($p < 0.001$) than soils under conventional agriculture. Measured across all sites, CA and conventional cowpea yields had coefficients of variation of 25 and 16%, respectively. However, CA's yield variability was offset by two times greater cowpea yields per hectare, on average, than conventional cowpea yields. The practice of CA contributes to soil health and food security in the DRC. Further long-term research is needed to understand CA impacts on crop yields in SSA.

Keywords: *Conservation agriculture, Democratic Republic of the Congo, Soil health, Soil biodiversity, Smallholder farming, Ecosystem*

3.1. Introduction

The Democratic Republic of the Congo (DRC) is endowed with arable land and freshwater resources but is unable to achieve food security (Marivoet, Ulimwengu, & El Vilaly, 2018). The DRC agriculture sector faces several challenges, including, and not limited to, insufficient domestic agricultural production, limited access to inputs, infrastructure issues (such as deteriorated and unmaintained roads), lack of extension and market services to assist farmers, and exposure to risks (such as floods, pests, and diseases) that hinder DRC's agriculture contribution to mitigating food insecurity and malnutrition (Marivoet et al., 2018; World Bank, 2018). Like many other countries in Sub-Saharan Africa (SSA), the DRC is also not spared from unsustainable cultivation practices such as slash-and-burn and continuous soil tillage that lead to low food productivity per capita, soil nutrients decline, and degradation of the agricultural lands (Ehui & Pender, 2005). Implementing sustainable agricultural practice in the DRC should improve crop production while taking care of the environment and subsequently enhancing smallholder farmers' household food security. Understanding the effects of a sustainable agricultural practice, such as conservation agriculture, in smallholder farming helps to guide agricultural and environmental policymaking and potential development donors' interventions in the DRC.

Only 10% of the estimated 80 million hectares of the DRC's arable land is actually used for agriculture and mostly under subsistence agricultural production (World Bank, 2018). Smallholder subsistence farming involves 62% of the DRC population, and 70% of the smallholder producers are women and operate in rural regions (World Bank, 2018). Smallholder farming in developing nations is usually described as crop production occurring on less than two hectares of land (Food and Agriculture Organization of the United Nations [FAO], 2010). For the majority of DRC smallholder farmers, land cultivation is associated with regular, manual hoeing of the soil. In the Eastern DRC, for instance, the hoe has a significant social value, making tillage a practice embedded in the culture (Arnoldussen, 2015). Despite being restorative for tropical soils, tillage methods accelerate soil erosion, deplete soil organic matter and fertility, and decrease soil biodiversity (Lal, 1993). Soil degradation resulting from erosion, nutrients, and fauna losses culminate in crop yield decline (Lal, 2009). Trial studies in Nigeria reported a 7 to 14% and 24 to 54% reduction in crop yield for cowpea and sorghum (*Sorghum bicolor*), respectively, due to soil tilling to a depth of 20 and 40 cm (Obalum, Amalu, Obi, & Wakatsuki, 2011; Olaoye, 2002). Tillage is also energy-intensive for DRC rural women farmers while, according to the World Bank (2018), women in the DRC are still facing unequal treatment concerning education at a younger age and land ownership, and 52% have faced physical violence, including rape. Considering that smallholder farmers can minimize tillage and still be better-off (Osewe, Mwungu, & Liu, 2020), one can argue that DRC women could use the time and energy saved by avoiding tillage to seize off-farm opportunities such as education on farming business or income-generating activity.

Furthermore, tillage in the DRC is often combined with the land-clearing technique of slashing then burning vegetation to constitute the slash-and-burn agricultural practice, which Sanchez et al. (2005) describe as shifting cultivation when the length of the fallow period exceeds 20 years. Slash-and-burn agriculture and shifting cultivation are common in the DRC's subsistence farming (Ministère de l'Environement Conservation de la Nature et Tourisme [MECNT], 2012). Studies indicate that agriculture (via shifting cultivation and slash-and-burn practices) is among the primary drivers of deforestation in the DRC (Ickowitz, Slayback, Asanzi, & Nasi, 2015; Turubanova, Potapov, Tyukavina, & Hansen, 2018; Tyukavina et al., 2018).

Slash-and-burn does not replenish soil nutrients removed by the crops (FAO, 2022). Tanzito et al. (2020) determined that in the territory of Faradje, DRC, a typical smallholder farmer producing paddy rice (*Oryza sativa*), maize (*Zea mays* L.), cassava (*Manihot esculenta*), peanut (*Arachis hypogaea*) and beans (*Phaseolus vulgaris* L.) on 0.81 hectares of land during two cropping seasons under slash-and-burn agriculture earns annually 189 US Dollars. This revenue keeps Faradje's farmers relying solely on crop production under the 1 US Dollar-per-day poverty line and subsequently fails to contribute to their households' food security (Tanzito et al., 2020). Smallholder farmers in the DRC are trapped in a situation of vulnerability as they rely on unsustainable farming options and do not have a full understanding of the effects of their cultivation methods on the environment. More precisely, DRC smallholder farmlands are undergoing degradation that farmers could handle with farming managements that take care of their soils while providing better crop yields. Following Lal's (2021) suggestion on reconciling agricultural productivity and the need to improve the environment by restoring soil health, conservation agriculture is an option for smallholder subsistence farming in the DRC.

Conservation agriculture (CA) is a cultivation approach that can help DRC's smallholder agriculture to abate food insecurity and hunger. Conservation agriculture is a sustainable practice that enhances productivity and maintains natural base resources (FAO, 2020). The implementation of CA on a farm is based on three interrelated principles: (1) the absence of soil disturbance or at least minimal soil disruption, (2) the maintenance of a permanent soil cover, and (3) the integration of crop rotation to diversify plant species (FAO, 2020). These CA principles need to be jointly applied to comply with CA's definition and increase rainfed crop productivity (Kassam, Friedrich, & Derpsch, 2019; Pittelkow et al., 2015). In the DRC's agricultural sector, CA could be a response to what Giller et al. (2021) call the soil health and biodiversity crisis, exacerbated by smallholder farmers' continuous tillage and slash-and-burn methods. Early promotion of CA in the DRC, first in Maniema province, to help smallholder farmers' communities cope with food insecurity and improve their natural resources management has also shown that CA contributes to empowering rural women (Mulimbi, Nalley, Dixon, Snell, & Huang, 2019).

Conservation agriculture can treat soil degradation and subsequently assist in reducing the complex issue of agricultural productivity in the DRC. A critical assessment is required to document the conditions under which CA works for the farmer (Giller, Witter, Corbeels, & Tittonell, 2009). Conservation agriculture generates multiple socioeconomic, agronomic, and environmental benefits (Food and Agriculture Organization of the United Nations [FAO], 2019). However, both the implementation and the adoption of CA are challenging due to the limitations of CA. Conservation agriculture is knowledge-intensive for the farmers, can interfere with livestock feeding and crop residue sales, has location-specific crop yields benefits, and takes time to increase crop yields (Corbeels et al., 2014; Corbeels, Naudin, Whitbread, Kühne, & Letourmy, 2020; Giller et al., 2009; Valbuena et al., 2012). Thus, the expansion and the adoption of CA require evidence of its adaptation to site-specific conditions (Gómez-Macpherson, Gómez, Orgaz, Villalobos, & Fereres, 2016; Palm, Blanco-Canqui, DeClerck, Gatere, & Grace, 2014); making this report unique for smallholder subsistence rainfed farming of Maniema province in the DRC.

Conservation agriculture has already been promoted in various parts of SSA to replace farming practices, such as slash-and-burn agriculture in the DRC. Research on CA adaptation in SSA smallholder farming and its challenges and drivers is needed as CA adaptation is a prerequisite for CA adoption by smallholder producers (Bouwman, Andersson, & Giller, 2021;

Osewe et al., 2020; Rodenburg, Büchi, & Haggar, 2021). An investigation of the effects of CA on farmer-related or site-specific factors contributes to reflecting CA adaptation to specific socioeconomic, agroecological, and climatic conditions and locations. Research studies have shown that soil quality improvement resulting from CA implementation is a statistically significant factor in smallholder farmers' adoption decisions (Lalani et al., 2016; Mugandani & Mafongoya, 2019; Ngwira et al., 2014). In Zimbabwe, Mugandani & Mafongoya (2019) indicated that, among CA adopters, 82% implemented CA because CA reduces soil erosion, and 72% chose CA for its land restoration potential. Using a quantitative socio-psychological approach to explore farmers' decision to adopt CA in Cabo Delgado, Mozambique, Lalani et al. (2016) showed that smallholder farmers' perception of soil quality improvement explains their intention to continue using CA in the next twelve months. The CA literature in the SSA smallholder farming communities also reports multiple ecosystems services accredited to CA, such as enhanced food security (Mango, Siziba, & Makate, 2017; Nyanga, 2012), increased financial profitability (Mupangwa, Mutenje, Thierfelder, & Nyagumbo, 2016; Ngwira, Kabambe, Simwaka, Makoko, & Kamoyo, 2020), and adaptation to drought stress (Thierfelder et al., 2015).

Several CA studies based on research-station or on-farm experiments highlighted changes in soil properties such as soil fauna and nutrients and crop yields in smallholder farming conditions. Eze et al. (2020) reported that CA improved soil hydraulic properties and structure during a 12-year long-term trial in Malawi. Results suggested that, with CA, there were increases of 5 to 15% in total porosity, 0.06 to 0.22 cm/min in saturated hydraulic conductivity, 3 to 7% in fine pores for water storage, and 3 to 6% in plant-available water storage (Eze et al., 2020). Using field trials at research stations and in farmers' fields in Ghana on lands that had been under fallow for ten years, Naab et al. (2017) demonstrated that CA preserved the soil even though maize (*Zea mays* L.) yields from CA were 26 to 46% lower than from conventional tillage on farmers' fields. After four years (2010 – 2013) of CA implementation, results suggested that soil organic carbon decreased by 24% under CA and 38% under conventional tillage, while total soil nitrogen decreased by 7 and 50%, respectively (Naab et al., 2017). However, CA was more profitable, with 20 to 29% less cost to produce maize or soybean (*Glycine max* L. Merril) than conventional tillage (Naab et al., 2017). In a series of trials conducted from 2011 to 2013 in Zambia, Muoni et al. (2019) reported that, compared to conventional tillage, CA led to 80% greater maize yields but also richer soil biodiversity. With average counts of 20 and 300/m^2, respectively, earthworms and termites were more abundant under CA than conventional tillage (Muoni et al., 2019). In two smallholder farmers' communities in Malawi, Ngwira et al. (2012) recorded 38% greater farmer returns per hectare on maize under CA and 51% when maize was intercropped with pigeon pea (*Cajanus cajan*). In addition to greater returns, another study in Malawi reported 2.3 ton ha^{-1} of maize more under CA compared to conventional tillage and improved biodiversity displayed by earthworm counts at 30 cm soil depth that was five times greater per square meter under CA than conventional tillage (Ngwira et al., 2013).

This research is about CA adaptability to the ecosystems of the DRC. The DRC farmers' population size and the country's soil heterogeneity and agroclimatic conditions justify this research's aim to supply the global agricultural community with evidence of CA performance in smallholder subsistence farming in the DRC. In SSA, it has been demonstrated that the influence of CA on crop yields, for instance, depends on agroecological and soil characteristics (Nyagumbo, Mupangwa, Chipindu, Rusinamhodzi, & Craufurd, 2020; Rusinamhodzi et al., 2011). However, no CA study has investigated potential CA effects on near-surface soil properties and crop production in the DRC. Considering the DRC's various agroecological and soil conditions, little is known about how CA can sustainably assist in curbing DRC's low agricultural productivity. This research analyzes the effects associated with CA on soils and crop yields within smallholder farmers' communities in a context of rainfed agricultural production where agrochemicals such as fertilizers and pesticides are absent as they are not available and farmers cannot afford them. This research used cowpea (*Vigna unguiculata*) to investigate CA's effects on yields and assess changes in soil chemical properties and soil biodiversity in two of DRC's ecosystems, the savannah and the forest, differing by their local soil, climatic and agroecological conditions.

Therefore, the objectives of this study were to (i) evaluate the change in soil chemical properties and soil biodiversity via the implementation of CA, (ii) assess cowpea yield change and variability under CA, and (iii) outline differences in soil chemical properties, soil biodiversity, and crop yields driven by CA in the savannah and the forest ecosystems when compared to conventional agriculture. It was hypothesized that soil chemical properties, biodiversity, and crop yields, respectively represented by soil nutrients, earthworms' population, and cowpea yields, would change positively under CA compared to conventional agriculture, and the conditions provided by the two DRC's main ecosystems, forest, and savannah, would drive those variations in soil chemical properties, biodiversity, and crop yields. This research is essential to donors and development actors involved in promoting sustainable agriculture and the government of the DRC as it reduces CA's knowledge gap and illustrates CA's adaptability in DRC's smallholder farming. This research is the first of its kind, as it shows how CA works in the DRC to contribute to incentivizing CA adoption and its dissemination as a sustainable farming practice in smallholder farmers' communities.

3.2. Materials and Methods

3.2.1. Research site and data

This study was conducted in the Maniema province in Eastern DRC. The province of Maniema has two types of climates: equatorial in the north and tropical humid in the south, and average annual temperatures range from 23 to 25^{o}C (Omasombo et al., 2011). The primary data were collected by the *Kulima Pasipo Kutipula* project implemented by Catholic Relief Services (CRS) and its local partners in Kabambare, Kailo, and Kasongo, which are three of the seven territories that constitute the Maniema province. The territory of Kailo is mainly a dense rainforest, with altitudes ranging from 500 to 1,000 m, average annual rainfall of 1,600 mm, and fertile sandy-clay soils (Famine Early Warning Systems Network [FEWS NET], 2016). Kabambare and Kasongo territories are in the southern part of Maniema, covered by a savannah. In the Kabambare and Kasongo territories, the soils, generally made up of more sand than clay, are moderately fertile, and the average annual rainfall is approximately 1,500 mm (FEWS NET, 2016).

The panel dataset provided by CRS (2012) for this study was comprised of soil chemical analysis results, earthworm counts, and cowpea yields. Data were collected from 19 project-demonstration sites across Kabambare, Kailo, and Kasongo, from 2009 through 2011. Cowpea is the third-largest legume produced in the DRC, following peanut (*Arachis hypogaea*) and beans (*Phaseolus vulgaris* L.) (Institut National de la Statistique [INS], 2017). Cowpea is the second most important legume in the province of Maniema (FEWS NET, 2016). The increasing demand for cowpea grain in the DRC is still not met due to low yields (Tshibingu, Lubobo, Baboy, &

Munyuli, 2018). On average, 79% of the cowpea harvested in Maniema is consumed, and 21% is taken to the market (CAID, FAO, & WFP, 2018).

3.2.2. Experimental design

This study consisted of a split-split-plot design, where the whole-plot factor was the agroecological region, forest, or savannah, referred to as ecosystems. Across the two ecosystems, seven demonstration sites in the forest and twelve in the savannah served as the experimental units (Table 3.1). Each experimental unit was split between two management practices, CA and conventional agriculture. The two agricultural practices are referred to in the remainder of this paper as practices. The term "conventional agriculture" referred to typical slash-and-burn and shifting cultivations involving tillage and implemented by smallholder farmers in the province of Maniema, DRC. The ecosystem is an experimental factor set to capture the influence of the savannah and the forest, two regions with distinct characteristics in the Maniema province of DRC. Demonstration sites were randomly selected from 45 villages of Kabambare, Kailo, and Kasongo territories where the CRS project was implemented (CRS, 2012). The split-split-plot factor was year, where three consecutive years of soil chemical properties and two consecutive years of earthworm counts and cowpea yields were recorded.

Table 3.1. Demonstration sites in Maniema province (CRS, 2012)

Ecosystem	**Territory**	**Site**
Forest	Kailo	Enombe, Kasenga, Kembe, Libenga, Lubangwana, Lubelenge, Nyoka
Savannah	Kabambare	Bakungu, Kibenga, Kayembe, Lubobola, Mukoko, Mukoloka, Mutingwa
	Kasongo	Kauta, Lukongo, Lupaya, Makiringi, Mwanakusu

All demonstration sites were seeded on the same day by smallholder farmers using the same lot of seeds provided by the CRS project. Each experimental unit had two side-by-side, 20- x 20-m plots, separated by a 2-m-wide driveway. No fertilization was applied to any of the demonstration sites to reflect the reality of input usage in the rural regions.

3.2.3. Soil sampling and analyses

In each plot, five soil cores were collected using a 1-m-long, 5.1-cm-diameter metallic pipe to a depth of 30 cm and combined for one soil sample per plot. The five sampling points were the center of the plot and random location between each plot's corner and the center along two diagonals passing through the center and linking opposite plot corners. Different clean metallic pipes were assigned to each plot to avoid potential contamination from plot to plot. The composited soil sample was then air-dried in the sun for 3 to 4 days at 24°C average ambient air temperature until a constant weight was achieved, and 1 kg of dried soil was shipped to the Catholic University of Bukavu for laboratory analysis.

Soil pH was determined potentiometrically using an electrode in a 1:2.5 soil mass to water volume suspension. Soil organic carbon (SOC) was determined using the Walkley-Black method (Walkley & Black, 1934). Soil organic matter (SOM) was obtained by applying the 1.72 conversion factor to SOC (SOM = SOC x 1.72). Soil nitrogen (N) was determined using the Kjeldahl method following the AFNOR French standards (X 31-111, 1983). The C/N ratio was calculated by dividing SOC by soil N. Soil phosphorus (P) was determined using the Olsen method (Olsen, Cole, Watanabe, & Dean, 1954). Extractable soil calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) concentrations and cation exchange capacity (CEC) were determined following the procedure in AFNOR French standards (NF X 31-130, 1993).

Counting earthworms to assess soil health is an indigenous practice implemented by smallholder farmers in the Maniema province (CRS, 2012). Farmers were asked to mark out a randomly located, 1-m^2 square spot in each of the two plots on the demonstration site, scrape it to about a 5-cm depth, making sure not to disturb the soil structure, and observe and count all earthworms present.

3.2.4. Crop yield determination

Cowpea harvest took place four months after planting. Extension agents and farmers passed thrice during the harvesting month on each plot where cowpea pods were hand-picked and dried to 12% humidity. Cowpea yield was obtained by summing the quantities harvested on each plot of the demonstration site. The sum retrieved per plot was then used along with the size of the plot to derive cowpea yield in Kg per ha.

The rotation under CA at the demonstration sites involved the most important crops planted by farmers in the demonstration site's area (CRS, 2012), including mostly maize, rice, cassava, peanut, and cowpea. However, cowpea was the only planted crop that occurred at least once at every demonstration site each year. Consequently, for this study, cowpea was the crop for which crop yield trends across years could be assessed.

3.2.5. Statistical analyses

The soil properties included in the analysis were soil pH, available N, P, K, Na, Mg, and Ca, SOC, SOM, soil C/N ratio, CEC, and earthworms' count. Normality and homoscedasticity were evaluated for each dependent variable using normal probability plots and Shapiro-Wilk and Levene's tests. Similar studies, such as Amuri et al. (2008) and Norman et al. (2016), also tested the effects of time and farming practice on soil properties. Unlike the later studies (Amuri et al., 2008; Norman et al., 2016) that used an analysis of covariance (ANCOVA) in the US, this study examined the effect of applying CA on soil properties over time using linear mixed-effects modeling (LMM) approach. The unbalanced nature of the study design, illustrated by the unequal experimental units per ecosystem (Table 3.1), justifies using the LMM approach for statistical analyses. Linear mixed-effects modeling estimation is appropriate for this study's data, as most standard analysis models are suitable for balanced data (Baayen, Davidson, & Bates, 2008; Lin, 2007; Nyagumbo et al., 2020; Yang, 2010).

The ecosystem (i.e., savannah or forest) and the agricultural practice (i.e., CA or conventional practice) were the experimental factors investigated, and the year factor was a fixed covariate, while the individual demonstration sites comprised the random component for the LMM. The year factor was included in the random component, considering that precipitation and temperature effects occur randomly and confound with the year's weather (Moore & Dixon, 2015). The soil properties were used as response variables. *Lme4* (Bates, Mächler, Bolker, & Walker, 2014) package was used to fit the LMM using restricted maximum likelihood (REML) and *lmerTest* (Kuznetsova, Brockhoff, & Christensen, 2017) was used to derive p-values using the Satterthwaite approximation. The *anova* command was used on the fitted LMM to assess potential interactions between fixed factors and *difflsmeans* for means difference examination. The inspection of residuals did not reveal substantive deviations from homoscedasticity or normality.

With an unbalanced design, the use of REML leads to unbiased LMM estimates, and the Satterthwaite method derives acceptable Type-I errors (Govaerts, Francq, Marion, Martin, & Thiel, 2020; Luke, 2017). A Linear mixed-effects model also accommodates missing data as one plot's cowpea yield was absent (Maxwell, Delaney, & Kelley, 2018). The stepwise methodological approach based on Kuznetsova et al. (2017) assisted with model identification. The selection of the best LMM that fit the response evaluated was based on the Akaike information criteria (AIC). The fitted LMM accounted for the random effect represented by the individual demonstration sites and allowed site-year interaction. As such, this study's LMM model specified two random variances levels: (i) locational variance represented by demonstration sites and (ii) location-across-year variance represented by site-year interaction. The resulting LMM model integrating possible interactions was the following:

$$Y = \alpha_0 + \sum_{j=1}^{3} \alpha_j \delta_{ij} + \alpha_{\vartheta ij} \vartheta_{ij} + u_s + v_{s:y} + \varepsilon_{ij} \qquad \text{(Eq. 1)}$$

where *Y* was the dependent variable measured at the i^{th} site, α_0 the overall mean representing CA practice in the savannah in 2009, *j* the number of categories of fixed factors, including practice (a dummy taking 0 for CA and 1 for conventional), ecosystem (a dummy taking 0 for forest and 1 for savannah), and year (representing 2009/2010 to 2011); α_j the regression coefficient associated with the *j*th factor, δ_{ij} a vector representing the *j*th factor for the *i*th site (i.e., replication), $\alpha_{\vartheta ij}$ the coefficient for interaction terms, and $\alpha_{\vartheta ij}$ the interaction terms between the *j* factors. The u_s and $v_{s:y}$ parameters were the random effects for site and site per year with variance σ^2_{Site} and, $\sigma^2_{Site:Year}$, respectively. The ε_{ij} parameter was the error term residuals with variance σ^2_e. The random variables were assumed independent and normally distributed with a mean of zero.

3.2.6. Yield variability and contributing factors analysis

Several methods can be used to assess the variability of crop yield across cropping systems (Piepho, 1998; Reckling et al., 2021). In this study, the LMM regression approach was used to gain insights into the variability of cowpea yields produced under CA and conventional practice in the forest and the savannah. Consistent with Williams et al. (2018), a practical technique adopted in this study was to extend Eq.1's locational variance with a random slope for practice per demonstration site. A random slope separates each site's variability between CA and conventional practice to capture how much annual cowpea yields are affected by practice at the site level. The random slope allows the effects of CA- and conventional practice on cowpea yields to fluctuate from site to site. Handling the location aspect and its interactions with year as random effects was convenient since demonstration sites in the DRC aimed to promote agricultural technology (Piepho, 1998; Yang, 2010). In addition, using random slope for practice reduces the risk of Type-I error (Barr, Levy, Scheepers, & Tily, 2013; Schielzeth & Forstmeier, 2009). The partitioning of the variance provided by the LMM approach (Eq.1) allowed for the interpretation of locational yield variability. Cowpea yield variances comparing CA ($\sigma^2_{CA.Site}$) to conventional practice ($\sigma^2_{Conv.Site}$) were derived from and restricted to the LMM variance-covariance structure. The environmental variance model illustrated by the LMM variance-covariance is a comprehensive technique for investigating yield variability (Piepho, 1999). Cowpea yield variability was reported using a coefficient of variation (CV), as the variance could amplify the influence of outliers (Anderson, Hammac, Stott, & Tyner, 2020). The CV was calculated as the standard deviation divided by the mean using the values of LMM cowpea yield analysis and was reported as a percentage.

In addition to LMM, this study used the classification and regression tree (CART) approach (Breiman, Friedman, Olshen, & Stone, 2017) to explore several study variables' potential contributions to cowpea yields. Cowpea yields were regressed against soil properties (including pH, available N, P, K, Na, Mg, and Ca, CEC, C/N, SOC, and SOM), practice, ecosystem, and year factors in the CART process. Using the *rpart* package (Therneau &

Atkinson, 2019) in R, a tree was generated by recursive partitioning starting at a root node, known as the first parent, using all variables of the entire dataset. The partitioning of the dataset was continuous, creating child nodes by splitting values such that the sums of squares error were minimized at each step. The branches eventually became terminal nodes or leaves containing the predicted dependent value. The CART approach allowed for the identification of cowpea-yield-contributing factors and their importance.

3.3. Results

3.3.1. Soil pH

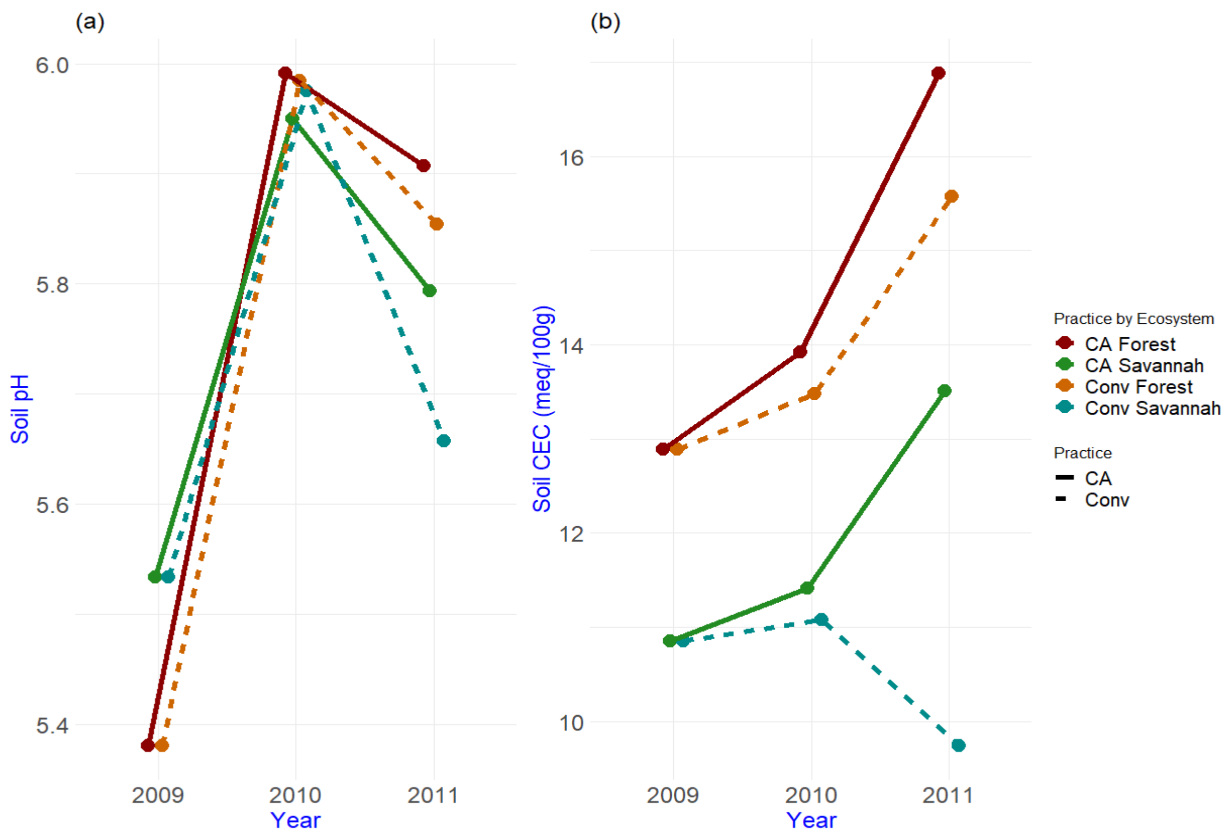

Figure 3.1. Mean annual soil pH (a) and CEC [cation exchange capacity] (b) by practice (CA = conservation agriculture, Conv = conventional practice) within each ecosystem (forest, savannah) from 2009 to 2011

Soil pH varied numerically among the three years (Fig. 3.1a). Soil pH was numerically lowest in 2009, numerically increased by 2010, then numerically decreased by 2011 in all four ecosystem – practice combinations (Fig. 3.1a).

Table 3.2. Summary of linear mixed-effects model analysis of variance results of the influence of ecosystem, practice, year, and their interactions on soil chemical properties from 2009 to 2011

	Source of variation (Ecosystem = E, Practice = P, Year = Y)						
Soil property	**E**	**P**	**Y**	**E x P**	**E x Y**	**P x Y**	**E x P x Y**
	p						
pH	0.950	0.561	**0.007**	0.863	0.608	0.634	0.884
CEC	0.121	0.192	0.45	0.596	0.707	0.325	0.725
N	0.096	0.902	0.094	0.902	0.259	0.389	0.965
P	0.101	**0.024**	0.100	0.230	**0.001**	**0.013**	0.074
K	0.107	**0.003**	0.251	0.659	0.361	**0.008**	0.772
Na	0.460	0.902	0.966	0.238	0.242	0.665	0.230
Mg	0.281	0.625	0.979	0.759	0.735	0.861	0.912
Ca	0.097	0.104	0.952	0.814	0.711	0.237	0.643
SOC	0.099	0.583	0.719	0.383	0.915	0.926	0.572
SOM	0.096	0.245	0.706	0.437	0.874	0.525	0.666
C/N	0.126	0.969	0.225	0.491	0.624	0.578	0.551

Note: Bold values represent p-value < 0.05

Based on the LMM ANOVA results, soil pH was unaffected ($p > 0.05$) by ecosystem or practice but varied over time ($p = 0.004$; Table 3.2). Averaged across ecosystem and practice, soil pH increased ($p < 0.05$) from 2009 to 2010, then soil pH remained similar between 2010 and 2011 and greater than that in 2009 (Table 3.3).

Table 3.3. Summary of the significant effect of year on soil pH

Year	**pH**
2009	5.46 b[†]
2010	5.97 a
2011	5.80 a

[†] Means in a column with the different letters are different at $p < 0.05$

3.3.2. Soil cation exchange capacity

During the three years, soil cation exchange capacity (CEC) was numerically greater in the forest than in the savannah (Fig. 3.1b). Soil CEC increased numerically from 2009 to 2011 in the ecosystem–practice combination that involved CA while taking different directions under the conventional practice. Soil CEC increased numerically under the conventional practice in the forest but numerically decreased during the same period in the savannah (Fig. 3.1b). However, results of the LMM ANOVA showed that soil CEC was unaffected ($p > 0.05$) by ecosystem, practice, or year (Table 3.2) and averaged 12.4 meq/100 g across all treatment combinations.

3.3.3. Soil available nitrogen, phosphorus, and potassium

Soil available N, P, and K in the top 30 cm numerically varied over time in all four combinations of ecosystem and practice (Fig. 3.2). Soil N in the forest was numerically low in 2009, then numerically increased in 2010, and continued to increase numerically in 2011 (Fig. 3.2a). In contrast, in the savannah, soil N numerically increased from 2009 to 2010, then numerically decreased from 2010 to 2011 under conventional, but numerically decreased then numerically increased for CA during the same period (Fig. 3.2a) regardless of treatment combination. Soil P numerically increased between 2009 and 2010 regardless of treatment combination. Soil P continued to increase numerically from 2010 to 2011 in the forest regardless of practice, while soil P in the savannah decreased numerically from 2010 to 2011 regardless of practice (Fig. 3.2b).

In contrast to soil N and P, which were numerically greater in the forest than in the savannah, soil K was numerically lower in the forest than in the savannah (Fig. 3.2c). Soil K in the forest numerically decreased from 2009 to 2010 before numerically increasing from 2010 to

2011 (Fig. 3.2c). However, soil K gradually numerically increased under CA but numerically decreased under the conventional practice in the savannah (Fig 2c).

Based on the LMM ANOVA results, soil N was unaffected ($p > 0.05$) by ecosystem, practice, or year (Table 3.2). Soil N concentration averaged 0.27 % across all treatment combinations.

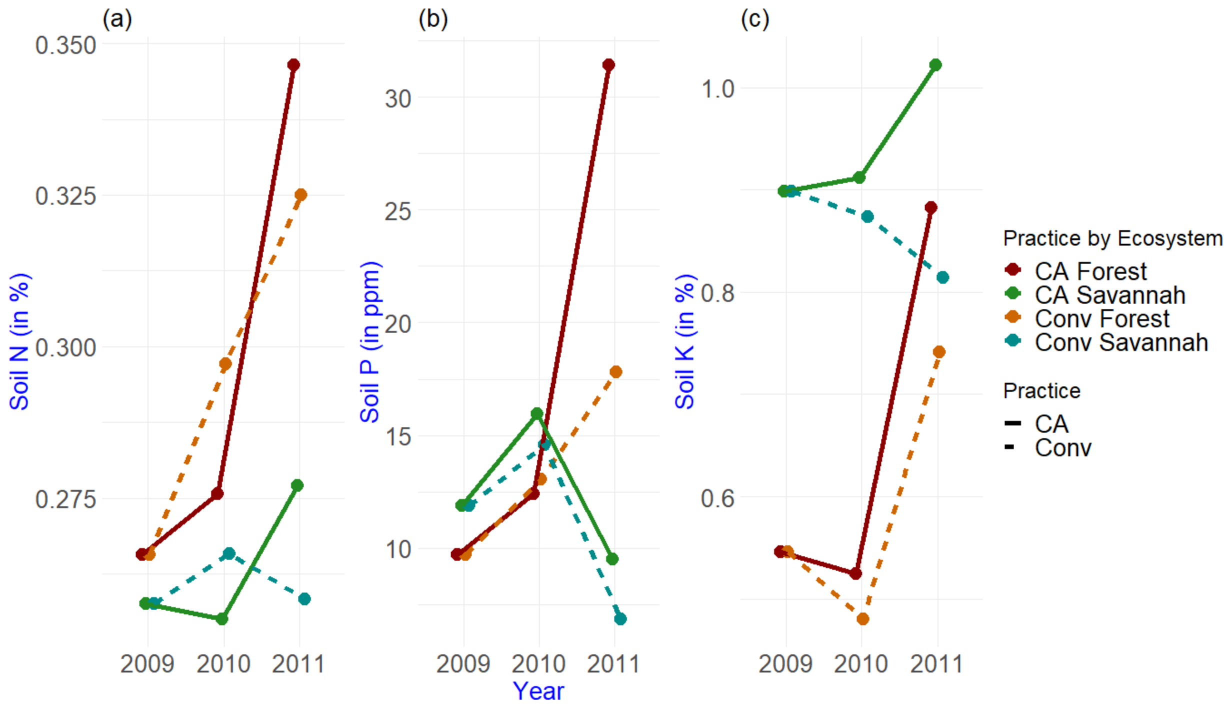

Figure 3.2. Mean annual soil N (a), P (b), and K (c) concentrations by practice (CA = conservation agriculture, Conv = conventional practice) within each ecosystem (forest, savannah) from 2009 to 2011

In contrast to soil N, soil P differed ($p < 0.05$) between ecosystems over time and differed ($p < 0.05$) between practices over time (Table 3.2). Averaged across practices, soil P was similar between practices in 2009 and 2010 but was 66.7% greater under CA than under the conventional practice in 2011 (Fig. 3.3). Soil P increased over time under CA but did not change over time under the conventional practice (Fig. 3.3). In 2011, soil P was largest under CA compared to all other practice-year combinations (Fig. 3.3). Averaged across ecosystems, soil P was similar between ecosystems in 2009 and 2010 but was three times greater in the forest than in the savannah in 2011 (Fig. 3.3). Soil P increased over time in the forest, and in the savannah, it increased in the second year but went back to its first-year level in the third year (Fig. 3.3). Soil P in the forest in 2011 was the largest compared to all other ecosystem-year combinations (Fig. 3.3).

Similar to soil P and in contrast to soil N, soil K was unaffected by ecosystem or year but differed ($p < 0.05$) between practices over time (Fig. 3.3). Averaged across ecosystems, soil K was similar between practices in 2009 and 2010 but was 22% greater under CA than under the conventional practice in 2011 (Fig. 3.3). Soil K increased over time under CA but did not change over time under the conventional practice (Fig. 3.3). Soil K was the largest under CA in 2011 compared to all other practice-year combinations (Fig. 3.3).

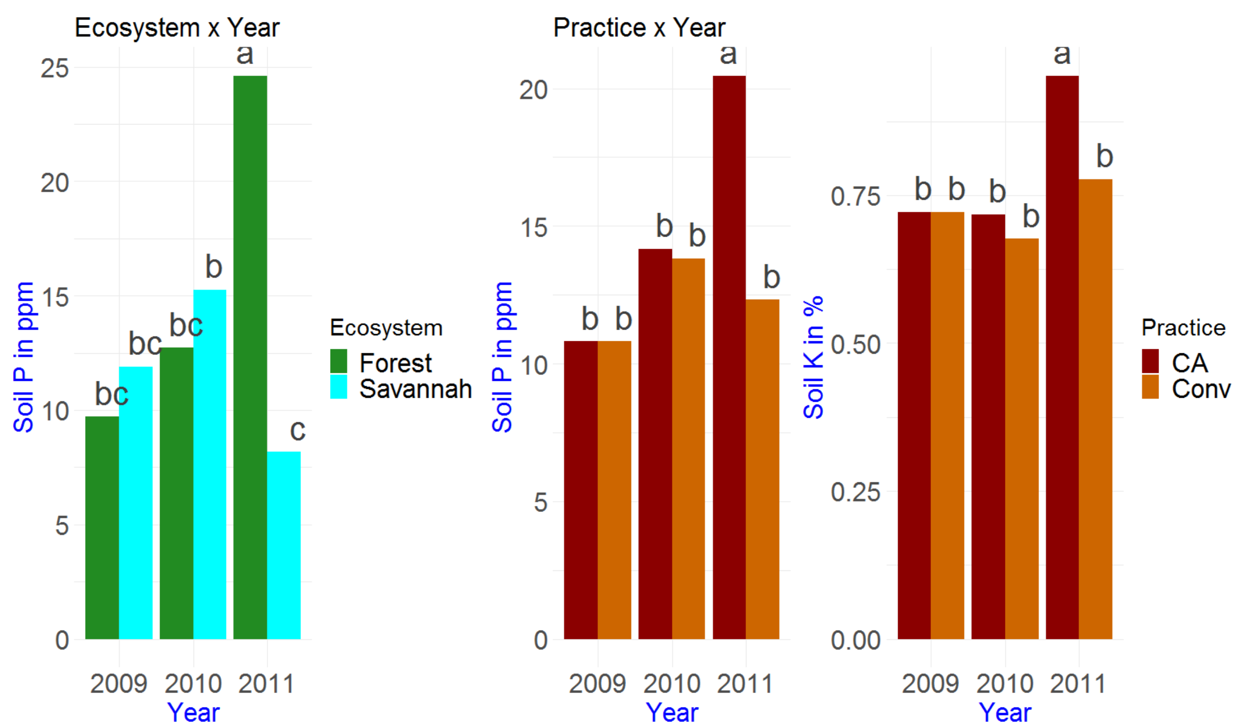

Figure 3.3. Summary illustration of the ecosystem–year and practice–year effects on soil available P and K concentrations. Practices (on the right) are CA = conservation agriculture (red) and Conv = conventional practice (orange), ecosystems (on the left) are forest (green) and savannah (cyan), and letters indicate statistical differences at $p < 0.05$.

3.3.4. Soil available sodium, magnesium, and calcium

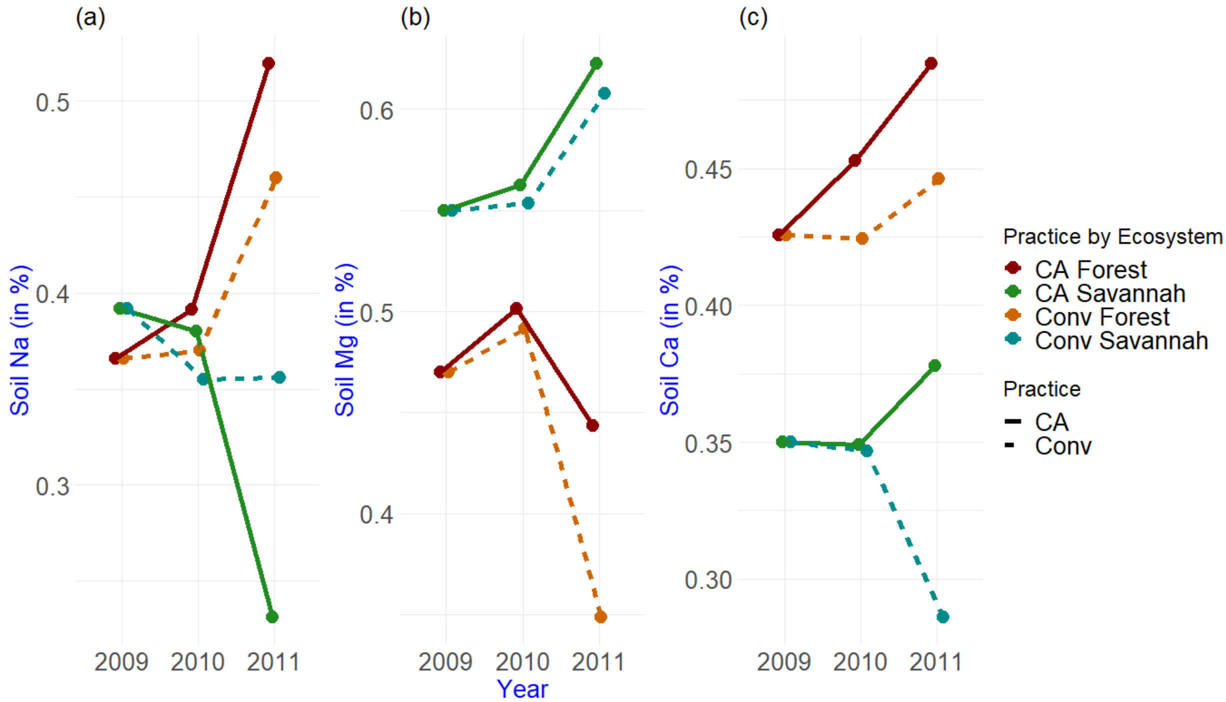

Figure 3.4. Mean annual soil Na (a), Mg (b), and Ca (c) concentrations by practice (CA = conservation agriculture, Conv = conventional practice) within each ecosystem (forest, savannah) from 2009 to 2011

Similar to soil available N, P, and K, soil available Na, Mg, and Ca concentrations in the top 30 cm varied numerically over time (Fig. 3.4). Ecosystem–practice combinations from 2009 to 2011 tended to increase numerically in the forest for soil Na under CA and conventional practice, while numerically decreasing in the savannah (Fig. 3.4a). Soil Mg in the savannah was numerically greater over time under both practices than in the forest and numerically increased from 2009 to 2011, while soil Mg in the forest numerically decreased over time (Fig. 3.4b). In contrast to soil Mg, soil Ca in the forest was numerically greater over time under both practices than in the savannah and numerically increased from 2009 to 2011, while soil Ca in the savannah numerically increased over time under CA and numerically decreased over time under the conventional practice (Fig. 3.4c). However, based on formal statistical analyses, soil Na, Mg, and

Ca were all unaffected by practice, ecosystem, or year ($p > 0.05$; Table 3.2). Across all treatment combinations, soil Na, Mg, and Ca averaged 0.37, 0.53, and 0.38%, respectively.

3.3.5. Soil organic carbon, soil organic matter, and C/N ratio

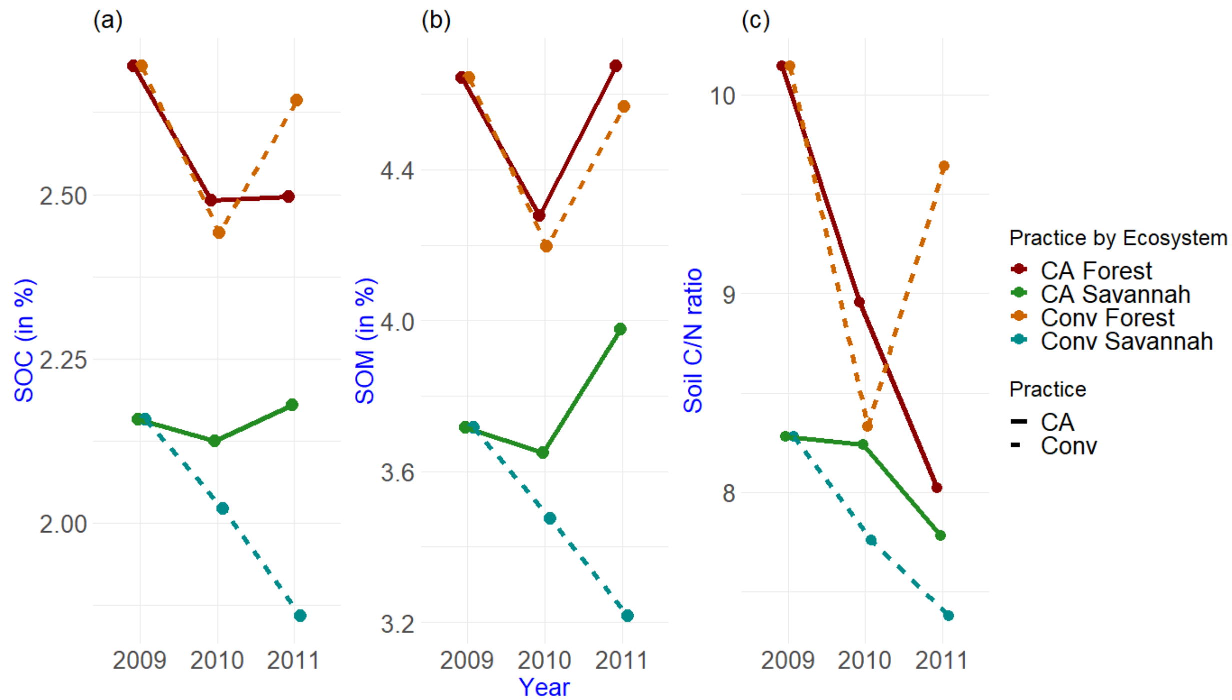

Figure 3.5. Mean annual soil organic carbon (SOC; a), soil organic matter (SOM; b), and C/N ratio (c) by practice (CA = conservation agriculture, Conv = conventional practice) within each ecosystem (forest, savannah) from 2009 to 2011

Similar to soil N, P, K, Na, Mg, and Ca, SOC and SOM concentrations and C/N ratio in the top 30 cm varied numerically over time (Fig. 3.5). Similar to soil Ca, SOC and SOM in the forest were numerically greater over time under both practices than in the savannah and numerically decreased from 2009 to 2011, while SOC and SOM in the savannah did not change over time under CA but numerically decreased over time under the conventional practice (Fig. 3.5a,b). Similar to SOC and SOM, soil C/N ratio in the forest was numerically greater over time under both practices than in the savannah and numerically decreased from 2009 to 2011, while soil C/N ratio in the savannah numerically decreased over time under both practices (Fig. 3.5c).

However, similar to soil Na, Mg, and Ca, based on formal statistical analyses, SOC, SOM, and C/N ratio were all unaffected by practice, ecosystem, or year ($p > 0.05$; Table 3.2). Soil SOC, SOM, and C/N ratio averaged 2.27%, 3.95%, and 8.42, respectively, across all treatment combinations.

3.3.6. Earthworms population

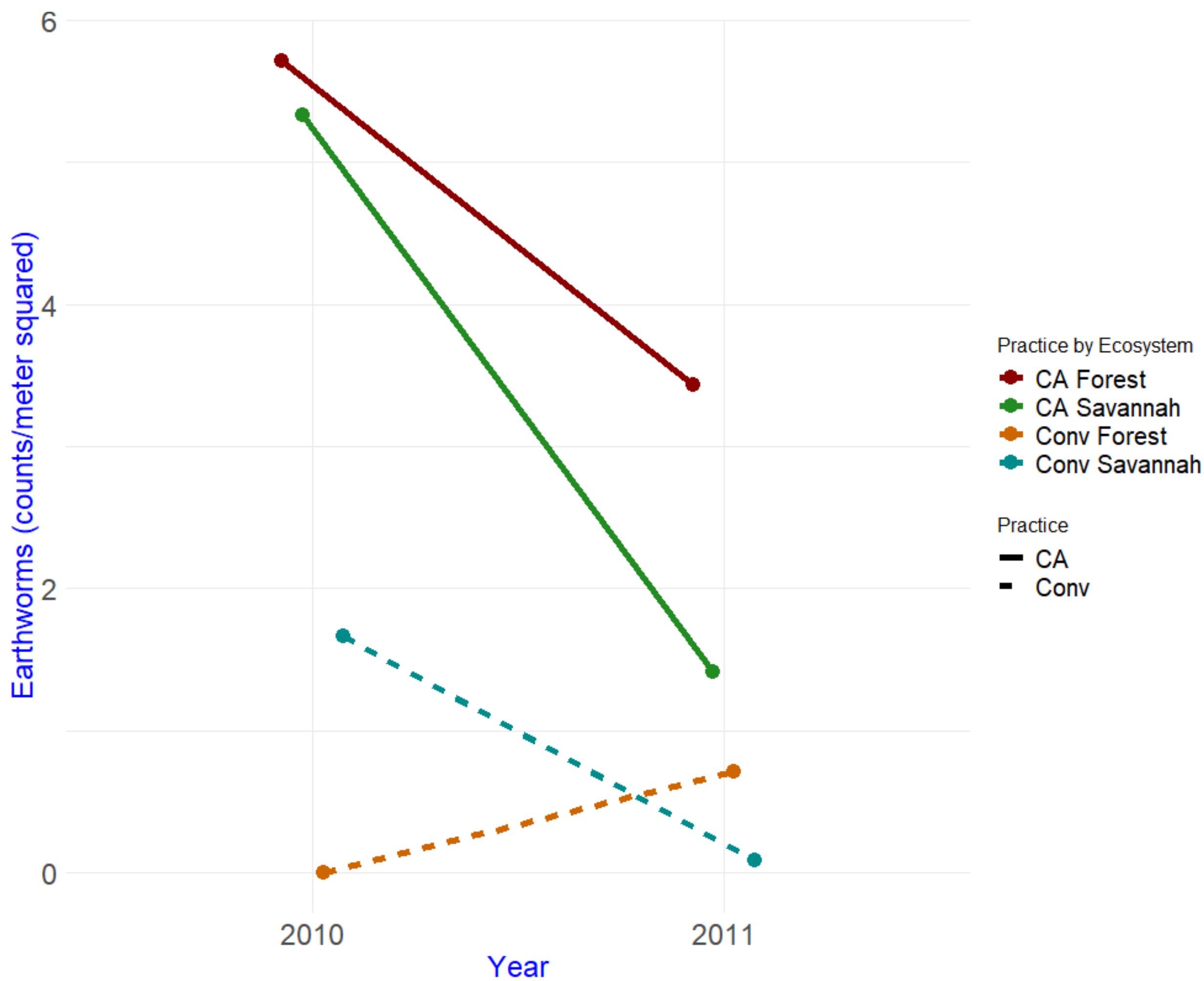

Figure 3.6. Mean annual earthworm counts by practice (CA = conservation agriculture, Conv = conventional practice) within each ecosystem (forest, savannah) from 2010 to 2011

The population of earthworms in the top 5 cm varied numerically between 2010 and 2011 among the ecosystem-practice combinations (Fig. 3.6). Earthworm counts were numerically greater under CA than the conventional practice in both ecosystems in 2010 but numerically decreased in 2011. Earthworms in the forest were numerically the lowest in 2010 under the conventional practice but numerically increased by 2011, while, in the savannah, earthworms under the conventional practice numerically decreased from 2010 to 2011. However, based on the LMM ANOVA results, the earthworm population was unaffected ($p > 0.05$) by ecosystem or year but differed between practices ($p < 0.001$; Table 3.4). Averaged across ecosystem and year, earthworm counts were 6.5 times greater under CA than the conventional practice (Table 3.5).

Table 3.4. Analysis of variance summary of the effects of ecosystem, practice, year, and their interactions on earthworms

Source of Variation	**Earthworm Population**
	— p —
Ecosystem	0.756
Practice	**< 0.001**
Year	0.099
Ecosystem x Practice	0.228
Ecosystem x Year	0.346
Practice x Year	0.064
Ecosystem x Practice x Year	0.813

Note: Bold values represent p-value < 0.05

Table 3.5. Summary of the practice effect on the earthworm population in the top 5 cm of soil

Practice	**Earthworms** (counts/m^2)
Conservation agriculture	4.0 a[†]
Conventional	0.6 b

[†] Means with different letters are different at $p < 0.05$

3.3.7. Cowpea yields

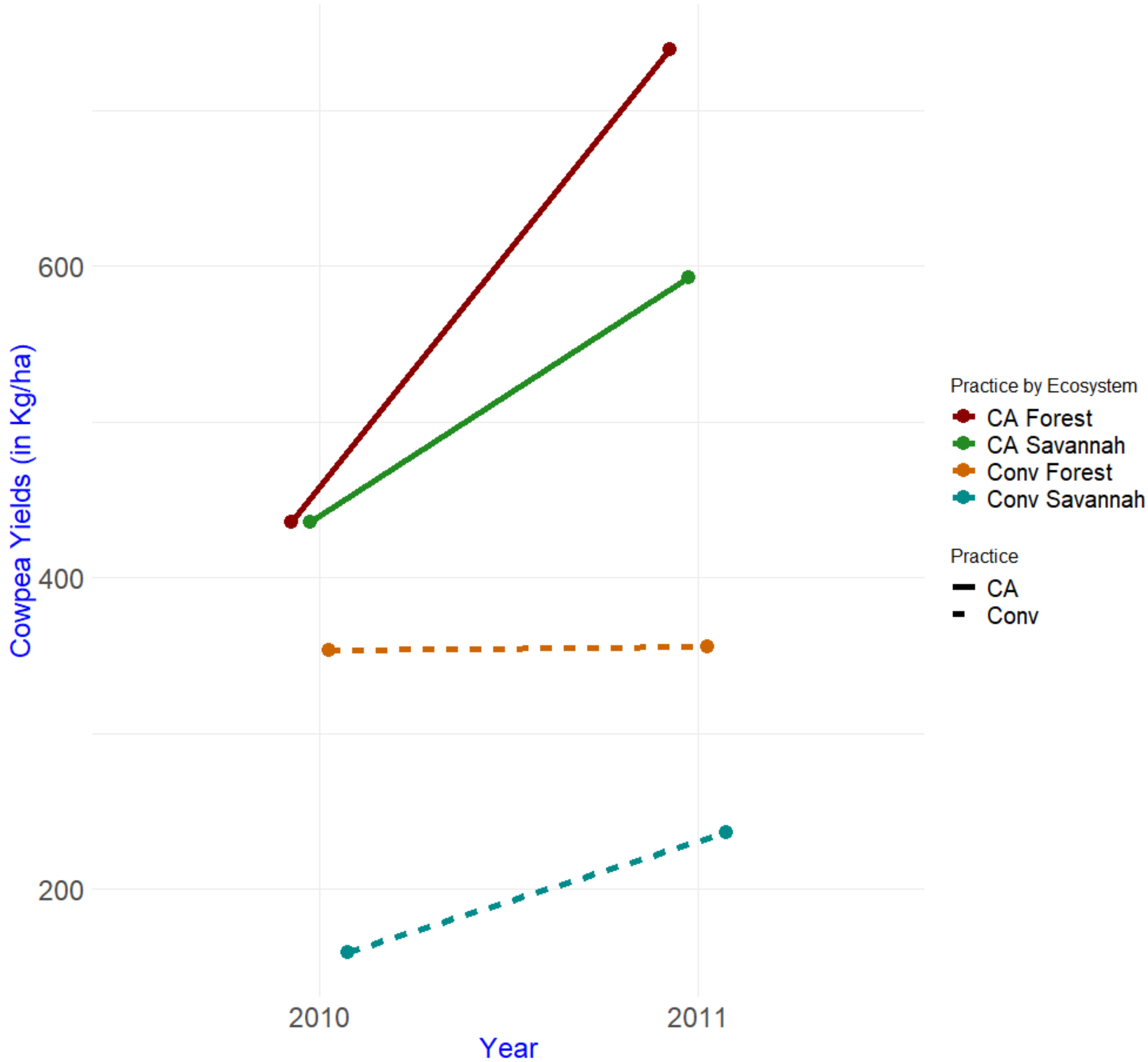

Figure 3.7. Cowpea yields by practice (CA = conservation agriculture, Conv = conventional practice) within each ecosystem (forest, savannah) from 2010 to 2011

In both 2010 and 2011, cowpea yields were numerically greater under CA than the conventional practice in both ecosystems (Fig. 3.7), where the largest numerical cowpea yield occurred under CA in the forest in 2011. Cowpea yields numerically increased from 2010 to 2011 under all ecosystem-practice combinations except for the forest-conventional practice combination (Fig. 3.7).

However, based on formal statistical analyses, cowpea yields were unaffected ($p > 0.05$) by ecosystem but varied between practices over time ($p < 0.001$; Table 3.6). Averaged across ecosystems, cowpea yields were at least 1.5 times greater from CA in 2011 than from any other practice-year combinations (Fig. 3.8), while cowpea yields from CA in 2010 were also at least 1.4 times greater than from the conventional practice in both years (Fig. 3.8). Conservation agriculture produced greater cowpea yields than the conventional practice each year (Fig. 3.8). Furthermore, cowpea yields increased from 2010 to 2011 under CA but did not change over time under the conventional practice (Fig. 3.8).

Table 3.6. Analysis of variance summary of the effect ecosystem, practice, year, and their interactions on cowpea yields in 2010 and 2011

Source of Variation	**Cowpea yield**
	—— p ——
Ecosystem	0.068
Practice	**< 0.001**
Year	**0.020**
Ecosystem x Practice	0.246
Ecosystem x Year	0.733
Practice x Year	**0.001**
Ecosystem x Practice x Year	0.118

Note: Bold values represent p-value < 0.05

The random component of the LMM allowed quantifying the variability in cowpea yields due to changing conditions between demonstration sites across the implemented agricultural practices. The variation in cowpea yields between sites across years, as measured by the variance, was almost 10 times greater under CA ($\sigma^2_{CA.Site}$) than the conventional practice ($\sigma^2_{Conv.Site}$) across sites. More importantly, the cowpea yield CV was 25.4 and 16.2% for CA- and conventionally produced cowpeas, respectively (Table 3.7). Thus, examining cowpea yield at the site level suggests that CA creates more yield variability than the conventional practice. The comparison of cowpea yields distributions (using data in Table 3.7) showed that under CA the probability of obtaining a greater yield than conventional is 97.5% (Fig. 3.9).

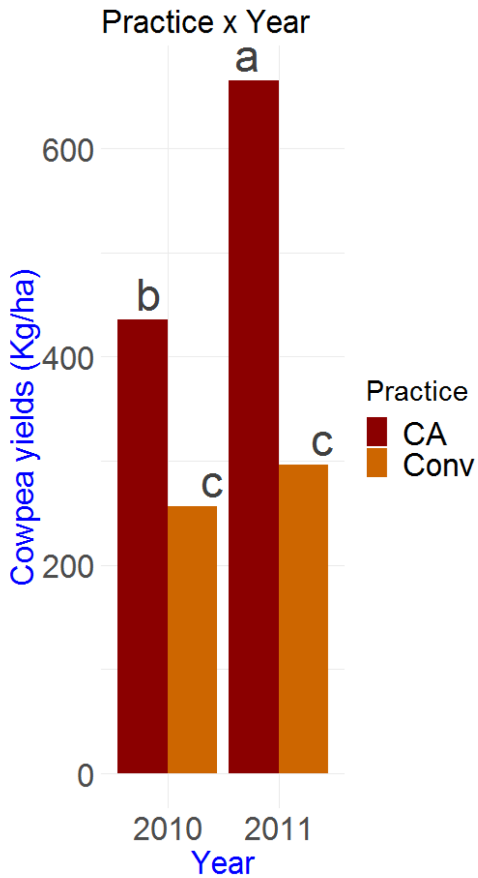

Figure 3.8. Summary illustration of significant effects of practices over time on cowpea yields in 2010 and 2011. Practices are CA = conservation agriculture (red) and Conv = conventional practice (orange), and letters indicate statistical differences at $p < 0.05$.

Table 3.7. Cowpea yield variability analysis

Statistic	**CA**	**Conv**
Mean	549.0	276.2
Standard deviation	139.6	44.8
Variance	19,490	2,007
Coefficient of variation (%)	25.4	16.2

Note:
- CA = conservation agriculture, Conv = conventional practice
- Mean value derived from LMM ANOVA
- Variance and standard deviation values derived from LMM variance-covariance structure

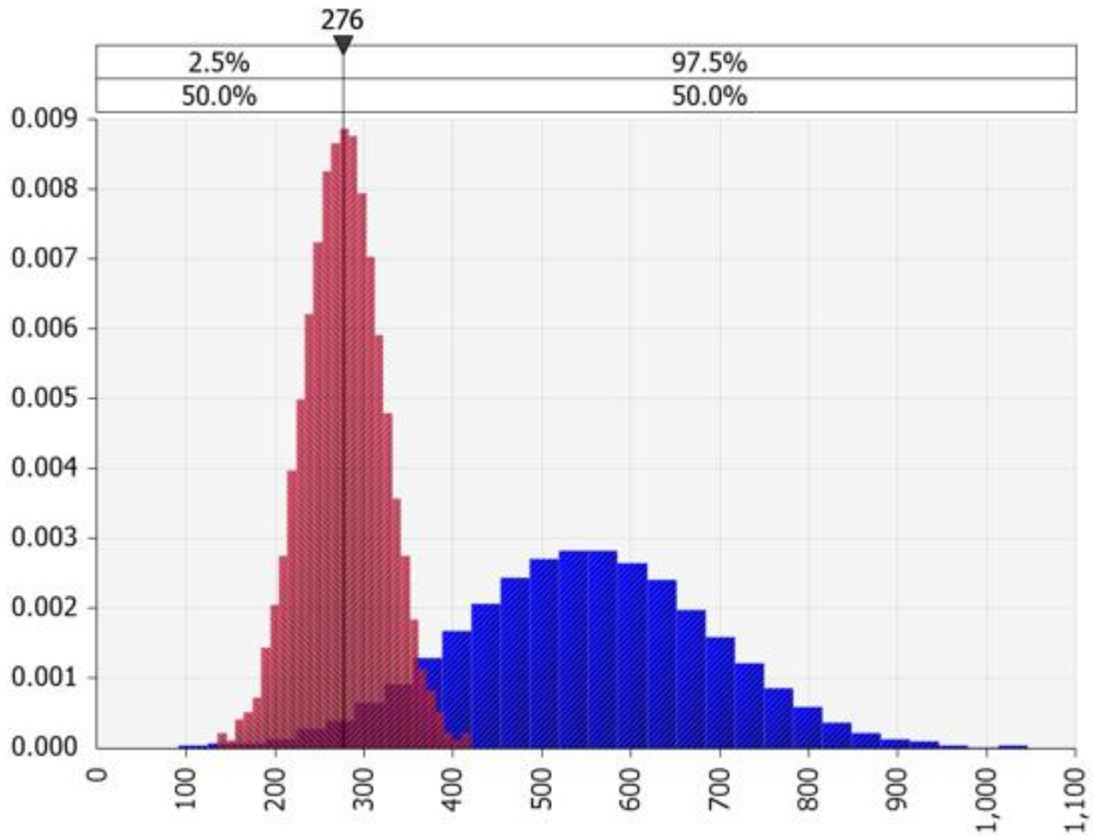

Figure 3.9. Cowpea yields (in kg ha-[1]) distributions comparison by practice across demonstration sites in Maniema, DRC. Practices are CA = conservation agriculture (blue) and Conv = conventional practice (red).

The cowpea yield regression tree partitioned all study's independent variables and showed that agricultural practice was the most important factor in determining cowpea yields (Fig. 3.10). The root node (396 kg ha^{-1}) at the beginning of the tree (top of Fig. 3.10) is the overall mean representing cowpea yields across all variable combinations. In terms of practice, the regression tree key finding is consistent with LMM ANOVA, demonstrating that CA led to greater yields than the conventional practice. However, Fig. 3.10 suggests that CA-cowpea yield would depend on soil pH and Ca concentration. Under CA, soil Ca concentration was the next important factor for cowpea yields, with the largest yields under CA predicted to be achieved when soil Ca concentrations were ≥ 0.44%, while when soil Ca concentrations were < 0.44%, cowpea yield predictions depended on soil pH. Predicted cowpea yields were intermediate when soil pH was ≥ 5.9, but when soil pH was < 5.9, predicted cowpea yields were close to conventional practice yields. Fig. 3.10 demonstrates that the ecosystem was the next important factor under conventional practice, with larger cowpea yields in the forest than in the savannah regions. However, cowpea yields depended on the soil Na concentration in the savannah regions, where soil Na concentrations < 0.33% had greater predicted yields than when soil Na concentration was ≥ 0.33 %.

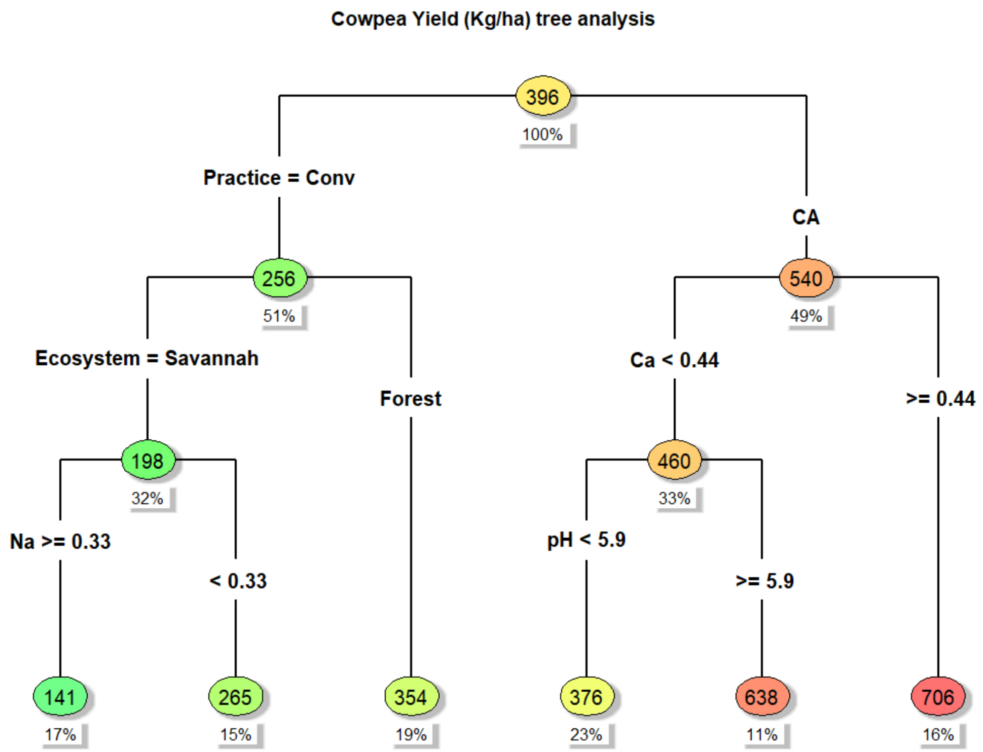

Figure 3.10. Summarized classification regression tree results partitioning 2010-2011 cowpea yields and showing contributing factors. *Note*: Numbers inside colored nodes represent predicted cowpea yields (in kg ha^{-1}), and below each is the percentage (%) of observations in the node. Conv = conventional, CA = conservation agriculture, Ca = soil calcium, Na = soil sodium. The values of Ca and Na are expressed in %.

3.4. Discussion

Agricultural practices affect several soil functions, also referred to as soil ecosystem services, such as water purification, climate regulation, soil carbon sequestration, nutrient cycling, water cycling and quality, and habitat and substrate for soil organisms (Baveye, Baveye, & Gowdy, 2016). Overall, the results of this study illustrated Dominati, Mackay, Green, and Patterson (2014)'s framework that farming practices, such as CA and conventional practices, are anthropogenic drivers that can affect various soil properties, namely soil pH, nutrients concentrations, SOM, and CEC. This investigation identified differences in several soil chemical properties, biodiversity, as measured by earthworm population, and cowpea yields in the DRC driven by agricultural practice, namely CA, alone and agricultural practice and/or ecosystem over time.

Few studies in SSA have explored soil functions in a context where no agrochemicals, including fertilizers, were applied. Nevertheless, a few on-farm and on-station trials under smallholder farming conditions conducted in SSA and can be used for comparison with the results of this study.

3.4.1. Soil chemical properties

As shown by the visual examination of this study's data, it was necessary to understand CA's influence on soil chemical properties over time and as affected by ecosystem. Results showed that, except for soil pH and the soil concentrations in available P and K, the rest of the chemical properties were unaffected by agricultural practice, ecosystem, or time. Excluding the no-effect for soil CEC, the lack of change in soil available N, Na, Mg, and Ca, SOC, SOM, and C/N ratio is inconsistent with Palm, Blanco-Canqui, DeClerck, Gatere, and Grace (2014), a review of hundred CA and ecosystem services research based on global literature and including smallholder farming in SSA. According to Palm et al. (2014), SOM and N should have increased, and a slight increasing or decreasing variation should have occurred for soil Ca and Mg with the implementation of CA. Worldwide, soil CEC has been shown to be variable, and the potential for CA to influence soil CEC is related to SOM and pH (Page, Dang, & Dalal, 2020). According to Page et al. (2020), soil CEC increases with SOM and decreases when soil pH decreases (i.e., becomes more acidic), which does not apply to Maniema, DRC, where results demonstrated increasing soil pH over time not due to CA and no change in CEC or SOM. However, early CA work on tropical soils by Agboola (1981) in Nigeria reported a decline in soil pH and CEC over four years and no change for soil Mg over time when no agrochemicals were applied. Another 2-year study in the rainforest of Nigeria with no mineral fertilizer use reported that both CA and conventional practices had no effect on soil Ca but decreased SOC, N, and Mg over time with a 50-100% greater reduction rate under conventional practice compared to CA (Agbede, 2008). In Ethiopia, Cherie (2021) demonstrated that over five years, CA increased SOC, soil CEC, and soil N by 44%, 18%, and 33%, respectively, relative to conventional practice. In a long-term study over 13 years in KwaZulu-Natal, South Africa, Sithole and Magwaza (2019) reported no change in SOC and soil Ca, Mg, and Na between CA and the conventional practice on a no-fertilizer treatment, while soil CEC increased by 59%. The absence of a CA effect on SOC and/or soil CEC in Maniema, DRC could be a plausible explanation for no change in soil N, Na, Mg, and Ca over time. Additionally, in the humid tropical regions of SSA, where soils are generally acidic, soils contain low N, Na, Mg, and Ca reserves, and soil pH affects soil CEC (Juo & Franzluebbers, 2003).

Soil pH increased over time from 2009 to 2011 in Maniema, DRC. The temporal change in pH indicated the influence of climatic conditions across years regardless of the agricultural practice used or the ecosystem. Rainfall in humid tropical regions is responsible for nutrient leaching, which can decrease soil pH over time (Juo & Franzluebbers, 2003). Inter-annual weather conditions, including temperature, humidity, and precipitation, that occurred in the DRC may have affected soil pH, but such factors were not considered in this study. Similar annual increasing soil pH effects not attributed to CA were reported in an 8-year field study in eastern Arkansas, US, in a context where mechanization and inorganic fertilization were used for wheat [*Triticum aestivum* (L.)] production (Amuri et al., 2008). In Ethiopia, Cherie (2021) conducted a study where soil was sampled to a 30-cm depth and reported a 7% increase in soil pH attributed to CA over five years. Cherie (2021) illustrated the potential of CA to improve soil pH in SSA. Similar improvements were seen in Malawi, where, after 2 and 5 years of applying CA, Mloza-Banda, Makwiza, & Mloza-Banda Mloza (2016) reported a 6% increase in soil pH under CA compared to ridge tillage. However, soil pH can increase or remain stable. Verhulst et al. (2014) mentioned that CA can decrease soil pH, as greater SOM accumulation in the topsoil can lead to acidity from decomposition. Similarly, Agboola (1981) reported a 3% decline in soil pH under CA and between 7 and 13% decline under conventional practices over a period of four years. The decline was caused by tillage and fertilizer additions that increased soil erosion and enhanced SOM breakdown, respectively (Agboola, 1981). In Zimbabwe, however, Nyamangara et al. (2013) compared the effect of CA to conventional agricultural practice with and without fertilization and reported no difference in soil pH between the two agricultural practices. Unfortunately, this study could not confirm CA effect on soil pH. The lack of a CA effect on soil pH in the present study agrees with studies that suggested soil pH changes occurred when CA affected SOC or SOM (Agboola, 1981; Ligowe, Nalivata, Njoloma, Makumba, & Thierfelder, 2017; Page et al., 2020).

Though a change in SOC could also be related to SOM and C/N, as the properties are all correlated to one another, this study identified no significant effect of agricultural practice or ecosystem on SOC. However, of the treatment combinations evaluated, SOC and SOM under CA in the savannah numerically increased from 2009 to 2011, whereas the other treatment combinations numerically decreased over time (Fig. 3.5). Evidence suggests that SOC and/or SOM differences between CA and conventional practices vary widely and are subject to change due to several factors, including climate, soil properties, time, sampling depth, and crop management (Page et al., 2020). However, the results of this study could not confirm a significant effect of agricultural practice and/or ecosystem on SOC, SOM, and C/N ratio, which is not unusual. Similar results to the current study were reported in Zambia, where, after 12 years, in a study that involved fertilizer usage, Martinsen, Shitumbanuma, Mulder, Ritz, and Cornelissen (2017) also reported that SOC, soil C stocks, and C/N ratio were unaffected by both CA and conventional practices. Nyamangara et al. (2013) also reported no CA-related change in SOM. While SOM was unaffected by CA in Ethiopia, the increase in SOM has been associated with N fertilization (Habtegebrial, Singh, & Haile, 2007). In a 2-year study with no mineral fertilizer use, Agbede (2008) reported a decline in SOC from both CA and conventional practices, but the decrease was more pronounced for conventional, with a 13% difference compared to CA.

It is important to identify two ecological aspects interfering with potential CA effects on SOM. Long-term trials have recently shown that CA does not affect SOM when crop residues are poorly managed (Eze et al., 2020). Evidence from a 9-year research trial in Zimbabwe demonstrated that the retention of crop residue under CA increased SOC by 15 and 62% in the top 30-cm depth on red clay and sandy soils, respectively, compared to conventional tillage

(Chivenge, Murwira, Giller, Mapfumo, & Six, 2007). Consequently, smallholder farmers should retain crop residues on the soil surface as a mean to improve soil surface hydraulic properties and increase near-surface SOM (Eze et al., 2020). Secondly, Martinsen et al. (2017) demonstrated that cultivated soils had greater soil C depletion under both CA and conventional practices than fallow land uses. Thus, sustainable agriculture would mean choosing CA for smallholder farming, as CA has fewer negative consequences on the environment than conventional practices. However, in the DRC and most of the humid tropical part of the SSA region, climate and human behavior can complicate the ability for SOM and SOC to increase. Long-term cultivation causes the greatest losses of SOC in humid tropical climates, with up to 58% compared to native vegetation (Ogle, Breidt, & Paustian, 2005). Nevertheless, CA may only marginally increase SOC and the largest SOC increases compared to conventional tillage (i.e., 23%) occurred in the humid tropics (Cheesman, Thierfelder, Eash, Kassie, & Frossard, 2016; Ogle et al., 2005). In the DRC, the use of crop residue to feed animals and the cultural tendency to dispose of residue through burning, inherited from shifting cultivation, are potential barriers to SOM/SOC improvement.

Over time, significant differences associated with agricultural practices occurred for soil P and K. The implementation of CA has been shown to increase soil P and K (Palm et al., 2014). Palm et al. (2014) reported that CA increased P and K in the topsoil layer and that soil K levels were mostly related to the type of crop residue used. The retention of 30% crop residue on the farm has been shown to increase soil Ca, P, Mg, and K in South Africa (Malobane, Nciizah, Mudau, & Wakindiki, 2020). However, the variations induced by CA on soil P and K in smallholder farming in SSA are numerous. In Nigeria, for instance, it was reported that soil P and K decreased on cultivated lands with low rates under CA compared to conventional practice

(Agbede, 2008). In contrast to decreases shown by Agboola (2008) on a CA treatment with no mineral fertilization, Ojeniyi and Adekayode (1999) reported an increase in soil P and K in the rainforest of Nigeria. Ethiopia's research trials reported 21% and 19% increases in soil P and K, respectively, under CA over time (Cherie, 2021). Studies also reported no significant change in soil P resulting from CA implementation in Zambia and Zimbabwe (Martinsen et al., 2017; Nyamangara et al., 2013). However, despite some non-significant effects, CA can minimize soil erosion and erosion-associated nutrient losses (Govaerts et al., 2009).

This study also revealed that soil P differed between ecosystems over time, reflecting the influence of agroecological and climatic conditions on soil characteristics in the DRC. Humid conditions affect soil fertility in the SSA region (Tindwa, Semu, Shelukindo, & Singh, 2020). Tindwa et al. (2020) concluded that the abundance of rainfall is responsible for more leaching, leading to acidification in the Congo Basin's topsoil in SSA. Tropical soils are deficient in P due to low SOM and intense weathering (Juo & Franzluebbers, 2003). This study did not confirm the generalization of tropical soils' P deficiency. Therefore, it is more likely that soils in the forest and the savannah in the DRC's Maniema region could have responded differently to CA due to regional disparity in annual precipitation, but such an outcome did not occur in this study.

Overall, this study's significant and numerical soil chemical property results illustrate CA's potential to maintain soil nutrients and reduce soil erosion, even in the short-term in the DRC. Results also corroborate the claim that heterogeneous local conditions cause soil responses to CA to be site-specific (Corbeels, Thierfelder, & Rusinamhodzi, 2015; Giller et al., 2009). Consequently, additional long-term research and field experiments in various locations in the DRC and elsewhere in SSA are necessary to understand the potential benefits of CA adoption further.

3.4.2. Soil biodiversity

Another important result of this study was the effect of CA on soil biodiversity, as measured by earthworm populations, where CA implementation led to greater earthworm counts than conventional farming practices. A greater earthworm population in the soil under CA than the conventional practice in this study matched the results of previous CA studies conducted on-station and under smallholder farming conditions in SSA (Muoni et al., 2019; Ngwira, Aune, & Mkwinda, 2012; Thierfelder & Wall, 2010). Increased earthworm populations have been associated with improving SOM under CA in SSA tropical soils (Ligowe et al., 2017). Research has described no-tillage, crop residue burning, and fertilization as factors explaining CA's influence on earthworm abundance (Coulibaly et al., 2022; Perego et al., 2019; Thomason, Savin, Brye, & Gbur, 2017). Crop residues, in particular, have an essential role in boosting soil biological activities, as illustrated by increased earthworm populations reported under CA (Blanco & Lal, 2008). Earthworms improve the soil's structural properties and nutrient cycling by breaking down litter and binding soil particles with their excrements (Lal, 2015; Palm et al., 2014). As such, the average earthworm abundance measured in this study might have been even greater had CA significantly increased SOM, but that result did not occur. Nevertheless, this study's findings are still relevant, illustrating how CA improves soil biodiversity in the rural DRC's forest and savannah. In the long-term, CA can be viewed as a restorative farming practice that could eventually help smallholder farmers and replace fallow farming practices.

3.4.3. Cowpea yields

The improvement in cowpea yield due to the implementation of CA is a prominent contribution to smallholder farming in the DRC and suggests the potential of CA to contribute to food security. The results of this study showed that, when converting from conventional farming practices to CA, cowpea yields had a relative increase of 70 and 125% in 2010 and 2011, respectively (Fig. 3.8). A recent on-station variety trial study in the savannah of Lomami Province in the DRC reported an average yield of 621 kg ha^{-1} from 10 improved cowpea varieties (Tshibingu et al., 2017). The study by Tshibingu et al. (2017) was implemented with no agrochemicals, no fertilizers, and under conventional tillage using a hand hoe. Results of the present research indicated that local CA-produced cowpea obtained in 2011 in Maniema, DRC out-performed cowpea production on some research stations by 7% (Tshibingu et al., 2017).

Compared to a few CA studies involving cowpea with no fertilization in SSA, results vary and sometimes contrast with the current study results. In a trial conducted under smallholder farming conditions with no herbicides in Zimbabwe, Mashingaidze et al. (2012) reported an average CA-produced cowpea yield of 250 kg ha^{-1} compared to 413 kg ha^{-1} cowpea yield for conventional tillage, where CA's underperformance was attributed to a consequence of early-season weed pressure under CA. In Nigeria, a trial where different tillage practices were compared to CA reported the two highest cowpea yields of 930 kg ha^{-1} for plowing plus harrowing and ridging, followed by 890 kg ha^{-1} for CA (Ojeniyi & Adekayode, 1999). In Malawi, cowpea yields were 310 kg ha^{-1} greater for conventional tillage than CA in a trial that used glyphosate for weed control (Ngwira et al., 2020). Results of this study suggest that cowpea might perform better in the forest of Maniema, such as in Nigeria, and that CA should boost cowpea yields, as no herbicides or fertilizers were applied in this DRC smallholder farming study. However, such interaction of farming practice and ecosystem was inconclusive in Maniema, DRC. Additionally, knowing that crops extract soil nutrients needed for subsequent cultivations, it would be valuable to verify Nyamangara et al. (2013)'s conclusion that greater yields could be achieved when CA is coupled with the application of fertilizers.

Cowpea yield variability was also examined in this study, where the notion of crop yield variability entails that there is a random, unpredictable aspect of the performance of a cropping system and that, if the random component (i.e., the variance) is prominent, so is the yield variability for the cropping system (Piepho, 1998). In the current study, the variability in cowpea yields assessed for the two agricultural practices across sites suggested that cowpea yields varied more under CA than under conventional cowpea production in Maniema, DRC, as illustrated by a greater variance and coefficient of variation. However, CA-cowpea yield variability should be a less important concern. Using the mean of conventional cowpea yield as a threshold, CA appears risky than conventional practice for the smallholder cowpea producers in Maniema, DRC, but with a greater probability of yielding more than conventional.

Many interactions at work did not allow a comprehensive evaluation of CA's yield stability and instead led to variability analysis. The short duration of this study's field experiment (i.e., two years for cowpea) was likely a major factor. The relevance of crop yield variability is amplified with unpredictable weather conditions (Andersson & D'Souza, 2014). Studies investigating CA yield variability for at least four years have shown that CA led to either no difference or lower yield variability than conventional tillage, and the difference also depended on the crop and the proper application of CA. Williams et al. (2018) reported a decrease in yield variability for soybean (*Glycine max* L. Merr.), but not maize (*Zea mays* L.) under CA compared to conventional farming practices in the US. Anderson et al. (2020), who also demonstrated the importance of CA's no-tillage and cover crop principles in the US, reported CVs of 20 and 19% for CA and conventional tillage, respectively, for soybean yields and 14 and 18% for CA and conventional tillage, respectively, for maize yields. In contrast, Rusinamhodzi et al. (2011) demonstrated that there was no difference in yield variability between CA and conventional practices for maize, and Knapp and Van der Heijden (2018) had a similar no effect of CA for 16 crops, including maize, soybean, wheat, sorghum, and rice. Knapp and Van der Heijden (2018) also reported that CA crop yields were lower than conventional practice's yields when CA's crop rotation and mulching principles were not applied together with the no-tillage principle. Another recent study in Zimbabwe demonstrated that the integration of cowpea in a CA-intercropping system involving maize made CA more stable than mono-cropped maize (Madembo, Mhlanga, & Thierfelder, 2020). Yield variability under CA remains a relevant question for smallholder farming in SSA, as maintaining yield across time and location could contribute to increasing CA adoption.

Beyond assessing yield variability, this study identified the major measured factors responsible for cowpea yield variability. The five most-influential factors identified through CART analysis were agricultural practice, ecosystem, soil pH, and soil Ca and Na. Results of the CART analysis were similar to ANOVA results in showing that CA was the single most influential factor leading to greater cowpea yields (Fig.3.9). However, ecosystem and soil pH, Ca, and Na were also identified as influential factors on cowpea yields. Results of the CART analysis also identified specific threshold values for soil pH, Ca, and Na that can be used as target values to maximize the benefits of CA implementation. Beyond the soil properties measured and factors evaluated in this study, it is possible that other non-measured properties affected cowpea yields and contributed to the large variability associated with CA. In the US, Jernigan et al. (2020) demonstrated that legacy effects could support such interactions.

The measured variability of cowpea yields from CA is a result that merits greater focus in future studies. In two years, the yield of CA-produced cowpea was shown to be dependent on the site and this reflects CA's site-specific feature that could be associated with agroecological and climatic conditions. As such, the effect of CA on cowpea yields must be further demonstrated in the long-term (i.e., > 3-year duration of consistent management). Furthermore, though not addressed in this study, attention needs to be given to the other crops involved in rotations with cowpea.

3.5. Conclusions

Promoting CA in SSA smallholder farming is a challenging strategy chosen to make farming more sustainable. The promotion of CA as a sustainable farming technique has been slowed by lack of evidence, minimal communication regarding CA, and CA's heterogeneous outcomes in SSA. Conservation agriculture is not a panacea to the issue of low productivity in SSA, but that should not prevent trying to figure out where CA fits, as CA's potential benefits outweigh the risk of not trying. This study has contributed to the body of knowledge surrounding CA by providing evidence about CA performance in smallholder farming in the DRC.

This research aimed to understand the differences in select soil chemical properties, biodiversity, and crop yields induced by CA, and potential interactions with ecosystem type and time in the Maniema Province of the DRC. Results indicated that CA plays a role in maintaining and improving soil health, as CA resulted in greater soil available P and K and increased earthworm populations compared to conventional farming practices. Additionally, CA produced greater cowpea yields. However, results also demonstrated that CA-produced cowpea yields were less stable than yields from conventional farming practice, a result actually restricted to cowpea in Maniema, DRC.

Conservation agriculture appears to be a viable alternative to conventional farming practices in the DRC due to CA's potential to enhance ecosystem services for the soil and smallholder farmers. Future investigations should (i) explore CA’s crop yield variability over time, as having a temporally stable yield could be an additional contributing factor to CA’s acceptance by smallholder farmers, (ii) evaluate the influence of the other crops involved in rotation with cowpea, (iii) conduct field trials in other locations and ecosystems in SSA, and (iv) extend study durations beyond the short-term (i.e., > 3 years).

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CHAPTER 4: INCORPORATING ENVIRONMENTAL DAMAGE AS AN INPUT TO NOT AN EXTERNALITY OF PRODUCTION: A SOUTH AFRICAN ILLUSTRATION OF TOTAL FACTOR PRODUCTIVITY AND PROFITABILITY IN CONSERVATION AGRICULTURE

Abstract

South Africa has been the second largest wheat (*Triticum aestivum* L.) producer (by area and production) in Sub-Saharan Africa, behind Ethiopia. Literature suggests that globally wheat yields must increase to meet current and rising global demand, and yields must improve despite the potentially negative consequences of increasing temperatures and changing precipitation patterns globally. One climate change coping mechanism in wheat production in the Western Cape of South Africa is conservation agriculture (CA). Conservation agriculture CA enhances soil moisture, which can help adapt to changing precipitation patterns, and has benefits to the ecosystem such as improved biodiversity. Using a data set of 1,043 plot-level wheat observations collected at Langgewens and Tygerhoek research farms from 2002 to 2020, this study applies a Life Cycle Assessment (LCA) approach to estimate the environmental and economic benefits of switching from conventional wheat production to applying CA's zero tillage (zero-till) and no-tillage (no-till) systems. The results indicate that for every kg of wheat produced, ecosystems damage are 0.89, 0.65 and 1.8 (2020 ZAR) in Langgewens for no, zero and conventional tillage wheat, respectively, and 0.7 and 0.6 in Tygerhoek for no and zero-till. In Langgewens, zero- and no-till are 113 and 55% more efficient, respectively, than conventional tillage at converting environmental damage into a kg of wheat. Findings also suggest that adoption of CA has led to a reduction of environmental damages between 269.2 and 402.5 million ZAR compared to 100% conventional tillage in Western Cape wheat production. This study provides policymakers and agricultural stakeholders with numbers to support CA promotion and reinforce South Africa's wheat industry.

Keywords: *Conservation agriculture, Environmental efficiency, Environmental impact, Wheat, Commercial farming*

4.1. Introduction

Conservation agriculture (CA) is a climate-smart agricultural practice that aims to increase sustainable agriculture and improve farmers' livelihoods in the midst of climate change (Food and Agriculture Organization of the United Nations [FAO], 2019; Shrestha et al., 2020). As an alternative to conventional tillage practices, which in some cases have led to land degradation, CA is a sustainable farming approach that internalizes both environmental and economic metrics when evaluating success (Mitchell et al., 2019). Like most agricultural practices, the benefits of CA are heterogeneous across and even within countries (Giller et al., 2009), with some benefits (such as increased yield) not internalized for several growing seasons (Corbeels et al., 2020). A better understanding of CA's holistic (environmental and economic) benefits and their respective spatial and temporal components could help increase CA adoption in low- and lower-middle-income countries as producers often have a higher discount rate for money. While there is extensive literature on CA and its effect on crop yields, little research has been conducted in monetizing CA's environmental impacts in Sub-Saharan Africa (SSA). Economists and producers often recognize the presence of environmental benefits from CA adoption but often fail to quantify these benefits with little to no attempt to monetize them. A more holistic (both economic and environmental) valuation of CA could help producers and policymakers adopt/incentivize the adoption of CA. Further, by monetizing the environmental costs of production, economists can begin to view environmental costs as an input to, rather than an externality of, agricultural production leading to more informed decision making.

Since the 1990s, global CA adoption has increased through producer education and non-governmental and governmental action to highlight the environmental and economic benefits of CA, specifically in the face of increased climate variability (Kassam et al., 2019). By applying

CA, producers can potentially internalize the economic, agronomic, environmental, and social benefits of CA adoption. Ideally, these benefits are not mutually exclusive (Food and Agriculture Organization of the United Nations [FAO], 2019; Fuentes Llanillo et al., 2020). Like potential benefits of CA, its adoption percentage is heterogeneous as North America, South America, and Australia have seen high relative rates of CA adoption, while CA adoption in Sub-Saharan Africa (SSA) remains low (Kassam et al., 2019, 2022). In SSA, previous research has shown that lack of operating skills combined with a poor understanding of CA principles, crop yields variability, residues management, weed pressure, and resistance to change are among the factors limiting CA adoption (Bunderson et al., 2017; Corbeels et al., 2015; Lee & Thierfelder, 2017; Ranaivoson et al., 2017). In Kenya and Ethiopia, Valbuena et al. (2012) found that crop residues from production were used to feed livestock and sold as animal feed, decreasing the volume of residues needed for CA's mulching, dampening its potential. Trials conducted in Malawi, Mozambique, Zimbabwe, and Zambia report that CA-maize yields were reduced by 50% compared to conventional farming when residues, vital to the success of CA, were taken out of the field (Thierfelder et al., 2013). In Burkina Faso, a 71% increase in labor was needed in sorghum due to extra weeding under CA, a situation that reduces the attractiveness of CA to producers and can threaten the expansion of CA across the African continent (Nana et al., 2014). Although CA has seen low adoption across Africa, given its large-scale commercial agricultural setting and increased frequency and severity of droughts and heat events, South Africa has experienced a large increase in CA adoption, specifically in dryland production areas. One important question in the South African context is, has the adoption of CA benefited producers, the environment or possibly both? Or was adoption of CA simply a product of a changing environment which could possibly reduce producer profitability and increase the metric of "environmental damage per unit of output?"

Traditional increases in agricultural total factor productivity (TFP) efficiency have been defined by the links between converting inputs (land, labor, capital, and materials) into outputs (fuel, food, and fiber) with little attention paid to the increasing efficiency of converting environmental damage into outputs. For example, converting dryland rice to irrigated rice may increase production efficiency, and the food supply, but increase the important metric of environmental damage per unit of production. Conversely, Burney, Davis, and Lobell (2010) found that while greenhouse gas (GHG) emissions from factors such as fertilizer production and application have increased, the net effect of higher yields has avoided GHG emissions up to 161 gigatons of carbon (GtC) (590 GtCO2e) since 1961. They concluded that investments in yield improvements compare favorably with other commonly proposed mitigation strategies. Further yield improvements should therefore be prominent among efforts to reduce future GHG emissions. While previous studies have analyzed specific metrics of environmental damage (CO_2 emissions, global warming potential [GWP]) with regard to increasing agricultural efficiency, none have monetized the environmental damage creating the important "environmental damage in Rand per unit of output" metric via a Life Cycle Assessment (LCA).

Investigations related to agricultural TFP in SSA are necessary to guide policy and support the promotion of sustainable agriculture. A study by Alhassan (2021) demonstrated that boosting agricultural productivity to meet food demand in SSA comes with a cost to the environment and that intensification of production in the absence of any offsetting measures to protect the environment has a negative environmental impact. It would appear that changing farming technologies in SSA is not free of environmental damage. A TFP accounting for environmental damage could translate the information on the environmental effects in agricultural production to policymakers. In South African context, Van der Laan et al. (2017) concluded that sustainable crop production is a product of genotype (G) x management (M) x environment (E). Significant gains in wheat varieties by plant breeders over past decades have masked the negative impact on the environment, which has been neglected due to lack of consideration of externalities, because environmental impacts play out over a long time, and because of the difficult to quantify the economic cost of environmental degradation. Degrading the environment, together with stagnation in yield enhancements through genetic progress, will present an ever-increasing challenge in many wheat growing regions globally including South Africa.

South Africa accounts for 51% of CA farmland in Africa (Kassam et al., 2022). Ghana, Malawi, Mozambique, Zambia, Zimbabwe, and South Africa accounted for 95% of the continental CA's farmland in 2019 (Kassam et al., 2022). The majority of the CA farmland in South Africa is found on large-scale mechanized farms (Corbeels et al., 2015). CA in South Africa has been a point of focus of agricultural research since the 2000s with the combined involvement of the Department of Agriculture, Land Reform and Rural Development (DALRRD), the Agricultural Research Council (ARC), universities, and non-governmental organizations (Strauss et al., 2021). The adoption of CA in commercial production in SSA has been traditionally associated with reduced costs and decreased soil degradation (Corbeels et al., 2015). Additional motives found in South Africa include coping with climate shocks, a growing CA awareness amongst producers, and a concerted effort to improve resource management (Blignaut et al., 2015). The Western Cape (WC) province, which accounts for 60% of South

Africa’s wheat production (USDA & GAIN, 2020), has experienced the largest relative and absolute adoption of CA.

According to the Agricultural Research Council [ARC] (2021) in South Africa, CA’s increased economic and biological sustainability are the contributing factors pushing its expansion in the WC province. Previous studies have shown that in the WC wheat production, CA has increased yields and profit, reduced soil erosion, and improved water quality and soil health (Knott et al., 2017; Swanepoel et al., 2018). CA is increasing in importance for South Africa’s rainfed agriculture sector as it responds to the country’s low and increasingly erratic rainfall and poor-quality soils (Van Antwerpen et al., 2021). The ARC endorses CA in WC rainfed wheat production in response to soil degradation and the adverse effects of climate change, such as drought and heat stress, as CA can increase soil moisture by decreasing water runoff (ARC - Small Grain, 2021; Patose & Ncala, 2020). Previous research has shown that wheat yield losses in South Africa are affected by extreme heat; increasing temperature by 1, 2, and 3^{o}C lead to 8.5%, 18.4%, and 28.5% yield reduction, respectively (Shew et al., 2020). In a 12-year trial study in Langgewens, Crookes et al. (2017) demonstrate that the CA’s crop diversification principle, illustrated by rotational wheat production systems, leads to wheat performing well under drought conditions. While CA adoption has seemingly been driven by an increase in both climatic variability and input costs, this study sets out to address if CA is more efficient from both an environmental and economic perspective. Adapting to climate change with a production method that in the short run could result in marginal profitability but, in the long run, could exacerbate climate change is not sustainable. As importantly, policy makers may start viewing environmental damage as an input to production and not simply a product of output. Thus, a monetization of the environmental damage per unit of output (kg of wheat) produced is a metric policy makers and producers may start internalizing as an input to minimize, relative to output.

The present study uses a stepwise Life Cycle Impact Assessment (LCIA) to monetize conventional tillage and CA's environmental impact in commercial wheat farming in the WC province of South Africa. The stepwise LCIA method allows the holistic quantification of environmental damages of a process or a product as a single score expressed in Rand per unit of output, Quality Adjusted Life Years [QALYs] or Biodiversity Adjusted Hectare Years [BAHYs] (Weidema, 2009). This study's stepwise LCIA uses primary data from long-term wheat trials in WC to examine two CA wheat production practices and their effects on changes in traditional profitably efficiency as well as changes in environmental efficiency (turning environmental damage into outputs).

This article is unique amongst the CA literature as it monetizes and then compares the efficiency of switching from conventional tillage to CA (zero or no-till) wheat production from both a producer profitability (turning inputs into profits) and environmental (turning environmental damage into output) standpoint. Using yearly data collected on 1,043 trial plots from 2002 to 2020 in Langgewens and Tygerhoek Research Farms, we compare stepwise LCIA single scores for one hectare and one kilogram of wheat produced in the WC under zero-till, no-till, and conventional wheat production. Policymakers can use the results of this study to potentially create incentives for producers in the WC and other wheat-growing areas of South Africa to adopt CA. A large contribution of this study is that when decision-makers evaluate input-reducing research, such as CA, they should look deeper than the cost savings or increased input use efficiency and internalize the wider environmental implications when trying to maximize agricultural production efficiency.

4.2. Literature review

4.2.1. CA adoption in South Africa

In 2020, some form of CA was estimated to be adopted on 25% of all South African cropland (Smith, 2021; Strauss et al., 2021). CA is typically implemented on large-scale commercial farms with limited adoption amongst smallholder farming operations across South Africa (Mazvimavi, 2010; Mudavanhu, 2015). While there is spatial heterogeneity in adoption, there is also a distinction between commercial and subsistence farming adoption rates with CA. It was estimated that CA was adopted on just 0.84% of subsistence farms across South Africa farmland in 2020 (Smith, 2021). The area under CA production in South Africa has increased by 366% from 2016 to 2019 (Kassam et al., 2022). Unlike in Europe and the United States, where there are government programs that incentivize CA adoption, in South Africa adoption has been producer-driven, likely a result of increased input costs and precipitation variability. Apart from the 2017 – draft CA policy by the South Africa Department of Agriculture, Forestry and Fisheries (DAFF), which aimed to guide the dissemination of CA in the South African agricultural production system through the implementation of sustainable land-use programs, there are no current governmental programs which incentivize CA adoption in South Africa.

Previous research has indicated that commercial farmers' decision to adopt CA in South Africa is individually-motivated, and these adopters were not incentivized by government programs (Findlater et al., 2019; Smith et al., 2017; Swanepoel, Swanepoel, et al., 2018). In the WC province, CA adoption was also facilitated by the availability of no-till machinery made possible in the late 1990s (Strauss et al., 2021). The higher cost of suitable planters and the lack of technical expertise were limiting the early adoption of CA in South African commercial farming (Modiselle et al., 2015; Smith et al., 2017).

In 2021, the WC province had a CA adoption rate estimated at 51% of its annual cropland, the highest area and percentage in South Africa (Smith, 2021). In the rest of South Africa, CA's major field crops range from maize, soybean, and sunflower to pastures, while in the WC, wheat in rotation with legumes is the primary winter cropping system found under CA (Smith et al., 2017). A survey conducted by Modiselle et al. (2015) suggests that 49% of commercial wheat farmers in the WC implemented all three principles of CA (no or low soil disturbance, mulching, and rotation), and another 49% implement at least one of the three CA principles.

4.2.2. CA and profitability in South Africa

Previous literature suggests that CA agricultural research in South Africa has increased in the last decade, mainly covering soil and agronomy themes, with limited research on the socio-economic aspects such as CA profitability (Swanepoel, Swanepoel, et al., 2018). The economic research has primarily focused on CA's crop diversification principle, which contributed to the dissemination of CA in South Africa, assessing financial profitability in wheat production (Knott, 2015; Visser, 2014). In the WC, Knott (2015) simulated a wheat farming budget over 20 years period, demonstrating that investing in wheat monoculture and conventional tillage led to negative present value [NPV] and internal rates of return (IRR) below the real interest rate (2.73%). Knott (2015) also found that CA led to varying positive IRRs and NPVs depending on the rotation option. Visser (2014) and Knott (2015) highlight the financial implication of implementing CA principles and show that crop rotations under CA improve wheat production profitability.

4.2.3. Environmental externalities of CA

Previous literature has shown that CA has the potential to provide environmental benefits in Southern Africa when compared to conventional tillage (Thierfelder et al., 2015). Some of the main environmental benefits can include increasing water infiltration, reduced soil erosion and run-off, improved soil structure, biodiversity increase, better soil, air, and water quality, and carbon sequestration (Food and Agriculture Organization of the United Nations [FAO], 2019; Thierfelder et al., 2015).

A large gap in the CA literature in South Africa is an attempted at monetizing environmental externalities from changing from conventional to CA practices and treating this monetized environmental damage as an input to production. Previous literature (Knot, 2014) quantified the environmental effect in the form of greenhouse gas (GHG) emissions between CA and conventional wheat production using inputs and assumed an arbitrary carbon tax of 120 ZAR per ton of CO_2-eq. Knot (2014) found that over seven years, CA implemented with no agrochemical inputs had a lower environmental cost compared to conventional tillage production. The main driver of environmental damage was the fact that conventional tillage used 79% more diesel per hectare than CA (Knot, 2014). While the Knot (2014) study provided a valuable first insight to GHG emissions and CA adoption, environmental degradation manifests itself in many alternative forms besides GHG emissions.

Although CA can reduce the amount of diesel requirements in production, empirical evidence has shown that CA can increase weed infestation, and CA crops can benefit from the increase in herbicide use (Corbeels et al., 2020; Singh et al., 2015). Under CA, the efforts to control weeds in Eastern Free State, were significantly higher per hectare due to more herbicides (Knot, 2014). A 2015 survey of commercial wheat farmers in the WC indicated that 60%

reported increased weed control costs, while 40% spent more on pest and insects control as a result of implementing CA (Modiselle et al., 2015). Unlike Knot (2014), whose assessment of the environmental impact of CA in South Africa was limited to analyzing GHG emissions, a life cycle assessment (LCA) approaches CA's environmental impact more holistically. The LCA provides various impact categories and accounts for all inputs and outputs of all processes and products involved in commercial wheat production.

4.2.4. Estimating the environmental impact of Wheat Production

Life cycle assessment (LCA) is a compilation and evaluation of a product system's inputs, outputs, and potential environmental impacts throughout its life cycle (International Standard Organization [ISO], 2006). LCAs cover a broad range of impacts, including social and economic, for which it attempts to perform a quantitative assessment (Hauschild et al., 2017). LCA method is used to examine environmental concerns in the RSA's agricultural and industrial food production and comply with international standards (Brent et al., 2002). According to the Department of Environmental Affairs and Tourism [DEAT] (2004), LCAs are used by South African companies in response to legislative pressures for sustainability.

The South African literature is not void on LCA research in the food and agricultural industry (de Kock et al., 2019; Devers et al., 2012; Pryor et al., 2017; van der Laan et al., 2015), but the LCA research on CA is limited. Using a life cycle inventory (LCI), which is the data collection portion of an LCA, de Kock et al. (2018), determined the carbon footprint of CA compared to conventional tillage in commercial wheat farming in WC. De Kock et al.'s functional unit was a ton of wheat delivered at the farm gate. The findings on carbon footprint in de Kock's report suggest that CO_2 emissions decreased by 3.5% when wheat farmers implemented CA instead of conventional practice and could reach as much as a 44% reduction if wheat producers implemented CA for twenty years. De Kock et al. (2018) also show that synthetic fertilizers led by N-fertilization contributed to 70% of total CO_2 emissions per hectare, a figure that could decrease to 61% in 20 years if the wheat farmers continuously implement CA. De Kock et al. (2018) is consistent with Knot (2014) on imputing some environmental burden to N-fertilization.

Unlike previous studies that assumed an arbitrary carbon tax (Knot, 2014) to value environmental damage and those who only focused on CO_2 emissions (de Kock et al., 2018), this study uses a stepwise LCIA to monetize multiple aspects of environmental damages from the production of a specific metric (per ton or per hectare) of wheat produced in the WC. In the TFP literature, this monetized environmental damage can be thought of as an input to obtain an output. Viewing environmental damage as an input allows economists to either, try and reduce environmental damage holding yield constant, increase yield while holding environmental damage constant, or, ideally, increase yield while reducing environmental damage by increasing the "efficiency" at turning environmental damage into a ton of wheat. Because the stepwise LCIA monetizes the value of environmental damage, we can treat this value as an input to production rather than an externality of it. Commercial wheat farming in South Africa provides an interesting medium for studying this new "efficiency" measurement as it has been identified as both an input reducing practice but one which has mostly been adopted out of necessity due to climate change (Archer et al., 2019).

4.3. Materials and Methodology

4.3.1. Research data and location

The WC wheat data used for this study was extracted from the long-term trials database of the Directorate Plant Sciences of the WC Department of Agriculture (DPS). The data set comprises 1,043 plot-level rainfed winter wheat production observations collected at the Tygerhoek and Langgewens research farms from 2002 to 2020 (Western Cape Department of Agriculture [WCDA], 2021). The individual plot size ranged from 0.5 to 2 ha. Each annual dataset contained data related to all plots used in a particular year and, for each plot, the information on the cropping system, gross income and margin, prices of wheat produced during the winter season, detailed types and costs of wheat seed, fertilizers, and amendments, fungicides, herbicides, insecticides, machinery, and operational field activities. Two CA systems were implemented: no tillage (no-till) and zero tillage (zero-till). According to the ARC (2021), both "no-till and zero-till" in the South African context refer to the seeder used to implement the CA system. In the case of no-till, a knifepoint opener is used to place seed and fertilizer, while for zero-till the placement is executed with discs. One could also describe the use of the knifepoint opener as "high disturbance" no-till and the use of discs as "low disturbance" no-till (Fig. 4.1).

Ideally, there would be head-to-head comparisons of CA and conventional tillage, but this was not available for the WCDA dataset. Therefore, the production information related to conventional tillage used in this study was sourced from Knott (2015) based on data collected at Langgewens experimental farm between 2007 and 2013.

Figure 4.1. Illustration of soil disturbance under CA systems at Langgewens research farm in Western Cape, South Africa: No-till (left) using a knifepoint opener and zero-till (right) using discs (Source: Strauss, Western Cape Department of Agriculture, 2022).

4.3.2. Environmental impact estimation

A Life Cycle Assessment (LCA) is used to quantify the cradle-to-farm gate environmental impacts of producing one kilogram (kg) and one hectare (ha) of wheat under CA's no-till and zero-till on two experimental farms in the WC. Following similar environmental impact studies (Durand-Morat et al., 2018; Nalley et al., 2016), the LCA aimed to elicit the environmental impacts of applying the two CA systems and conventional commercial wheat production. Comparisons were made between one kg and one ha of wheat produced under no-till and zero-till using the LCA software SimaPro 9.1.0.8.[2] (PRé Consultants bv) and the Ecoinvent and Agri-footprint databases (Durlinger et al., 2017; Wernet et al., 2016). Estimating two functional units in LCA research (like one kg and one ha of wheat here) is not uncommon and depends on the study's objectives (Cerutti et al., 2013; Hayashi, 2013; Nemecek et al., 2011). The LCA evaluation provides an environmental cost, which means it monetizes, in ZAR, the environmental externalities of producing one kg and one ha of wheat using the preceding farming practices in the WC Province. Table 4.1 presents the impact categories included in the LCA.

The average yields for each farming practice at Tygerhoek and Langgewens (Table 4.2) were entered into SimaPro along with respective input types and amounts to serve in the computation of environmental damage per kg and hectare in the LCA Stepwise analysis. The production cost and subsequent variance in Langgewens is larger (Table 4.2), which is explained by the larger amounts of fertilizers and soil amendments required. The other inputs entered in SimaPro included diesel fuel, fertilizers, amendments, herbicides, insecticides, and fungicides

[2] There were no data related to conventional tillage at Tygerhoek and as such only the two CA production methods could be compared. In Langgewens, data existed for all three production methods for a more complete comparison.

used per hectare in Tygerhoek and Langgewens (Table A.4.1 in appendix). The amounts of these inputs were all averaged across year and plot by production practice.

Table 4.1. Environmental impact categories used in the Life Cycle Assessment (LCA) for CA vs Conventional Wheat Production in South Africa (Stepwise method).

Category	Units	Description
Carcinogens	kg C_2H_3Cl-eq	Human toxicity from carcinogens (e.g., pesticides, chemicals)
Non-carcinogens	kg C_2H_3Cl-eq	Human toxicity from non-carcinogens (e.g., heavy metals)
Respiratory inorganics	kg $PM_{2.5}$ eq	Primary and secondary particulate emissions
Ionizing radiation	Bq C-14-eq	Damages to human health and ecosystems that are linked to the emissions of radionuclides
Ozone layer depletion	kg CFC-11-eq	Accumulated ozone-depleting compounds emissions
Ecotoxicity, aquatic	kg TEG-eq w	Ecosystem toxicity associated with emissions to water bodies
Ecotoxicity, terrestrial	kg TEG-eq	Ecosystem toxicity associated with emissions to land
Nature occupation	m^2-years agri	Agricultural land occupation – a proxy for effects on biodiversity
Global warming potential	kg CO_2-eq	Accumulated greenhouse gas emissions (IPCC 2006 characterization factors)
Acidification	m^2 UES	Terrestrial acidification driven by acid gases; UES =Unprotected Ecosystem
Eutrophication, aquatic	kg NO_3-eq	Freshwater and marine eutrophication driven by nutrient run-offs
Eutrophication, terrestrial	m^2 UES	Excess nutrients on land
Respiratory organics	pers*ppm*hr	Human health effects from volatile organic compounds
Photochemical ozone, vegetation	m2*ppm*hr	Damage to vegetation estimated from ozone emission
Mineral extraction	MJ extra	Mineral extraction energy consumption
Non-renewable energy	MJ primary	Fossil fuel energy consumption

The Stepwise Life Cycle Impact Assessment (LCIA) method applied in SimaPro provided a combined score for both human and environmental effects in monetary terms (Weidema, 2009). A consistent framework for estimating the cost of environmental externalities was provided by this method in South Africa, comparing genetically modified (GM) and conventional maize adoption (Ala-Kokko et al., 2021). The stepwise method has midpoint characterization factors and endpoint characterization factors (Weidema, 2015; Weidema et al., 2008). In addition, normalization and weighting factors based on European Union cumulative per-capita emissions in 1995 are included. The method extends other impact assessment approaches based on damage characterization to human health and the ecosystem as defined by quality-adjusted life years (QALY) and biodiversity-adjusted hectare years (BAHY). The two measures are related to estimated costs associated with various contributing factors to different midpoint impact categories, as presented in Table 4.1. Further, the method assigns a cost of 1/14 QALY per BAHY (Weidema, 2015; Weidema et al., 2008). The costs presented are the estimated expense to offset environmental and human health externalities when choosing to implement CA's no-till and zero-till or conventional farming in wheat production. That is, to restore full QALYs and BAHYs based on the "ability to pay," derived from resource constraints and the equivalence factor between QALY and BAHY adopted by the method. The stepwise cost outputs were generated in Euro 2003, adjusted to Euro 2020, accounting for inflation, then converted to ZAR 2020.

Table 4.2. Average yield and production costs (2020 ZAR) per hectare for No-till and Zero-till in Tygerhoek and Langgewens: 2002-2020

Location/Tillage	N	Wheat yield (ton/ha)		Cost (ZAR/ha)[a]	
Tygerhoek	572	Mean	SD	Mean	SD
• No-till		3.61	1.00	4,512	677.24
• Zero-till		3.37	1.52	4,425	568.59
Langgewens	471				
• No-till		3.43	1.02	5,455	1,276.34
• Zero-till		3.30	0.83	5,238	2,094.73

[a] Summation of all costs associated with one hectare of wheat production given specified test plot inputs averaged across all years of production derived from Appendix 1.

4.3.3. Environmental efficiency

Environmental efficiency has received several names in agricultural LCA research, but its interpretation is based on the environmental impact found on ecosystems. Common names seen in LCA literature include agricultural eco-efficiency (Wang et al., 2022), productive efficiency (Tricase et al., 2018), EcoX indicator (Brentrup et al., 2004), eco-efficiency (Masuda, 2016; Nemecek et al., 2011), and environmental efficiency (Cerutti et al., 2013). In this study, the term "environmental efficiency" used by Cerutti et al. (2013) is preferred as it considers mass-based interpretation to better define the environmental performance of a production system.

The comparison of the LCA single score (the combined impact of all LCA categories from Table 4.1 into one monetized score) in 2020 ZAR[3] per kg of wheat allows for a comparison in efficiency between the two CA production methods and conventional tillage. The increase in environmental efficiency is described as the change in the ratio of monetized environmental damage, and was calculated as

$$\Delta\, Env.Efficiency = \frac{Env.SS_{Conv} - Env.SS_{CA}}{Env.SS_{CA}} * 100 \quad (1)$$

where $Env.SS_{conv}$ and $Env.SS_{CA}$ are respectively LCA single score costs for conventional and CA wheat, respectively.

4.3.4. Profitability of commercial wheat production

This study also implements a profitability analysis comparing no-till versus zero-till in Langgewens and Tygerhoek and a comparison of all three production methods in Langgewens. We use plot-level wheat production reports from 2002 to 2020 (WCDA, 2021) to estimate

[3] The conversion rate of USD to ZAR is 1 USD = 16.17 ZAR as of May 10, 2022 (https://www.oanda.com/currency-converter).

average wheat yields, prices, and production costs across years. All price and cost values were given in ZAR and inflation-adjusted to January 1, 2020. Table 4.2 summarizes the information used for profit simulation.

Profitability for wheat production under CA's no-till and zero-till in Langgewens and Tygerhoek, respectively, was simulated using @Risk© (Palisade, Ithaca, NY). Following similar studies (Nalley et al., 2016; Ala-Kokko et al., 2021), 1,000 iterations were run for each of the two sites, and a two-tailed t-test was used to test for statistical differences between the profitability of producing wheat under no-till and zero-till. The simulated profit and environmental impact [the environmental cost obtained from stepwise LCIA] are used to derive the net impact of switching from conventional to no-till and zero-till. The economic impact of switching is the profit difference between no-till and zero-till, respectively, and conventional tillage.

The simulated net profit (NP) without environmental benefits for a hectare of wheat production was calculated as

$$NP_{ij} = TR_{ij} - TC_{ij} \quad (2)$$

where NP_{ij} is the simulated net profit as a function of total revenue (TR_{ij}) and total cost (TC_{ij}) per hectare of producing wheat under i^{th} CA system (zero-till or no-till) in j^{th} site (Langgewens or Tygerhoek) all of which were simulated using a normal distribution from the statistics given on Table 4.2. The TR_{ij} was obtained from

$$TR_{ij} = Y_{ij} * P \ (3)$$

where Y_{ij} the simulated wheat yield in ton per hectare under i^{th} practice (zero-till or not-till) from Table 4.2 at j^{th} site (Langgewens or Tygerhoek) was multiplied by the simulated price of wheat per ton (P), from 2002-2020 in 2020 ZAR. The simulated price mean was 3,804.06 ZAR with a standard deviation of 741.64 ZAR per ton (WCDA, 2021).

The environmental benefits (EB_i), in ZAR, from switching from conventional to CA production system *i* per hectare can be calculated as:

$$\Delta EB_i = EB_{con} - EB_{CA} \quad (4)$$

where EC_{con} is the LCA single score cost of producing one hectare of conventionally tilled wheat and EC_{CA} is the LCA single score cost of producing one hectare of wheat using CA system *i*.

The total benefits (TB) in ZAR per hectare of switching from conventional wheat production to either zero-till or no-till production in Langgewens was calculated as

$$TB_i = \Delta NP_i + \Delta EB_i \quad (5)$$

where the difference in net profit from Equation 2 (ΔNP) between conventional and CA system *i* (zero-till or no-till) is summed with the change environmental benefits (ΔEB) from Equation 4 of switching from conventional to CA system *i* (zero-till or no-till) wheat production.

4.4. Results and Discussion

4.4.1. Wheat production environmental efficiency

Results of the LCIA single score in Table 4.3 represent, in ZAR, the monetized environmental cost for producing one kilogram of wheat under zero-till, no-till, and conventional farming at Langgewens and Tygerhoek research sites in WC. Table 4.3 also provides the LCIA single score disaggregated per impact category.

The LCA single score results in Table 4.3 indicate that for every kg of wheat produced in Langgewens there was 0.89, and 0.65 ZAR in ecosystems damage under no-till and zero-till wheat production, respectively. In Tygerhoek, the LCA single score was 0.71 and 0.6 ZAR in ecosystems damage under no-till and zero-till wheat production, respectively. Given the additional N-fertilizer usage requirements in Langgewens and lower yields, it is not surprising that its single scores were higher than Tygerhoek. The single scores for conventional tillage wheat production were 2.9, 1.8, and 1.4 ZAR per kg in ecosystems damage in a poor, average, and good yield year, respectively, in Langgewens. These findings suggest that CA wheat production has a lower environmental impact than conventional wheat production and, among CA systems, zero-till has a lower environmental impact than no-till.

Table 4.3. Environmental impact costs for various wheat production methods using stepwise LCIA method for 1 kg of wheat production in Western Cape, South Africa (in 2020 ZAR)

	Langgewens					**Tygerhoek**	
	No-till	**Zero-till**	**Conventional tillage**[a]			**No-till**	**Zero-till**
			Poor	*Average*	*Good*		
Total environmental cost (single score)[b]	**0.887**	**0.646**	**2.919**	**1.796**	**1.374**	**0.711**	**0.599**
Human toxicity, carcinogens	0.0129	0.0101	0.0452	0.0278	0.0213	0.0131	0.0095
Human toxicity, non-carcinogens	0.0102	0.0065	0.0275	0.0169	0.0129	0.0085	0.0062
Respiratory inorganics	0.2891	0.2104	0.9198	0.5660	0.4328	0.2396	0.1930
Ionizing radiation	0.0003	0.0002	0.0008	0.0005	0.0004	0.0003	0.0002
Ozone layer depletion	0.0001	0.0000	0.0002	0.0001	0.0001	0.0001	0.0000
Ecotoxicity, aquatic	0.0009	0.0007	0.0026	0.0016	0.0012	0.0010	0.0007
Ecotoxicity, terrestrial	0.0152	0.0098	0.0420	0.0258	0.0198	0.0112	0.0088
Nature occupation	0.0069	0.0049	0.0206	0.0127	0.0097	0.0062	0.0045
Global warming, fossil	0.5240	0.3835	1.7687	1.0884	0.8323	0.4087	0.3567
Acidification	0.0036	0.0026	0.0117	0.0072	0.0055	0.0030	0.0024
Eutrophication, aquatic	0.0010	0.0008	0.0035	0.0022	0.0016	0.0013	0.0012
Eutrophication, terrestrial	0.0128	0.0094	0.0430	0.0264	0.0202	0.0097	0.0085
Respiratory organics	0.0005	0.0004	0.0017	0.0011	0.0008	0.0004	0.0004
Photochemical ozone, vegetation	0.0094	0.0069	0.0312	0.0192	0.0147	0.0076	0.0066
Mineral extraction	0.0003	0.0002	0.0007	0.0004	0.0003	0.0002	0.0001

[a] Conventional wheat production based on LCA inputs sourced from Knott (2015). Knott (2015) established three wheat yields scenarios based on seasonal variations: poor, average and good yield with respectively 1.6, 2.6, and 3.4 ton/ha for conventional tillage wheat production in the Western Cape.
[b] Summation of all impact categories.

These results provide important metrics about the efficiency at turning environmental damage (input) into a kg of wheat (output). Table 4.3 suggests that zero-till is 352, 178, and 113% more efficient at converting environmental damage into a kg of wheat than conventional tillage under poor, average, and good yielding scenarios, respectively. Another way of viewing this efficiency gain is that for the same environmental damage as one kg of conventional tillage under poor, average, and good yielding scenarios, you could yield 3.52, 1.78, and 1.13 more kg of wheat, respectively, with zero till wheat production in Langgewens. Using the same methodology, no-till is 229, 102, and 55% more efficient at converting environmental damage into a kg of wheat than conventional tillage under poor, average, and good yielding scenarios, respectively.

Estimating per hectare environmental damage is a function of the single scores reported in Table 4.3 multiplied by the average yields in Table 4.2. It was estimated in Langgewens to be 3,039; 2,134, and 4,671 ZAR worth of environmental damage per hectare for no-till, zero-till, and conventional wheat production, respectively. In Tygerhoek, this environmental cost per hectare was estimated to be 2,567 and 2,018 ZAR for no-till and zero-till, respectively.

The total environmental cost expresses the cost of the overall damage wheat production inflict on ecosystems, estimated per kg of wheat produced in Langgewens and Tygerhoek and disaggregated per impact category (Table 4.3). Respiratory inorganics and effects associated with global warming from fossil fuels accounted for 91.7% of the environmental costs of the damage associated with conventional, no-till, and zero-till wheat production at Langgewens and Tygerhoek. The other environmental burdens were clustered around photochemical ozone, terrestrial eutrophication, terrestrial ecotoxicity, human toxicities, and land occupation (Table 4.3).

While increasing environmental efficiency is important for policy makers and to some extent producers, the driving factor of agricultural technology is producer profitability. If CA is found to be less profitable than conventional tillage, and without government incentives, commercial wheat producers will continue to practice conventional tillage.

4.4.2. Profitability differences between CA and conventional wheat production

CA systems economic profitability

The results of the profit simulations (using Equation 2) indicate in Table 4.4 that the average gain in ZAR per ha obtained from CA wheat production varies by location and CA system. In Tygerhoek and Langgewens, the no-till profit is 6% and 4% higher than zero-till, respectively. Finding profits that vary with location in South Africa is no uncommon (Knott, 2015; Nell, 2019). CA economic profit is a function of several factors, including crop yields that also change with locations in South Africa, as noted by Swanepoel et al. (2018).

Table 4.4. Estimated net profit per hectare (2020 ZAR) for CA wheat production in Western Cape, South Africa

	Average profit[a]	5% confidence interval	95% confidence interval
Tygerhoek			
• No-till	9,200	-748	19,638
• Zero-till	8,598	2,050	16,936
Langgewens			
• No-till	7,590	523	16,271
• Zero-till	7,318	537	14,953

[a] Calculated from Equation (2)

Holistic benefit of switching to CA systems in Western Cape

The results of the LCA single scores suggest that there are more benefits beyond the economic profit from CA adoption. Table 4.4 provides the traditional metric of profit (not accounting for environmental damage), the environmental metric (LCA single score per hectare), and a combined metric (traditional plus environmental) for profitability between CA systems and conventional tillage per hectare in Langgewens. Importantly, Table 4.5 may shed some light on why CA has not reached full adoption potential as the difference between conventional profitability under a good year of conventional tillage is only marginally different than CA systems. When accounting for the environmental benefits (which most producers do not internalize, and rightfully so given the lack of incentives), the benefit from switching from conventional to zero-till goes from 55 ZAR per hectare under the traditional method of measuring profitability to a 2,593 ZAR per hectare. Under poor and average yields for conventional tillage CA seems to make economic sense, even in the traditional profitability accounting system. However, there seems to be some hesitation to CA adoption when looking at conventional tillage with good yields, specifically given the fact that a 2015 survey of commercial wheat farmers in the WC indicated that 60% reported increased weed control costs and more health risks, while 40% spent more on pest and insects control as a result of implementing CA (Modiselle et al., 2015).

Table 4.5. Average Total benefits (2020 ZAR per hectare) associated with switching to CA from conventional tillage systems in Langgewens

	Net profit difference[a]		Ecosystem damage cost difference[b]		Total benefits[c]	
	Zero-till	No-till	Zero-till	No-till	Zero-till	No-till
Conventional Good Yield	55	327	2,538	1,629	2,593	1,956
Conventional Average Yield	3,098	3,370	2,538	1,629	5,636	4,999
Conventional Poor Yield	6,902	7,174	2,538	1,629	9,440	8,803

[a] Calculated using Table 4.4 and estimates from Knott (2015). Points estimate of profit for conventional wheat production from Knott (2015) in 2020 ZAR are 7,263; 4,220; and 416 per ha, respectively for good, average and poor yield.
[b] Calculated by multiplying Table 4.3 single scores by wheat yields in Table 4.2.
[c] Obtained by equation (4)

While Table 4.5 is important because it shows averages, Table 4.6 estimates the percentage chance of being more profitable by adopting CA using the traditional (straight profit), environmental (per hectare LCA single score), and combined (traditional plus LCA single score) metrics. Table 4.6 shows that on average (with average conventional yields), zero and no-till have a 75 and 74% chance of being more profitable than conventional tillage, respectively. When accounting for the environmental services from switching from conventional to CA, Table 4.6 shows that zero and no-till have a 90 and 86% chance of being more profitable than conventional tillage, respectively. Interestingly, assuming a "good yield" for conventional tillage, zero and no-till only have a 48 and 46% chance of being more profitable than conventional tillage, respectively, indicating they are less profitable. These numbers increase to 70 and 62% for zero and no-till, respectively, indicating that without accounting for the environmental services that CA can provide, what on the surface looks like a lucrative production practice, "conventional tillage," can provide misleading results from a holistic standpoint. That is, without accounting for the ecosystem services provided by CA adoption, producers and policymakers may think that conventional tillage is the correct practice to adopt and endorse for long-run sustainability.

Table 4.6. Estimated probability of being more profitable per hectare by switching from conventional tillage to CA systems in Langgewens.

	Straight Profit		Environmental + Economic Benefits	
	Zero-till	No-till	Zero-till	No-till
Conventional Good Yield	47.93%	46.39%	70.26%	62.03%
Conventional Average Yield	74.67%	73.54%	89.86%	85.57%
Conventional Poor Yield	95.52%	95.53%	99.06%	97.39%

The conventional profits for good, average and poor yield were estimated in 2020 ZAR at 7,263; 4,220; and 416 per ha hectare, respectively (Knott, 2015). Percentages were based on 1,000 simulations from Table 4.4's profits comparing CA to conventional tillage profitability.

Proposed ideal wheat production scenario for Western Cape

While a per-hectare analysis provides a small snapshot of the benefits of any technology, it is important to extrapolate the benefits of a technology to the actual adopted area. As such, we ask the counterfactual question based on the findings from the LCA single scores, "how much additional environmental damage would have occurred if wheat producers in the WC did not adopt CA?" We take the LCA single scores by production type (Table 4.3) and their respective yields (Table 4.2) to calculate the environmental damage that would be incurred to produce the entire 2020 wheat crop in the WC. The difference between any two production practices provides the changes in environmental damage by switching production methods. Not surprisingly, from the LCA single scores, 100% conventional tillage had the highest damage. However, given that an estimated 51% of the WC is under CA (Smith, 2021), the actual difference in environmental damage via CA adoption is 51% of the total difference between full adoption of conventional and full adoption of CA. In other words, without 51% of the wheat area under CA, the estimated environmental damage would have been 402.5 and 269.2 million ZAR more than if 100% of the land was under conventional tillage annually for zero and no-till, respectively (Table 4.7). Worth noting, these differences assume a "good yield" for conventional tillage, and the benefits of CA would increase under an "average" or "poor" yielding conventional year.

Another way of looking at Table 4.7 is what are the additional environmental benefits still left to obtain if the remaining 49% of the wheat area in the WC adopted CA. Table 4.7 indicates that if the remaining 49% of conventional tillage wheat producers switched to CA that there would be an additional 386.7 and 258.6 million ZAR annually in environmental gains to be captured if the remaining conventional wheat area adopted zero and no-till, respectively. The environmental benefits of CA adoption highlight two important concepts. First, by CA adoption in wheat production in the WC, TFP is increased both from an input/output (increased profitability with less inputs) standpoint as well as environmental damage/output (reduced environmental damage per kg of wheat produced) standpoint. Importantly, in using the well-established categories defined by the UNEP/SETAC framework for LCIA (Jolliet et al., 2004), our results show that CA wheat leads to multiple environmental improvements over conventional production, a large addition to the literature which previously only looked at GHG emissions. Overall, the results from the producer, consumer, and environmental portions of this study are significant as agricultural scientists attempt to sustainably produce 70% more calories projected to be needed by 2050 for a growing human population (Adhya et al., 2014).

Table 4.7. Ecosystem benefits (2020 ZAR) of complete adoption of zero and no-till wheat production in the Western Cape from conventional tillage practice

	Conventional tillage	Zero-till	No-till
LCA single score (per kg) [a]	1.37	0.65	0.89
Yield (Mt) [b]	3.40	3.30	3.43
Total hectares needed for 2020 wheat crop[c]	319,101	328,731	316,504
Environmental cost for entire wheat crop [d]	1,490,393,565	701,155,109	962,590,581
Reduction relative to conventional tillage	-	-789,238,456	-527,802,984
Total Reduction in ecosystem damages from CA adoption [e]	-	-402,511,613	-269,179,522

[a] From Table 4.3
[b] From Table 4.2 and Knott (2015).
[c] Total output of 2020 dryland wheat crop in Western Cape was 1,084,944 MT (Southern African Grain Laboratory [SAGL], 2021). Thus, hectares needed are estimated by dividing total output by the mean yield of each respective tillage practice.
[d] The product of the LCA single score, yield per hectare, and number of hectares needed for total Western Cape crop.
[e] Given that estimated CA adoption in WC was 51% in Western Cape (Smith, 2021), as such only 51% of potential benefits have been derived from CA wheat production.

While producers will likely not “capture” the environmental gains or increased environmental efficiency gains estimated in this study, as environmental concerns increase for consumers and policymakers alike the comparative statics from these estimates could be used for purchasing decisions. For instance, the global wheat industry may begin to source wheat from “more sustainable” production practices, and policymakers may provide incentives/disincentives for more/less sustainable production practices. While CA adoption in South Africa has been more of a mean of coping with climate change and mitigating increases in input costs and to date has not been marketed as holistically “sustainable” production, understanding the broader environmental implications of its adoption is important.

An important caveat with the scaling up of results to the province level is that we assume that all wheat area in the WC can implement CA simultaneously, which is not a viable option. Because CA requires rotation out of wheat only a portion of the current land used for wheat production in the WC could be available to produce wheat at any given time. Other crops integrated with wheat includes crops like barley and pasture which would require less inputs compared to wheat. That being said, 100% CA could dampen the supply of wheat annually given the requirements of such a rotation.

4.5. Conclusions

Given increased consumer and political awareness of environmental sustainability globally, it is time for economists to rethink the traditional definition of TFP to possibly include environmental damage as an input. There is not a perfect correlation with simply reducing input amounts and a reduction in environmental impact, given differences in active ingredients and their environmental impacts across substitutable inputs (for instance, different types of herbicides). This study used a stepwise LCIA to quantify and compare CA to conventional farming in wheat production using the single score for environmental damage per kg of wheat as a measure of efficiency across production methods. Our findings suggest that CA is more profitable and has a greater environmental efficiency than conventional tillage wheat production in the WC. Importantly, this study does not capture the temporal benefits of CA, such as increased soil health and yields, which are likely enhanced, to some point, over time.

In the current era of trying to achieve sustainable agricultural systems to feed a growing global population, the promotion of “sustainable” agricultural practices like CA requires increasing evidence, in our case, efficiency metrics, to guide policy design and agricultural development in order to make climate-smart decisions, which will both enhance food security and reduce environmental degradation. In promoting sustainable development, the South African authorities could use LCA in pressing producers to use cleaner production methods (DEAT, 2004). Based on the identified environmental cost of switching to CA, the government of WC could invest in promoting CA and supporting commercial farmers to disseminate CA, as CA is more sustainable than conventional tillage. While producers will likely not receive payments for any of the ecosystem benefits they provide by switching from conventional to CA, the South African government could attempt to provide incentives for CA adoption in an effort to promote a sustainable wheat industry moving forward.

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Appendices

Table A.4.1. List of inputs used per hectare in the stepwise LCIA by location and CA system.

			Langgewens		Tygerhoek		Langgewens (Knott, 2015)	
Group	**Description / Product name (Active ingredients)**	**Unit**	**No-till**	**Zero-till**	**No-till**	**Zero-till**	**No-till**	**Conv.**
Fuel (Diesel)								
	Pre-harvest/harvest farming operations	liter/ha	27.3	23.9	26.2	26.6	20.5	27.65
Fertilization and amendments								
	Nitrogen	kg/ha	75.7	53.6	58.5	49.34	60.0	120.0
	Phosphorus	kg/ha	15.1	9.6	18.7	8.32	14.0	14.0
	Potassium	kg/ha	3.8	3.7	-	0.01	1.0	1.0
	Sulfur	kg/ha	0.3	3.8	11.4	2.00	9.0	9.0
	Calcitic lime	kg/ha	173.1	51.0	243.3	-	-	-
	Dolomitic lime	kg/ha	152.6	79.4	-	-	500.0	500.0
	Gypsum lime	kg/ha	176.5	140.5	8.9	-	-	-
	Manganese sulfate	kg/ha	0.02	-	-	-	-	-
	Potassium sulfate	kg/ha	0.001	-	-	-	-	-
	Bortrac 11%B / LiquiBor 10%B (B-based application)	kg/ha	0.17	0.06	0.01	-	-	-
	Coptrac / Coptrel (Cu-based application)	liter/ha	0.07	-	-	-	-	-
	Foliamag (Mg-based application)	liter/ha	0.001	-	-	-	-	-
	Mantrac (Mn-based fertiliser)	kg/ha	0.04	-	-	-	-	-
	Solubor 20.5%B (B-based application)	kg/ha	0.003	-	-	-	-	-
	Zintrac (Zn-based fertiliser)	kg/ha	0.03	-	-	-	-	-
Pesticides								
Weed control								
	2.4D Amien (Dimethylamine salt)	liter/ha	0.02	0.10	0.3	0.5	-	-
	Achieve (Tralkoxydim)	liter/ha	0.03	-	0.01	-	-	-
	Ally (Carfentrazone-ethyl/metsulfuron methyl)	g/ha	-	-	0.7	-	-	-
	Aurora (Carfentrazone-ethyl)	Kg/ha	0.001	0.01	0.003	0.01	0.02	0.02
	Axial (Pinoxaden)	liter/ha	0.09	-	0.01	-	-	-
	Boxer (Prosulfocarb)	kg/ha	0.07	-	0.1	0.04	-	-
	Bromoksinil-225 / Buctril-DS (Bromoxynil)	liter/ha	-	-	0.1	0.1	0.5	0.5
	Brush-off / Ally-20DF (Metsulfuron-methyl)	g/ha	0.88	0.77	0.3	4.3	-	-
	Cossack (Iodosulfuron-methyl-sodium/mesosulfuron-methyl/mefenpyr-diethyl)	kg/ha	0.03	-	1.4	-	-	-

Table A.4.1. (Cont.)

Group	Description / Product name (Active ingredients)	Unit	Langgewens No-till	Langgewens Zero-till	Tygerhoek No-till	Tygerhoek Zero-till	Langgewens (Knott, 2015) No-till	Langgewens (Knott, 2015) Conv.
	Derby 175 SC (Florasulam/flumetsulam)	liter/ha	0.01	-	-	-	-	-
	Difflan (Diflufenican)	liter/ha	-	-	-	0.003	-	-
	Ecopart (Pyraflufen-ethyl)	liter/ha	-	-	0.01	-	-	-
	Express Super (Chlorsulfuron/metsulfuron-methyl/tribenuron methyl)	g/ha	-	-	4.4	-	-	-
	Garlon (Triclopyr)	liter/ha	-	-	0.1	-	-	-
	Glean / Reaper (Chlorsulfuron)	g/ha	-	-	0.7	3.2	-	-
	Glyran / Glyran-710 (Glyphosate[ammonium])	kg/ha	-	-	0.23	0.2	-	-
	Harmony M (Metsulfuron-methyl/thifensulfuron)	g/ha	-	-	6.3	-	-	-
	Hoelon (Diclofop-methyl)	liter/ha	-	-	0.1	-	-	-
	Hussar (Iodosulfuron-methyl-sodium/mefenpyr-diethyl)	liter/ha	0.004	-	0.04	-	-	-
	Logran (Triasulfuron)	g/ha	1.11	-	1.6	-	0.02	0.02
	MCPA (2-methyl-4-chlorophenoxyacetic acid)	liter/ha	0.03	-	0.4	0.5	-	-
	Pallas (Pyroxsulam)	liter/ha	0.01	-	0.004	-	0.4	0.4
	Paraquat / Skoffel / Gramoxone / Paragone / Preeglone	liter/ha	0.91	0.69	0.9	0.7	1.5	1.5
	Resolve (Bromoxynil/pyrasulfotole/mefenpyr-diethyl)	liter/ha	0.11	0.90	-	-	-	-
	Roundup / Erase / Sting / Glyphosate360 (Glyphosate [isopropylamine])	liter/ha	-	0.90	1.3	2.6	3.0	3.0
	Roundup WSG /Erase granule / Glyphosate WSG (Glyphosate [sodium])	kg/ha	-	-	0.5	-	-	-
	RoundupTurbo (Glyphosate[potassium])	liter/ha	-	-	-	1.4	-	-
	Sakura (Pyroxasulfone)	kg/ha	0.02	0.10	0.002	0.12	-	-
	Topik (Clodinafop-propargyl)	liter/ha	0.02	-	0.006	-	-	-
	Trifluralin / Triflurex / Crew (Trifluralin)	liter/ha	0.79	-	1.1	-	1.5	1.5
Pest control								
	Bulldock (Beta-cyfluthrin)	liter/ha	0.01	-	-	-	-	-
	Chlorpyrifos	liter/ha	-	-	0.04	-	-	-
	Cylam (Lambda-cyhalothrin 50g/liter)	liter/ha	-	-	0.01	-	-	-
	Cyperfos 500EC / Cyperphos (Chlorpyrifos/cypermethrin)	liter/ha	0.05	-	0.04	-	0.8	0.8
	Cypermetrin	liter/ha	-	-	0.01	-	-	-
	Dimethoate / Fetron / Demet / Rogor (Dimethoate)	liter/ha	0.14	-	0.56	1.21	0.5	0.5

Table A.4.1. (Cont.)

			Langgewens		Tygerhoek		Langgewens (Knott, 2015)	
Group	**Description / Product name (Active ingredients)**	**Unit**	**No-till**	**Zero-till**	**No-till**	**Zero-till**	**No-till**	**Conv.**
	Double star (Acetamiprid)	liter/ha	-	-	-	0.26	-	-
	Folimat (Omethoate)	liter/ha	-	-	0.02	-	-	-
	Lirifos (Chlorpyrifos 480g/liter)	liter/ha	-	-	0.05	-	-	-
	Metasystox (Oxydemeton-methyl)	liter/ha	-	-	0.18	-	-	-
	Methomex / Methomyl 200 (Methomyl)	kg/ha	0.08	-	0.01	-	-	-
	Mospilan (Acetamiprid)	g/ha	38.74	20.00	28.08	39.69	-	-
	Slakpille (Sluggem [Carbaryl/metaldehyde)	kg/ha	-	-	0.16	-	-	-
Fungal control								
	Abacus (Epoxiconazole/pyraclostrobin)	liter/ha	0.07	0.89	-	0.20	-	-
	Acanto (Picoxystrobin)	liter/ha	-	-	0.04	0.12	-	-
	Bumper (Propiconazole)	liter/ha	0.12	-	0.06	-	0.5	0.5
	Capitan (Flusilazole)	liter/ha	-	-	0.03	-	-	-
	Ceriax (Epoxiconasole/fluxapyroxad/pyraclostrobin)	liter/ha	-	-	-	0.01	-	-
	Duet Ultra (Epoxiconazole/thiophanate-methyl)	liter/ha	-	-	-	0.11	-	-
	Duett (Carbendazim/thiophanate-methyl)	liter/ha	0.65	-	0.34	-	0.8	0.8
	Folicur / Tebuconazole / Embrace/ Orius (Tebuconazole)	liter/ha	0.14	-	0.06	-	-	-
	Opus (Epoxiconazole)	liter/ha	0.26	-	0.17	-	-	-
	Prosaro (Prothiconazole/tebuconazole)	liter/ha	-	-	0.06	0.17	-	-
	Prosper Trio (Spiroxamine/tebuconazole/triadimenol)	liter/ha	0.04	0.44	-	0.41	-	-

Notes:

- Conv = Conventional tillage
- Active ingredients identified from AVCASA (Association of Veterinary and Crop Associations of South Africa) manuals 2018 (www.croplife.co.za)

Table A.4.2. Average annual wheat prices per ton by location and CA system extracted from WCDA dataset (2021) and adjusted to 2020 ZAR.

Location	CA system	Year	Price
Langgewens	No-till	2002	4232.18
		2003	3106.67
		2004	2451.28
		2005	2690.74
		2006	3213.50
		2007	4199.55
		2008	3527.86
		2009	2915.40
		2010	3865.57
		2011	3605.73
		2012	4652.04
		2013	4603.51
		2014	4511.74
		2015	5366.13
	Zero-till	2016	4372.79
		2017	4654.04
		2018	4667.69
		2019	3814.86
		2020	3761.00
Tygerhoek	No-till	2002	4278.29
		2003	3078.24
		2004	2207.67
		2005	2568.40
		2006	2985.20
		2007	4696.30
		2008	3764.06
		2009	2944.57
		2010	3491.58
		2011	3576.21
		2012	4612.87
		2013	4039.05
		2014	3926.78
		2015	4859.45
	Zero-till	2016	3711.20
		2017	4063.12
		2018	3874.88
		2019	3847.91
		2020	3816.11

Prices adjusted for wheat quality grade (GRAIN SA, 2022)

Table A.4.3. Environmental damage by location and farming practice estimated using stepwise LCIA for 1 kg of wheat produced in Western Cape, RSA

		Langgewens, Knott (2015)						Langgewens		Tygerhoek	
		No-till			**Conventional**			**No-till**	**Zero-till**	**No-till**	**Zero-till**
		Average	*Good*	*Poor*	*Average*	*Good*	*Poor*				
Impact category	**Unit**	**Ecosystem damage**									
Human toxicity, carcinogens	kg C_2H_3Cl-eq	0.0025	0.0020	0.0039	0.0039	0.0030	0.0064	0.0018	0.0014	0.0019	0.0013
Human toxicity, non-carcinogens	kg C_2H_3Cl-eq	0.0016	0.0012	0.0025	0.0023	0.0018	0.0038	0.0014	0.0009	0.0012	0.0009
Respiratory inorganics	kg $PM_{2.5}$ eq	0.0002	0.0002	0.0003	0.0003	0.0002	0.0005	0.0002	0.0001	0.0001	0.0001
Ionizing radiation	Bq C-14-eq	0.6528	0.5100	1.0201	0.9434	0.7214	1.5330	0.5095	0.3811	0.4856	0.4066
Ozone layer depletion	kg CFC-11-eq	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ecotoxicity, aquatic	kg TEG-eq w	6.1215	4.7824	9.5649	8.0193	6.1324	13.0314	4.7651	3.3466	5.0545	3.4098
Ecotoxicity, terrestrial	kg TEG-eq s	0.5292	0.4135	0.8269	0.8723	0.6671	1.4175	0.5144	0.3299	0.3767	0.2959
Nature occupation	m^2-years agri	0.0024	0.0019	0.0038	0.0038	0.0029	0.0062	0.0021	0.0015	0.0019	0.0013
Global warming, non-fossil	kg CO_2-eq	0.0002	0.0002	0.0003	0.0003	0.0002	0.0005	0.0001	0.0001	0.0001	0.0001
Global warming, fossil	kg CO_2-eq	0.2710	0.2117	0.4234	0.4892	0.3741	0.7950	0.2356	0.1724	0.1837	0.1603
Acidification	m^2 UES	0.0208	0.0162	0.0324	0.0348	0.0266	0.0566	0.0172	0.0126	0.0146	0.0118
Eutrophication, aquatic	kg NO_3-eq	0.0006	0.0005	0.0010	0.0008	0.0006	0.0013	0.0004	0.0003	0.0005	0.0004
Eutrophication, terrestrial	m^2 UES	0.0433	0.0338	0.0676	0.0797	0.0610	0.1295	0.0387	0.0283	0.0293	0.0257
Respiratory organics	pers*ppm*hr	0.0001	0.0001	0.0001	0.0002	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001
Photochemical ozone, vegetation	m^2*ppm*hr	1.1258	0.8795	1.7590	1.9294	1.4754	3.1353	0.9423	0.6919	0.7667	0.6585
Non-renewable energy	MJ primary	2.2596	1.7653	3.5306	3.5866	2.7427	5.8283	1.8310	1.4063	1.6434	1.4066
Mineral extraction	MJ extra	0.0021	0.0017	0.0033	0.0038	0.0029	0.0061	0.0025	0.0014	0.0015	0.0013

CHAPTER 5: CONCLUSION

Given the low adoption of CA in SSA, the current dissertation has filled some existing gaps in the literature. In the first article, through contingency valuation, a potential demand for CA is illustrated by the presence of a niche group of urban consumers (who happen to be producers living in the city, especially women producers) who are willing to pay to support CA adoption in the DRC. Moreover, this economic valuation indicates that the average urban consumer is indifferent, at least from a WTP standpoint, about how maize flour is produced. The first article's main findings also mean the public in urban DRC, even though aware of socio-environmental issues in the rural DRC, is not willing to pay for the sustainable agricultural production such as CA, at least in terms of maize flour. In the second article, this research demonstrates that CA increases the concentrations of two soil available nutrients (P and K) and the population of earthworms in the soils of Maniema, DRC compared to conventional tillage practice. The findings suggest CA improves soil quality and soil biodiversity. Additionally, CA leads to greater cowpea yields, which depict agricultural productivity improvement compared to traditional conventional cowpea production. In the third article, this research shows that CA is more profitable and more efficient compared to conventional tillage in commercial wheat production in the Western Cape of South Africa. This research illustrates that a holistic analysis would be better when accounting for CA ecosystem services in wheat production. More importantly, this research approaches environmental damage in a different light and hypothesizes that environmental damage could be better considered as input to production than just an externality. Taken together, the three core articles forming this dissertation research address the demand for CA in SSA from an urban-consumers standpoint, reveal the effects of CA on soils and crop yields in smallholder farming in SSA, and show that CA is a more sustainable practice for commercial farming in SSA.

Several implications for sustainable agriculture research and development, policymaking and food system development emerge from this dissertation. Below is the nexus of this dissertation research findings with those recommendations and suggestions for further explorations.

5.1. Article 1: Demand for CA

1. The only consumers who were found to be willing to pay a premium for CA were those who self-identified as producers. Funding for CA projects in the future could focus on making consumers better aware of the benefits of CA as to boost CA's demand and ultimate price. As the public in urban DRC was not WTP a premium for agricultural production, future research could explore other pathways, such as global green funds, through which CA adopters would be rewarded for their CA ecosystem services.
2. Despite knowing about deforestation and violence against rural women, urban consumers in Bukavu are not willing to pay a premium for CA-produced white maize flour. As this indicates no market incentives to combat these issues, efforts should be made to expand alternative incentives to help mitigate deforestation and empower rural women.

5.2. Article 2: CA adaptability in smallholder farming

1. Most farmers in Maniema, DRC, are used to practicing conventional farming, which involves hand-hoe tillage and slash-and-burn practices. Conventional farming contributes to soil degradation. As CA has been shown to improve soil health and quality, efforts should be made to help farmers switch from conventional farming to CA. Long-term

research involving various crops, community demonstrations and incentives are needed for CA promotion.

2. Smallholder farming has been associated with cutting the DRC rainforest. Promoting CA would help farmers revive fallows and their old farms instead of opening new farms in the forest. Here efforts should be made to help the farmers adjust CA to their local conditions.

3. CA performed well with no agrochemicals in Maniema. This would not be obvious elsewhere in the DRC. Mineral fertilization is a luxury that most smallholder farmers in Maniema do not access. There is a need to assess the integration of affordable fertilization options to sustain the promising agricultural productivity improvement shown through CA.

4. Preserving ecosystems in Central Africa particularly should be given more attention, as the region holds a significant part of the "Lungs of the Earth", the African tropical rainforest. As such, more research should be conducted to better adapt CA and understand its impact on deforestation and crop yields.

5.3. Article 3: Impacts of CA in commercial wheat farming

1. Given the large environmental benefits estimated for CA adoption in commercial wheat production, it could be beneficial for public agencies (Universities, governments, etc.) to promote these benefits to other parts of South Africa with hopes to increase CA adoption.

2. The holistic examination of CA has been shown to be a better way of assessing food production adaptation. The use of stepwise LCIA method illustrates that monetization of ecosystem services is possible in commercial farming in SSA. This LCA approach would

be a key tool to use in internalizing the benefits of sustainable agricultural production in SSA.

3. The stepwise LCIA also helps in rethinking total factor productivity in way that accounts for environmental burdens in commercial farming. The environmental damage efficiency defined by LCIA heralds the debate on linking cleaner agricultural production with policy and program design.