THE EFFECTS OF MICROVEG RECOMMENDATIONS ON SOIL QUALITY, YIELD, AND PROFITABILITY FOR *AMARANTHUS CRUENTUS* FARMERS IN THE RAINFOREST, SAVANNA, AND SUDANO SAVANNA ECO-REGIONS OF NIGERIA AND BENIN REPUBLIC

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ABSTRACT

The MicroVeg Project is a set of agronomic recommendations to increase indigenous vegetable production in Nigeria and Benin Republic. The aim of the project is to increase food security through increased production as well as targeting women farmers, incorporation of vegetables in food processing, improved marketing channels, advocating for policy change, limiting soil degradation processes, and scaling up the model into local, national, and regional food security programs in West Africa. The project has successfully completed the experimentation phase and has disseminated the information to local farmers using the recommendations. The objective of this research focuses on the agronomic and economic benefits rural farmers reported from MicroVeg compared to local practices as a means to confirm the results found at research sites. The study also examined the effect MicroVeg had on soil properties including pH, soil organic carbon, cation exchange capacity, available and total nitrogen and phosphorus, and analyzed carbon and nitrogen cycling using X-ray Absorption Near Edge Structure spectroscopy. In addition to soil sampling, interviews were conducted with each farmer and with Extension Agents working with the project to determine yields, revenues, and expenses. The same process occurred with farmers who grew the same vegetables using traditional or local farming methods. Soil and economic data were analyzed and compared between the two farming systems to determine whether MicroVeg was an improvement over local farming practices.

The soil chemical analysis reported farmers using MicroVeg recommendations displayed lower soil nutrient levels. While these levels varied between eco-region, the general trend was persistent across the Savanna and Sudano Savanna regions. These results were most pronounced in the Savanna eco-region, where soil pH, CEC, SOC, total N, and available and total P were significantly lower in MicroVeg soils. This was likely a result of differences in soil texture, as MicroVeg soils in the Savanna were much sandier compared to the local practice soils. Conflicting results were observed from XANES analysis that were consistent with MicroVeg soils being more abundant in labile forms of nitrogen like amide-N, while soils using traditional/local practices had higher levels of decomposed nitrogen forms like pyrrolic-N species, indicating supplemental N may be more available under MicroVeg practices. Differences between C species in MicroVeg and traditional soils were less pronounced, and species clustered based on their eco-region. The economic analysis indicated that MicroVeg farms produced higher yields and gross profits in all

three eco-regions and reported acceptable returns for farmers in the Rainforest and Savanna eco-regions. For MicroVeg farmers in the Sudano Savanna region, gross profits were only slightly higher than local practices and a negative return on investment was reported for MicroVeg recommendations. These findings suggest that MicroVeg practices are a suitable option for farmers in the Rainforest and Savanna eco-regions to increase income.

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SSA	Sub-Saharan Africa
ICRISAT	International Crop Research Institute for the Semi-Arid Tropics
NiCanVeg	Nigeria Canada Indigenous Vegetable Project
INuWaM	Integrated Nutrient and Water Management Project
MV	MicroVeg
LP	Local Practices
GDP	Gross Domestic Product
ISFM	Integrated Soil Fertility Management
OM	Organic Matter
HYV	High Yielding Varieties
GM	Genetically Modified
SOM	Soil Organic Matter
SOC	Soil Organic Carbon
OC	Organic Carbon
XANES	X-ray Absorption Near Edge Spectroscopy
SHF	Smallholder Farmer
EA	Extension Agent
RF	Rainforest
SV	Savanna
SS	Sudano Savanna
CEC	Cation Exchange Capacity
NMDS	Nonmetric Multidimensional Scaling
V/C	Value-Cost
GPM	Gross Profit Margin
IRR	Internal Rate of Return
I/O	Input-Output

1. INTRODUCTION

Since 2014, the number of people considered food insecure has increased and an estimated 820 million people are considered food insecure (FAO, 2018). Sub Saharan Africa is home to almost 265 million citizens considered food insecure and that number is likely to increase, as Africa is expected to see the largest global population growth by 2050. (Index, 2016; FAO, 2018). The increase in African population has not mirrored an increase in African agricultural production, as per capita food production over the last 20 years has declined, and residents of sub-Saharan Africa consume less than the recommended calories for a healthy lifestyle (Bationo et al., 2007). Pressure to increase production has resulted in degraded soils due to continuous cultivation and low input farming systems. (Abdoulaye and Sanders, 2005; Bationo et al., 2007; Aune and Bationo, 2008).

The majority of farmers in sub-Saharan Africa (SSA) are considered smallholder farmers; farming less than two hectares of land (FAO, 2009; Foster and Rosenzweig, 2010). Growth in agriculture would not only increase food production but generate employment and increase wealth for the poorest citizens who are the dominant labour force in the agricultural industry (FAO, 2009). But agricultural growth is difficult to attain in Africa, as farms are characterized by low input systems, degraded soils, and have limited access to resources. Fertilizers used to replenish nutrients lost through harvest and erosion can be expensive and uncertainty in weather makes purchasing fertilizer a risky investment for African farmers (ICRISAT, 2009). Additionally, quantity and availability of fertilizers play a role in the lack of use, as farmers are often unable to secure credit/funds to purchase the recommended amount and fertilizer is often unavailable at the time when it is most effective to apply.

Degraded soils combined with high risk and poor access to fertilizers has led to low input farming systems that have been unable to sustainably produce adequate yields, leading to food insecurity. To address this issue, researchers at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) developed a practice known as fertilizer microdosing to encourage the use of fertilizers to increase yields and decrease risk for farmers. The focus of microdosing is on the method and rate of application, stressing the importance of placement to ensure maximum fertilizer use efficiency. Microdosing is a precise placement of a small amount of fertilizer in soil beside the plant after seeding. This has been the backbone of much research in the last 10 years as experimentation with rates, timing, and type of fertilizer has been done to fine tune the process (Hayashi et al., 2008; Twomlow et al., 2010; Kibunja et al., 2012; Camara BS et al., 2013; Sime and Aune, 2014; Bielders and Gérard, 2015; Adams et al., 2016).

Microdosing is part of the MicroVeg Project, which is a set of agronomic recommendations to sustainably increase indigenous vegetable production in Nigeria and Benin Republic. *Telfairia occidentalis* (Hook.f) (Ugu), *Solanum macrocarpon* (L.) (Igbagba), *Amaranthus cruentus* (L.) (Tete) are the three vegetables chosen for production in Nigeria and *Ocimum gratissimum* (L.) (Tchiayo) is substituted for Ugu in Benin due to their viability, marketability, and potential economic effect. These vegetables are harvested for their leaves and incorporated in local snack foods. MicroVeg is a multi-disciplinary research project addressing the different facets of food security. The MicroVeg project is funded by the Canadian International Food Security Research Fund and is a continuation of two previous International Development Research Centre projects; the Nigeria-Canada Indigenous Vegetable Project (NiCanVeg) and the Integrated Nutrient and Water Management (INuWaM) project in the Sahel. MicroVeg has reported increased yields at research stations and has been successfully advertised and adopted by numerous farmers in three eco-regions of Nigeria and Benin Republic. The final phase of the MicroVeg project is to assess effects MicroVeg has on soil health as well as the economic benefits farmers are receiving from implementing MV recommendations through soil samples and on-site interviews.

The objective of this study was to determine the effects of MicroVeg recommendations on soil fertility and economic profitability for rural African farmers in three eco-regions of Nigeria and Benin Republic. Tete was the most common vegetable across the three eco-regions and will be the vegetable of focus for this study. We hypothesize MicroVeg (MV) farmers will report higher yields, soil nutrient levels, and higher margins than farmers using traditional or local farming practices (LP) to produce Tete. The local methods used to produce Tete varied widely across eco-regions and farmers, and there was no consistency in methods used other than they did not use the recommendations of MicroVeg practices. The thesis is laid out in two manuscripts, the first chapter compares the difference in soil fertility between farmers implementing the MV recommendations, and those that are producing Tete with local practices using soil samples collected from seedbeds at each farm. The second chapter compares the economic profitability of the two farming systems from revenue and expense data gathered from on-site interviews with farmers and extension agents. As well, a testimonial section is included in the second chapter highlighting the success and failures of farmers interviewed. The thesis contains a literature review outlining the current state of agriculture, soil fertility, and food security in Africa, and provides context on the research objectives. The thesis finishes with two sections reporting the limitations that were encountered during our research visit and highlight some of the inherent limitations of development work, and a conclusion and synthesis of the highlights of the project. The conclusion also includes potential recommendations for improvement to the MicroVeg recommendations and areas of future research that may provide benefits to smallholder farmers.

2. Literature Review

2.1. Food Security

World population is predicted to increase by over two billion people by 2050, with the largest growth occurring in developing nations (OECD/FAO (Eds.), 2016). To sustain the increased population developing nations will need to double current production to keep pace with growth (FAO, 2009; Tester, 2011). While other developing nations in Asia and Latin America have increased yield production, Africa has lagged behind, and any yield increases that have occurred have been a result of land expansion rather than increases in crop productivity (Bationo et al., 1998; FAO, 2009; Vanlauwe and Zingore, 2010). Agriculture is the main employer for the majority of SSA workers; increasing the gross domestic product (GDP) in the agricultural sector has proven to be the most effective in reducing poverty for the poorest of the poor in SSA. (Christiaensen et al., 2011). With over 75 % of the poor depending on agricultural related activities for income, and roughly 80% of farms operating on less than two hectares, increasing food production not only contributes to food security, but creates employment and generates incomes for rural workers (FAO, 2009). But socio-economic issues such as poor infrastructure and political instability and agronomic problems such as poor soil fertility and rising temperatures create substantial roadblocks that hamper efforts to increase food production and keep the gap between potential and realized yields from decreasing. (Abdoulaye and Sanders, 2005; Aune and Bationo, 2008; Camara BS et al., 2013; Bachmann et al., 2016).

Nigeria and Benin, the countries of focus in this study, rank low on the human development index level ranking 151st and 168th out of 185 countries measured (United Nations Development Programme, 2016). Undernourishment, stunting, and child mortality are still considered serious problems in these regions (Index, 2016). While not all food security issues are a result of low agricultural production, problems like soil degradation, farming of marginal lands, and low input farming practices further exacerbate the issue. While past practices such as fallow periods were often utilized to maintain long term productivity, population pressure and intensification have decreased soil nutrient levels, limiting the ability of farmers to produce high enough yields to be food secure (Bationo et al., 1998; Abdoulaye and Sanders, 2005; Aune and Bationo, 2008). Innovative approaches to address hunger as a result of food insecurity like fertilizer microdosing, no-till agriculture, crop rotations that include legumes, and other feasible options have been proposed as possible solutions to declining yields and soil fertility.

2.2. Soil Fertility in Africa

Soil fertility is the starting point for food production and can be described as the ability of a soil to supply plant roots with adequate amounts of nutrients, water, and air (Jones et al. 2013). Soil fertility is dependent on numerous factors. Some factors such as texture, parent material, and topography, are intrinsic, but others such as land management can strongly influence fertility (Lal, 2015). Due to increases in population, agricultural systems have had to intensify their operations to keep up with the rising demand for food (Bationo & Mokwunye, 1991; Bots & Benites, 2005; FAO, 2009). Anthropogenic and natural processes such as farming and climate change disturb the natural production and cycling of nutrients (Lal, 2015). The continual harvesting of crops without replenishment of nutrients to the soil via fallow periods, residues, or fertilizers, has caused soils in many developing countries to be depleted of nutrients (Bationo & Mokwunye, 1991; Bots & Benites, 2005).

Soils in SSA are characterized by low inherent fertility due to the sandy texture and weak structures that break down from continual disturbance (Bationo and Mokwunye, 1991; Lahmar et al., 2012). In addition to low fertility, factors such as variability in climate, erratic rainfall patterns, high soil temperatures, erosion, acidity, surface crusting, shortened fallow periods, farming of marginal lands, and the continual harvesting of crops and returning nothing back into the soil in the form of residues or fertilizers have all contributed to poor soil structure and degraded land (Bationo and Mokwunye, 1991; Bationo and Buerkert, 2001; Lahmar et al., 2012; Adams et al., 2016). To put this in context of a nutrient budget, soils in Africa lose on average 26 kg of N, 3 kg of P and 19 kg of K a year for each hectare of cultivated land (Smaling et al., 1993).

It is estimated that 50 percent of global food production comes from the addition of mineral fertilizers (Roberts, 2009), but purchasing fertilizer at the recommended rates is difficult for rural farmers due to high fertilizer costs, poor infrastructure, and limited access to credit (Callo-Concha et al. 2013; Bachmann et al. 2016). Inadequate knowledge and resources coupled with untimely droughts leading to food scarcity has discouraged farmers from investing in fertilizers (Camara et al. 2013). In addition to those constraints, a high rate of return (over 100 percent) is needed before farmers will consider the opportunity cost high enough to invest (CIMMYT, 1998).

The effects of soil degradation can be reversed, though it takes a considerable amount of time and resources (Bationo and Mokwunye, 1991; Vanlauwe and Zingore, 2010; Gentile et al., 2011; Kibunja et al., 2012; Adams et al., 2016). Degradation from natural causes such as climate change is difficult to mitigate, but degradation due to anthropogenic activity can be limited through proper land management practices. Conservative tillage, residue recycling, and fallows can decrease crusting, erosion, and loss of microbial diversity. Rotations using cover and nitrogen fixing crops and using organic and mineral fertilizers can help replenish nutrients in soils and are part of the integrated soil fertility management (ISFM) practices that aim to maximize production while limiting degradation (Bationo & Mokwunye, 1991; Bationo et al, 1998; Callo-Concha et al, 2013; Adams et al. 2016). Unfortunately, several of these options are difficult or unrealistic for rural farmers in developing nations to implement. The increase in population has led to less land being left fallow, (Bationo & Mokwunye 1991; Callo-Concha et al. 2013) incorporating cover or leguminous crops may not provide high enough economic returns to be considered useful for the farmer, crop residues are often used for fuel, building materials, or food for livestock, and mineral fertilizers can be expensive and risky to purchase (Abdoulaye & Sanders, 2005).

2.3. Integrated Soil Fertility Management

Integrated soil fertility management (ISFM) practices are a holistic approach to improving crop production through the use of fertilizers, seed varieties, and other agronomic practices that are practical for smallholder farmers, and fundamental for sustainable agricultural production (Aune and Bationo, 2008; Hayashi et al., 2008; Vanlauwe and Zingore, 2010). One aspect of ISFM is the use of mineral fertilizers to increase crop production, as mineral fertilizers provide a readily accessible form of nutrients for plant uptake (Kibunja et al., 2012; Gentile et al., 2013). Though mineral fertilizers are used by African farmers, poor application methods can result in large amounts being lost to the environment before plant uptake. Microdosing, a precise fertilizer placement technique developed by the International Crops Research Institute for the Semi-Arid Tropics involves the application of a reduced fertilizer rate during or after sowing (ICRISAT, 2009). The aim of microdosing is to maximize returns on small investments in fertilizer rather than maximizing yields (ICRISAT, 2009). The point source application of fertilizer used in microdosing improves fertilizer efficiency compared to broadcasting, and has increased yields by 30 to 70% when using as little as three kg ha^{-1} compared to plots receiving no fertilizer (Aune et al., 2007), and larger yield increases are reported with increasing fertilizer rates (Aune et al., 2007; Hayashi et al., 2008; Twomlow et al., 2010). The increased yields while using relatively little fertilizer decreases the risk farmers face while purchasing fertilizer, and increases profits eventually leading to an increase in investment of agricultural inputs over time (Aune and Bationo, 2008). However, studies have reported conflicting data when microdosing is compared to more fertile plots. Soils that were heavily manured or followed a fallow period showed little benefit from microdosing, and did not report favourable returns for farmers (Bielders and Gérard, 2015). In other studies, microdosing alone was unable to adequately sustain yields over the long term, as rates are too low to off-set nutrient losses when crops are harvested, further depleting the soil of nutrients. (Aune et al., 2007; Adams et al., 2016).

The addition of manures and crop residues is another pillar in ISFM and is a proven method to increase soil health. (Bationo et al., 1998; Bationo and Buerkert, 2001; Abdoulaye and Sanders, 2005). Crop residues can increase soil phosphorus (P) availability, buffer against acidification of mineral fertilizers, increase soil organic carbon, and provide protection to soils from wind and water erosion (Bationo and Buerkert, 2001; Bationo et al., 2007; Kibunja et al., 2012). But these benefits are only realized when high rates of residues are returned after harvest, which is problematic as residues are often used as food for animals, fuel, or building materials (Abdoulaye and Sanders, 2005). Studies using lower quality residues (higher in Carbon) have reported a reduction in the amount of plant available nitrogen (N) lost through leaching. The addition of lower quality residues can increase the soils C:N ratio, leading to the immobilization of plant available N (often added in the form of mineral fertilizers) early on in the growing season (when plant uptake of nutrients is lower) only to be released later in the growing season when plant demand is greater (Gentile et al., 2009). But adding residues may not always be beneficial, as studies have found lower residue rates can have a negative effect as residues can stimulate microbial activity that leads to a mineralization of organic carbon (Bationo and Buerkert, 2001). The residues added can become a ‘hotspot’ of microbial activity that remains after the input is exhausted of its nutrients, leading to the decomposition of organic matter already in the soil (Kuzyakov, 2010). For this reason, it is important to add adequate amounts of residues (over 2 tonnes ha^{-1}) to ensure further degradation of organic matter (OM) in soils does not occur (Bationo et al., 2007).

Manures act similarly to residues adding nutrients, improving soil structure and water retention, and providing fuel for microbial activity (Nyamangara et al., 2001; Abdoulaye and Sanders, 2005). In long term trials, adding manure by itself resulted in higher yields for longer periods of time compared to when mineral fertilizers alone were used (Bationo et al., 2012; Kibunja et al., 2012). Manures provide an initial increase in SOC when applied, yet failed to maintain the original levels over longer periods of time (Kibunja et al., 2012), and only when exceedingly high rates were used (15,000-40,000 kg ha^{-1}) did SOC increase (de Ridder and van Keulen, 1990; Bationo et al., 2007; Adams et al., 2016). Compounding the problem for smallholder farmers, the manure used is often of lower quality, since livestock graze on residues that are often low in N and P, and as a result, farmers need even higher amounts of manures to offset the poor quality (Twomlow et al., 2010). As well, manure loses available nutrients when exposed to periods of high temperatures and sun, common for many farmers in west Africa (Abdoulaye and Sanders, 2005).

Applying the recommended rates of organic or mineral fertilizers alone is often unattainable for farmers but combining both fertilizers at lower rates provides positive benefits and is more affordable. Aside from being the most affordable option for farmers, combining lower rates of mineral and organic fertilizers has proven to have a synergistic effect increasing yields over longer periods of time compared to when either is used alone (Bationo et al., 2012; Kibunja et al., 2012; Gentile et al., 2013). Manures and residues retain water, making it more profitable to add small amounts of inorganic fertilizers, and can reduce acidification from mineral fertilizers (Abdoulaye and Sanders, 2005). Using organic and mineral fertilizers together has reported drawbacks, decreasing available N and P levels in soils (Bationo et al., 2007; Kibunja et al., 2012; Adams et al., 2016). A potential reason for this is in addition to N and P, manures supply other nutrients like potassium and calcium that are important for plant growth. Yield increases as a result of additional micronutrients can increase N and P uptake from soils, and can deplete soil if adequate rates of residues or manures are not used (Kibunja et al., 2012; Ibrahim et al., 2016).

Using improved seed varieties that are higher yielding and more tolerant to environmental stresses like heat and drought is another practice low input rural farmers can implement to increase income (Tester, 2011). Unlike fertilizer use, adoption of high yielding varieties (HYV) in Africa is comparable to other regions that have experienced growth in the agricultural sector, but the increase in yields as a result of HYV for African farmers is substantially lower than other developing nations (Sanchez, 2002). As a result of the low input farming systems and nutrient deficient soils, HYV have not generated the same success in Africa as in Asia and Latin America, and traditional varieties tend to perform comparably to HYV under stressful conditions (Aune and Bationo, 2008). In addition to HYV, defining the optimum plant population density is an important agronomic practice to maximize returns on crops. Using seeding densities that are too high can lead to unproductive or dead plants as a result of overcrowding, while low densities do not maximize resources like water, light and nutrients. Increased seeding densities were able to compensate for late sowing, or less fertile conditions, while other studies reported higher yields by increasing seeding densities rather than increasing fertilizer rates (Yanggen et al., 1998; Bielders and Gérard, 2015).

Finally, using genetically modified (GM) seeds has the potential to increase yields as it allows for the development of traits that are not present in naturally occurring populations. Building into the seed insect and disease protection, while increasing the plants nutritional content are applications currently used in GM crops, yet restrictions and wide spread adoption of these seeds has not occurred mainly as a result of political issues (Tester, 2011).

2.4. Soil Carbon and Nitrogen and Their Effects Soil Health.

Soil organic matter (SOM) and soil fertility are strongly correlated, and SOM is one of the most important factors in sustaining high yielding soils. SOM consists of plant material like residues and roots, soil biota, and inputs like manures, representing difference phases of degradation (Bot and Benites, 2005; Bationo et al., 2007; Gentile et al., 2013). SOM plays an important role in soil aggregation, water retention, microbial activity, providing nutrients like carbon, nitrogen, and phosphorus, and is a potential source of climate mitigation acting as a sink for carbon (Bationo et al., 2007; Schmidt et al., 2011; Lehmann and Kleber, 2015). Initially, SOM was thought to decompose into a complex recalcitrant molecule through the process of ‘humification’, and was relatively resistant to microbial breakdown (Bot and Benites, 2005; Lehmann and Kleber, 2015). As research progressed, the idea of SOM degrading into a large complex recalcitrant molecule evolved to a more accurate understanding that organic matter is degraded or preserved in soils as a result of complex biotic and abiotic processes within soils (Fig. 2.1) (Schmidt et al., 2011; Wickings et al., 2012; Cotrufo et al., 2013; Lehmann and Kleber, 2015; Doetterl et al., 2016). The complex molecule known as ‘humus’ that was thought to be relatively stable and resistant to further degradation, can in fact be decomposed by microbes in a relatively short period of time given the right conditions (Lehmann and Kleber, 2015)

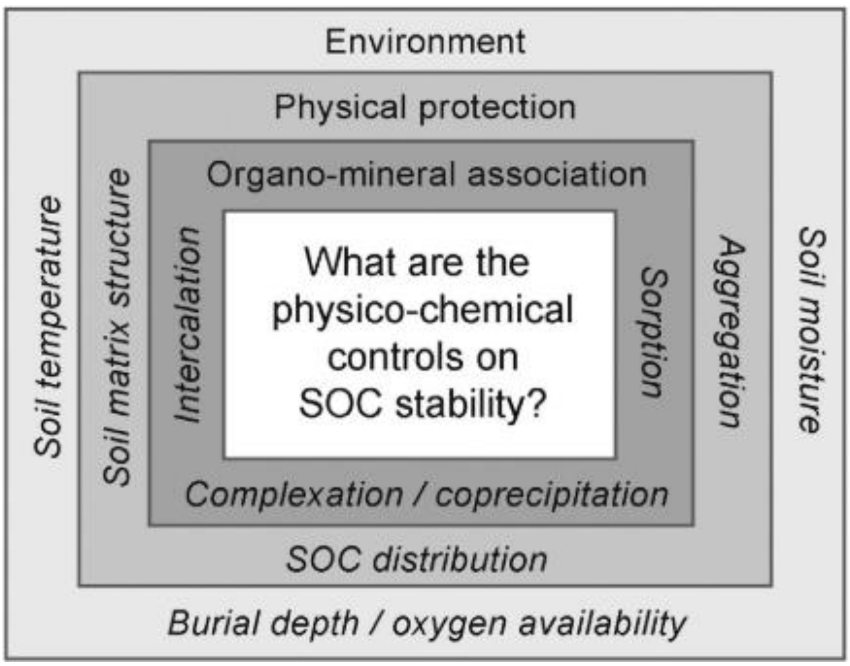


Fig. 2.1 Factors influencing the accumulation of SOC (from Doetterl et al., 2016)

Soil organic matter is important in the provision of nutrients like carbon and nitrogen. Soil organic carbon (SOC) is important in soil physical, chemical, and biological health. Recent research has shed light on the importance of chemical and physical properties of soil for organic carbon (OC) stabilization (Lehmann and Kleber, 2015; Doetterl et al., 2016). Soil OC can become stabilized through sorption to mineral surfaces, which is highly dependent on soil texture, as clay sized particles provide a larger surface area for interactions than sand particles (Cotrufo et al., 2013; Doetterl et al., 2016). Implementing management practices that limit soil disturbance can lead to the accumulation of OC through physical protection as soil aggregates can physically encapsulate OC, protecting it from water, oxygen, and microbial enzymes (Doetterl et al., 2016). When the soil is disturbed, these aggregates can break apart, exposing OC to conditions that will lead to its decomposition (Lehmann and Kleber, 2015; Doetterl et al., 2016)

Increasing SOC is an important step to increase soil health and provide food security through sustainable farming practices, but has proven difficult due to inherent soil conditions, climate, and poor management practices. Since physical protection is crucial in the build-up of OC, coarser textured soils, common for African farmers, are less capable of binding and protecting OM from microbial degradation (Gentile et al., 2013; Doetterl et al., 2016). Long term studies have reported a decrease in OC levels compared to original levels under continual crop production and only when rates of inputs were exceedingly high, or soil was higher in clay content, did SOC increase (Gentile et al., 2011; Bationo et al., 2012; Kibunja et al., 2012; Adams et al., 2016).

Nitrogen is one of the most limiting nutrients for plant growth in Africa and is a macronutrient required in the synthesis of amino acids, DNA, and chlorophyll (Gentile et al., 2011; Andrews et al., 2013; Karamanos, 2013). Nitrogen is commonly added to soils through mineral fertilizers and organic inputs like manures and residues but can also be added through biological and atmospheric N fixation by legume plants. Plant demand for N is greatest during early season growth and placement of fertilizer is important to ensure N is available when crops demand it (Karamanos, 2013). Once N is in the soil microbes begin the process of mineralization or immobilization depending on the C:N ratio. Mineralization occurs when microbes metabolize and depolymerize organic N into forms useable for plant uptake (Leary et al., 2014; Jacoby et al., 2017). Immobilization occurs when the C:N ratio is high in soils, and microbes need more N to metabolize organic matter. Microbes will scavenge N from soils to complete their metabolic processes potentially reducing the amount of plant available N. The immobilized N in microbes is eventually released back in to the soil with microbial death. This process can be detrimental to plant growth if a large portion of plant available N is immobilized during peak times of plant demand (Leary et al., 2014). Though a temporary immobilization of plant available N can be detrimental to plant growth, it may also be beneficial reducing the amount of N that can be leached out prior to plant demand.

Plants take up nitrogen in two forms, nitrate (NO_3^-) and ammonium (NH_4^+) (Andrews et al., 2013). Through the process of nitrification, N added to the soil in the form of NH_4^+ converts to NO_3^-, releasing an H^+ in the soil. Nitrogen that transforms to NO_3^- (the more common form of plant available N in soils), can be taken up by plants or lost due to leaching, as NO_3^- is mobile in soils (Andrews et al., 2013). In coarser textured soils, high precipitation events can lead to N losses when large amounts of NO_3^- are available in times of low plant demand. Losses can also occur under dry conditions through the process of volatilization when proper fertilizer application methods are not used. In particular, when Urea fertilizer is broadcast on the soil surface, losses due to the conversion of Urea to ammonia (NH_3) gas can occur if a precipitation event does not soon follow application (Overdahl et al., 2016).

2.5. Determining C and N quality using X-Ray Absorption Near Edge Spectroscopy

Lehmann and Kleber (2015) identified soil carbon as a continuum, with different products at different stages of decomposition. Identifying molecular species representative of different stages of decomposition can lead to a better understanding of how management practices are influencing nutrient turnover and soil health (Solomon et al., 2005; Gillespie, 2010; Gillespie et al., 2014b). X-ray Absorption Near Edge Spectroscopy (XANES) can determine the speciation of different C and N compounds (known as fingerprints) within soil samples directly (Solomon et al., 2005; Gillespie et al., 2011). Soil samples are exposed to photons from x-rays that excite the core electrons of a specific atom causing it to move to an unoccupied orbital. When an inner shell electron is removed, the atom becomes unstable which causes an electron from a higher orbital to fill the void from the excited electron, resulting in an emission of photons measured by fluorescence detectors in the beamline. This fluorescence can be measured as a function of incident photon (excitation) energy to produce an x-ray absorption spectrum; these spectra are then used to identify and fingerprint the structural characteristics of the molecule (Myneni, 2002; Solomon et al., 2005; Lehmann and Solomon, 2010; Adams et al., 2016; Dhillon et al., 2017). For this study, C and N fingerprints were mapped at a range of 270 to 320 eV for C, and 380 to 430 eV for N. The XANES results for C and N spectra were graphed and represent a fingerprint of the specific C and N compounds in the sample (Lehmann and Solomon, 2010). The peaks of each spectra are representative of difference species of that element and are determined from reference compounds either as part of the experiment or via comparison with literature (Myneni, 2002; Lehmann et al., 2009; Lehmann and Solomon, 2010).

The advantages of using X-ray spectroscopy is that it can decipher the specific forms of molecules in soils rather than reporting the total quantity of organic C and N. While SOM levels are important in assessing soil health, XANES provides insight on how management practices are influencing nutrient cycling of certain elements. The decomposition of SOM is influenced by numerous biotic and abiotic factors like chemical composition, mineralogy, and microbial community (Gillespie et al., 2014b). Different fingerprints for molecules represent different stages of decomposition. Soils that display an abundance of molecules like carbohydrates and amide-N tend to represent soils where little OM is being cycled, as these molecules are considered more labile and decrease as decomposition progresses (Kögel-Knabner, 2000; Vairavamurthy and Wang, 2002; Gillespie et al., 2014a; Adams et al., 2016). Soils higher in compounds like ketones and pyrrolic-N molecules are an indicator of quicker OM turnover as these products are often stripped of their most bioavailable components and are a result of metabolic processes of microbes (Gillespie et al., 2014a; b). Quantifying the abundance of different species within soils can thus provide clues to the mineralization potential of different nutrients in soils, and whether management practices (such as inputs and tillage) are influencing OM turnover.

Finding new ways to monitor and limit soil degradation in SSA is essential for increased food security, but these practices will only be successful if smallholder farmers are incentivized to adopt these new technologies. Without addressing the factors that inhibit adoption, new practices and technologies will fail to gain traction with smallholder farmers, and any potential benefits reported at research trials will not be realized by the end user. Understanding the nuances of adoption for African farmers is vital when striving towards food secure citizens.

2.6. Adoption of New Agricultural Practices

The majority of the world's poor work in the agriculture industry with the majority of farmers being considered smallholder farmers (SHF), farming less than two hectares of land (FAO, 2009; Foster and Rosenzweig, 2010). Adoption of new technologies for SHF is dependent on a number of factors: profitability, relative profitability, risk, education levels, size of farming operation, difficulty in learning new skills to adopt the technology, success of adoption by neighbouring farmers, and success or failure of previous adoption of new technologies (CIMMYT, 1988; Yanggen et al., 1998; Foster and Rosenzweig, 2010; Bachmann et al., 2016). Adoption of new agriculture practices often comes in a step-wise fashion and each incremental step takes time for farmers to adopt (Aune and Bationo, 2008). The first step of adoption involves practices that have little financial cost and are based on locally available resources, such as adding manures and using seed priming methods. The next step would involve more financial cost such as purchasing fertilizer or better-quality seeds. The farmer continues to take steps forward that have more financial cost but also larger financial rewards for implementing a technology. Over time, as adoption progresses and technologies improves the creation of well-defined markets and regulations with institutional backing that can stabilize the industry (Aune and Bationo, 2008).

For adoption to occur, farmers assess not only the profitability of the potential investment but also the opportunity costs associated with that particular investment. Benefits gained from a certain activity (fertilizer, seeding densities) are weighed against the costs of performing that activity (time, labour, cost) and farmers assess the net benefit rather than profit of that activity (CIMMYT, 1988). While different financial ratios are used to determine adequate returns (Value-Cost Ratio, Marginal Value Cost Ratio, etc.) the general consensus is that farmers need a minimum rate of return of 100% on an investment to consider it a worthwhile risk (CIMMYT, 1988; Yanggen et al., 1998). For farmers that are more risk averse, or areas where the new technology has a greater risk of failing or involves a new skill, the minimum rate of return increases. While investment in agriculture has seen profitable returns and has increased food security and decreased poverty rates, it's important to compare the opportunity costs of other investments, like education, migration, and off farm business activities, to determine whether agriculture is the best investment option.

2.7. Migration

In 2017, an estimated 258 million people migrated to different countries, with Africans representing just under 14% of migrants (United Nations, 2017). As a result of migration, remittances have increased steadily, accounting for over US $400 billion in payments (United Nations, 2017). Remittances are seen as a private welfare system that redistributes wealth from the richest to the poorest family members within a community (Gupta et al., 2009). Remittances have been viewed as a potential solution to poverty and act as an economic stimulus for family and community members, providing a means for investment in education, health care, and businesses (Gupta et al., 2009). A multiplier effect of $2-3 for every $1 sent back is found with remittance money, as those receiving money often spend it in the local economy, while every $1 of income from agriculture has a multiplier effect of about $1.3-1.5 elsewhere in the economy, suggesting remittance dollars may go a longer way in increasing wealth (Taylor, 2006; Christiaensen et al., 2011).

But migration is costly and risky for families with no guarantee of returns. Along the migration path, migrants are at risk of human traffickers and boarder detention. If migrants do make it to their country of destination there is the possibility of culture shock, language barriers, failing to land a job, homelessness, poverty, and difficulty in transferring money back to the family (Taylor, 2006). For poorer families, sending a member involves the risks mentioned above, as well as difficulty in funding the migration trip. Families often do not have enough savings to carry the costs of migration and an outside source of income through loans, financing, and trades is needed, which involves its own set of risks (Taylor, 2006). Migration, then, is for the upper middle-class families, who are wealthy enough to fund the migration journey, but not wealthy enough to be content in their current situation. The migration of upper middle class families does not necessarily reduce poverty or food insecurity, since these families are likely already food secure, and it may in fact decrease living standards for those in the community as a result of human capital, in the form of educated workers, being exported from the village (Taylor, 2006; Gupta et al., 2009).

2.8. Education

In 2016, roughly 40% of students continued to upper secondary school (equivalent to high school age) in Sub Saharan Africa (UIS, 2018). In Nigeria and Benin, the average years of schooling for residents is 6 and 3.5 years and both countries have low literacy rates, with only 56 and 38% of the population being literate (United Nations Development Programme, 2018). This presents a problem for development as those who are educated are more likely to adopt technologies as they have developed literacy skills to read and write and are able to decode problems and learn more quickly than those who lack education. It is estimated that each year of education adds about 2.5% to farm outputs, and has been associated with a 7% increase in future income (Psacharopoulos, 1994; Foster and Rosenzweig, 2010; Peet et al., 2015). Along with increased income, investment in education is linked to non-monetary benefits like increased health, life enjoyment, savings, social cohesion, charity, political knowledge, and lower crime rates (Dickson and Harmon, 2011). Though the returns are high (both financially and socially) for investing in education, similar problems arise for education as with migration. The Aid for Africa charity estimates it costs US $650 for one student to go to high school in the east African countries of Tanzania, Kenya, and Uganda (Aid for Africa, 2014). In those same countries 47, 34, and 35% of the population lived at or under the US $1.90 per day poverty line (United Nations Development Programme, 2016). Investing in children's education may be unrealistic for many SHF as they are unable to pay school fees for multiple children while still providing money for the necessary costs of farming (fertilizer, seeds, ploughing) and food. In addition to school fees, family, and in particular children, make up a crucial part of the workforce for SHF and income is foregone when children are at school rather than working (Psacharopoulos, 1994). Investment in education is a better long-term investment than either migration or agriculture in terms of both monetary and non-monetary benefits, but education carries a high opportunity cost. Withholding children from school to work on the farm or other labour-intensive jobs provides immediate financial returns in the form of higher yields or current wages. Education is likely to be the most beneficial for those who are least likely to be able to forego an earning for an extended period of time.

2.9. Agriculture

The emergence of the Green Revolution in the 1970's in Asia and South America led to a growth in agricultural production through technological advances (fertilizers and high yielding varieties) and stimulated economic growth in other industries. This provided evidence that increasing agricultural production through investment could spur economic growth in other industries and increase national GDP (Tiffin and Irz, 2006; Christiaensen et al., 2011; Zylbersztajn, 2017). As the majority of the world's poor live in rural agricultural settings, and the most important industry in poorer countries is agriculture, growth in this sector will likely result in an increase in wealth for the country's poorest residents (Foster and Rosenzweig, 2010). Christiaensen et al., (2011) found that growth in the ag industry is better at reducing poverty for those living under the US $1/day while non-ag industries is better for reducing poverty for the better off poor (US $2/day).

Increased production in agriculture leads to a direct increase to farmers income, but also leads to a decrease in the price of food, which is considered a wage good (Tiffin and Irz, 2006). A decline in the price of food can lead to economic growth through industrial competition and creation of jobs (industrial workers can be paid a lower wage yet still purchase the same amount of food), and Engels law takes effect, where less money is spent on food (lower prices) and more money is spent on non-agricultural related products (clothes, education, etc.) (Tiffin and Irz, 2006; Christiaensen et al., 2011). In addition to food, agriculture can provide the raw materials needed for certain industrial sectors like manufacturing and can also provide an economic stimulus through land taxes that fund government projects like roads, (Tiffin and Irz, 2006).

However, other studies have argued that the agricultural sector displays a "productivity gap", where the value added by workers in non-agricultural industries is more than the value added by workers in agriculture, hence investing in agriculture to increase GDP is a misallocation of resources (Gollin and Waugh, 2014). In addition to non-agricultural workers providing more value, agricultural growth is linked to industries that provide inputs or machinery that make farming more efficient. Technological developments to these manufacturing industries can have a spillover effect and increase agricultural production (Tiffin and Irz, 2006). Data has shown that GDP growth in agriculture has trailed growth in non-ag sectors, and as a country develops agriculture becomes less important to economic growth that non-ag industries (Christiaensen et al., 2011).

While growth in both ag and non-ag sectors is important for the development of a country, limited resources and capital should be allocated to industries that have the largest effect on poverty reduction. Resource limited farmers are faced with a multitude of problems in determining the best course of action to increase wealth. Developing agronomic practices that require no additional capital should be undertaken by institutions like universities and humanitarian foundations that can be dispersed to farmers easily. For example, educating farmers on proper fertilizer application methods is a relatively small change with little additional expenditures (assuming farmers are using fertilizer) that can increase yields and maximize returns. Other agronomic practices like seed priming and optimum seeding densities require no additional financial investment yet can lead to increased earnings. These changes in agronomic practices without the investment of capital allows farmers to allocate financial resources in other directions, like education or entrepreneurial opportunities that provide a source of non-ag income. Continued work and investment in the ag sector to increase yields in a sustainable manner is needed to ensure the poorest of the poor have a means to break the cycles of poverty

3. The Effects of MicroVeg Recommendations on Soil Quality and *Amaranthus cruentus* Yield in the Rainforest, Savanna, and Sudano Savanna Eco-Regions of Nigeria and Benin Republic

3.1. Preface[1]

To consider a set of agronomic recommendations beneficial for farmers it must be tested at the farm level. This chapter evaluates the effects MicroVeg recommendations have on soil fertility and yields, and compares the results to the local practices in the area. Results from research plots reported MicroVeg recommendations increased Tete yields but did not report the effects it had on soil fertility. This chapter compares soil samples and yield data from MicroVeg and local farms in Nigeria and Benin producing Tete. Results from this research will provide insight on the actual benefits farmers receive from recommendations developed on research plots, and determine if these practices are providing more value to farmers than local practices.

3.2. Abstract

Sub Saharan Africa is the only location in the world where per capita food production has remained stagnant over the last 35 years due to a combination of high population growth, droughts, and low soil fertility. Sustainable intensification of agriculture is required to provide food security but requires innovations to be effective for the resource-limited rural farmers. The MicroVeg project is a set of agronomic recommendations that has proven successful at increasing *Amaranthus cruentus* (Tete) yields on experimental plots in Nigeria, and Benin Republic. The current study utilized a variety of approaches to evaluate the effects MicroVeg has on yield and soil fertility from on-farm studies. Soil samples and yield data from farms implementing MicroVeg (MV) recommendations and farms using traditional or local practices (LP) to produce Tete were taken from three eco-regions of Nigeria and Benin and compared using soil chemical analysis and X-ray absorption near edge structure (XANES) spectroscopies at the C and N K-edges. Farms using MicroVeg recommendations increased yields but displayed lower soil nutrient levels.

[1] Manuscript will be submitted to an acceptable academic journal for publication during the thesis review process. Coauthors include G.S. Dhillon (XANES analysis, interpretation, discussion and figures), D. Peak and D. Natcher (financial assistance, laboratory facilities, consultation, editing, and direction), G. Kar (laboratory assistance), D.Oyedele (PI on MicroVeg project in Nigeria), P. Akponipke (PI on MicroVeg project in Benin), C. Adebooye (PI on MicroVeg project in Nigeria).

XANES analysis found the functional group composition of C did not change with the short-term adoption of MicroVeg recommendations, however, the MicroVeg sites showed higher abundance of amide-N and lower abundance of more decomposed N forms such as pyrrolic-N, indicating supplemental N may be more available for plant uptake following MicroVeg recommendations. We conclude that MicroVeg is a beneficial innovation for resource limited rural farmers to increase yields and fertilizer efficiency but cannot be considered sustainable until further long-term research has been conducted.

3.3. INTRODUCTION

Global agricultural outputs will need to increase by 70 % to keep pace with population growth, which is expected to rise 114 % by 2050 (FAO, 2009). While other developing nations like Asia and Latin America have increased yield production, Africa has lagged behind, and any yield increases that have occurred have been a result of land expansion rather than increases in crop productivity (Bationo et al., 1998; FAO, 2009; Vanlauwe and Zingore, 2010). Poor infrastructure, limited access to resources, the risk averse nature of smallholders farmers, and at times war and political instability keep the gap between potential and realized yields from decreasing (Abdoulaye and Sanders, 2005; Aune and Bationo, 2008; Camara BS et al., 2013; Bachmann et al., 2016). In addition to socio-economic constraints, agronomic problems like poor soil fertility, erratic rainfall patterns, and rising temperatures further widen this gap (Bationo and Mokwunye, 1991; Abdoulaye and Sanders, 2005; Twomlow et al., 2008).

Though many of these issues cannot be controlled by rural farmers, adopting different facets of soil fertility management practices can help restore low fertility soils (Bationo and Mokwunye, 1991; Bationo et al., 2007; Vanlauwe and Zingore, 2010). The practices farmers adopt need to be economically viable as well, or adoption will not occur. For example, large additions (15,000-40,000 kg ha^{-1}) of organic inputs (crop residues, manures) is a proven way to increase organic carbon levels, soil aggregation, buffer against pH decreases, and increase cation exchange capacity (de Ridder and van Keulen, 1990; Bationo et al., 2007; Adams et al., 2016). However, these rates are unrealistic for rural farmers to apply as it is difficult to acquire such large quantities and these resources are often used for other reasons, such as fuel and building materials

(Abdoulaye and Sanders, 2005). Providing recommendations for rural farmers that are financially feasible, agronomically beneficial, environmentally sustainable, and economically profitable is the aim of the MicroVeg project.

The MicroVeg project is a collaborative international research partnership among universities in Benin, Canada, and Nigeria funded by the Canadian International Food Security Research Fund and is a synergy of two previous International Development Research Centre projects. MicroVeg is a set of agronomic recommendations developed to increase indigenous vegetable production in Nigeria and Benin Republic. *Telfairia occidentalis* (Ugu), *Solanum macrocarpon* (Igbagba), *Amaranthus cruentus* (Tete) are the three vegetables chosen for production in Nigeria and *Ocimum gratissimum* (Tchiayo) is substituted for Ugu in Benin due to their viability, marketability, and potential economic effect. Tete was the most common vegetable across the three eco-regions and will be the vegetable of focus in this thesis chapter.

The MicroVeg approach combines microdosing and agronomic practices such as improved land preparation, optimum seeding rates, staking, raised seedbeds, breaking seed dormancy, specific harvest intervals, and the application of manures as a sustainable way to increase yields (Akponikpe et al., 2016). Microdosing, a precision fertilizer technology, was developed by the International Crops Research Institute for The Semi-Arid Tropics (ICRISAT) and is the agronomic practice of precisely placing a reduced amount of fertilizer close to the seed during planting (Twomlow et al., 2008; ICRISAT, 2009; Camara BS et al., 2013).

The purpose of microdosing is not to maximize yields, but to maximize fertilizer use efficiency, and decrease financial risk associated with purchasing fertilizer. A wide range of research has been conducted on the profitability of microdosing over the short term (Aune and Bationo, 2008; Twomlow et al., 2010; Vanlauwe and Zingore, 2010), and more recently, research has been conducted to determine its long term sustainability (Adams et al., 2016; Ibrahim et al., 2016). Microdosing alone can increase short-term yields, but at an unsustainable rate (Aune and Bationo, 2008; Twomlow et al., 2008; Adams et al., 2016). Using only organic inputs (manures, residues) is also insufficient, as the high rates needed to supply adequate nutrients to crops are often unavailable (Abdoulaye and Sanders, 2005; Vanlauwe and Zingore, 2010) . Using both inorganic and organic fertilizers in conjunction rather than separately, has proven beneficial as it can increase yields, buffer against soil acidification of mineral fertilizers, encourage soil aggregation and moisture retention, replenish soil organic carbon, and add micronutrients vital for plant health. Using both fertilizers in combination is part of the integrated soil fertility management system (ISFM) that recommends using agronomic practices that aim to replenish depleted soils (de Ridder and van Keulen, 1990; Bationo et al., 2007; Vanlauwe and Zingore, 2010; Gentile et al., 2013; Lal, 2015).

Although research has been done on improving yield and soil fertility using ISFM practices, much of the data had been gathered from experiments done at controlled research sites (Bationo et al., 2007, 2012; Hayashi et al., 2008; Adams et al., 2016). Research that has occurred off site involving rural farmers has focused on yields and financial returns instead of fertility and sustainability (Twomlow et al., 2008; Camara BS et al., 2013). The objective of this study was to work with smallholder farmers to evaluate the effects of MicroVeg recommendations on soil fertility and Tete yields. We hypothesize MicroVeg farmers will report higher yields and will have higher levels of nutrients in their soils than farmers using local practices to produce Tete. Qualitative data from interviews with farmers and records from extension agents were used to gather yield data. Soil samples were taken from plots implementing and not implementing MicroVeg recommendations and analyzed to determine soil fertility. X-ray absorption near edge structure (XANES) spectroscopy was used to determine how farming practices are affecting the chemical speciation of C and N, deepening our understanding of how management practices influence turnover times and nutrient cycling (Gillespie et al., 2011, 2014b). Site specific data such as climate, soil type, eco-regions, and elevation was obtained from a Geographic Information System (GIS) database developed by the project. Finally, all sites were georeferenced during collection, resulting in the possibility of future long-term research to monitor the benefits or drawbacks farmers are receiving from the MicroVeg project

3.4. Materials and Methods

3.4.1. Site Selection

This project involved one field season during the dry season cycle in three eco-regions spanning the countries of Nigeria and Benin (Fig. 3.1), between March 20 – April 5, 2017. In each eco-region, farm sites were selected by Extension Agents (EA) working with farmers implementing MicroVeg (MV) practices and farmers using the traditional or local methods (LP) to produce Tete. The Rainforest (RF) region had three MV and three LP farm sites selected, the Savanna (SV) had four MV and four LP farm sites, and the Sudano Savanna (SS) had three MV and three LP farms sites sampled (Fig. 3.2).

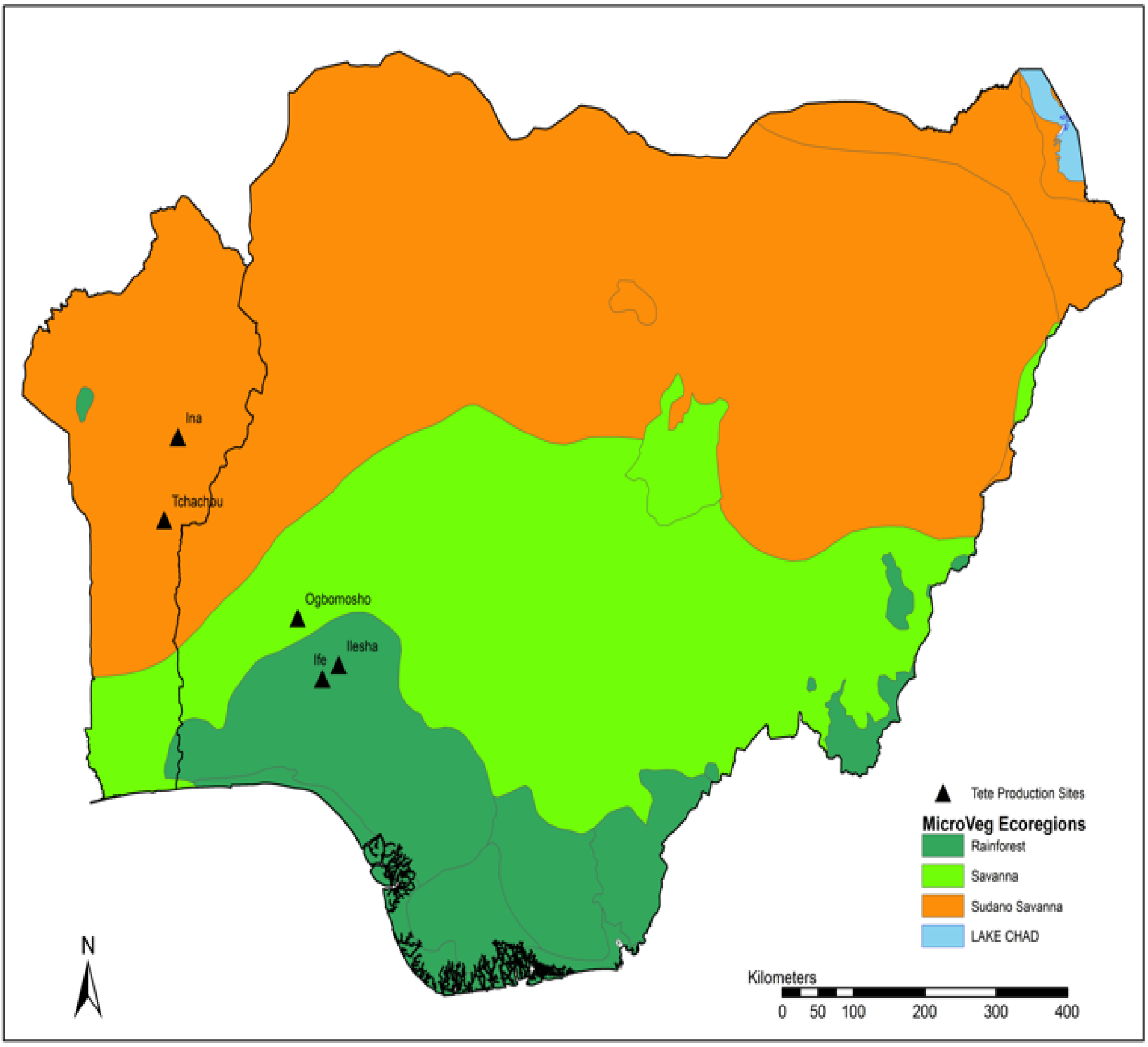


Fig. 3.1 The Rainforest (Dark Green), Savanna (Lime Green), and Sudano Savanna (Orange) eco-regions of Nigeria and Benin.

Soils were classified as Haplic Lixisols (LXha), Eutric Nitisols (NTeu), and Plethnic Plinthosols (PTpx), for the three eco-regions (Fig. 3.2) (Jones et al., 2013, Minielly, unpublished data, 2018). Lixisols are considered marginal lands that are slightly acidic and increase in clay content with depth, and depositional spots can have an enrichment of base cations through aeolian deposits. The clay is kaolinite that is limited in nutrient holding capacity and biomass production but are still able to produce crops with the addition of fertilizers. Lixisols are prone to erosion and crusting due to high impact rainfalls and lack any sort of developed soil structure (Jones et al. 2013). Plinthosols contain plithite, an iron rich, humus poor mixture of kaolinite, quartz, and other minerals that can harden permanently when exposed to air and sunlight. Its properties are strongly influenced by groundwater (Jones et al. 2013). Nitisols are dominated by kaolinite clay and developed on iron rich basalt rock. They are productive agricultural soils, though they can be plagued by phosphate fixation due to the large amounts of iron. Fertilizer is necessary for crop production (Jones et al. 2013). Because of the large geographical distance between farm sites within an eco-region, large differences in soil texture between MV and local farm sites was common. Large variation in texture was found in the RF and SV region, where soil texture ranged anywhere from clay to loamy sand (Table 3.1).

Table. 3.1 Soil texture for each site.

	Rainforest			**Savanna**			**Sudano Savanna**		
	Sand†	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
MV1	21	47	32	87	5	8	76	14	10
MV2	82	11	6	83	6	10	81	9	10
MV3	24	35	41	85	5	10	55	26	19
MV4	-	-	-	22	49	29	-	-	-
LP1	64	21	15	21	32	47	68	19	13
LP2	72	22	6	45	33	22	71	16	13
LP3	30	43	27	59	22	19	71	15	14
LP4	-	-	-	35	36	29	-	-	-

†Numbers recorded in percentages

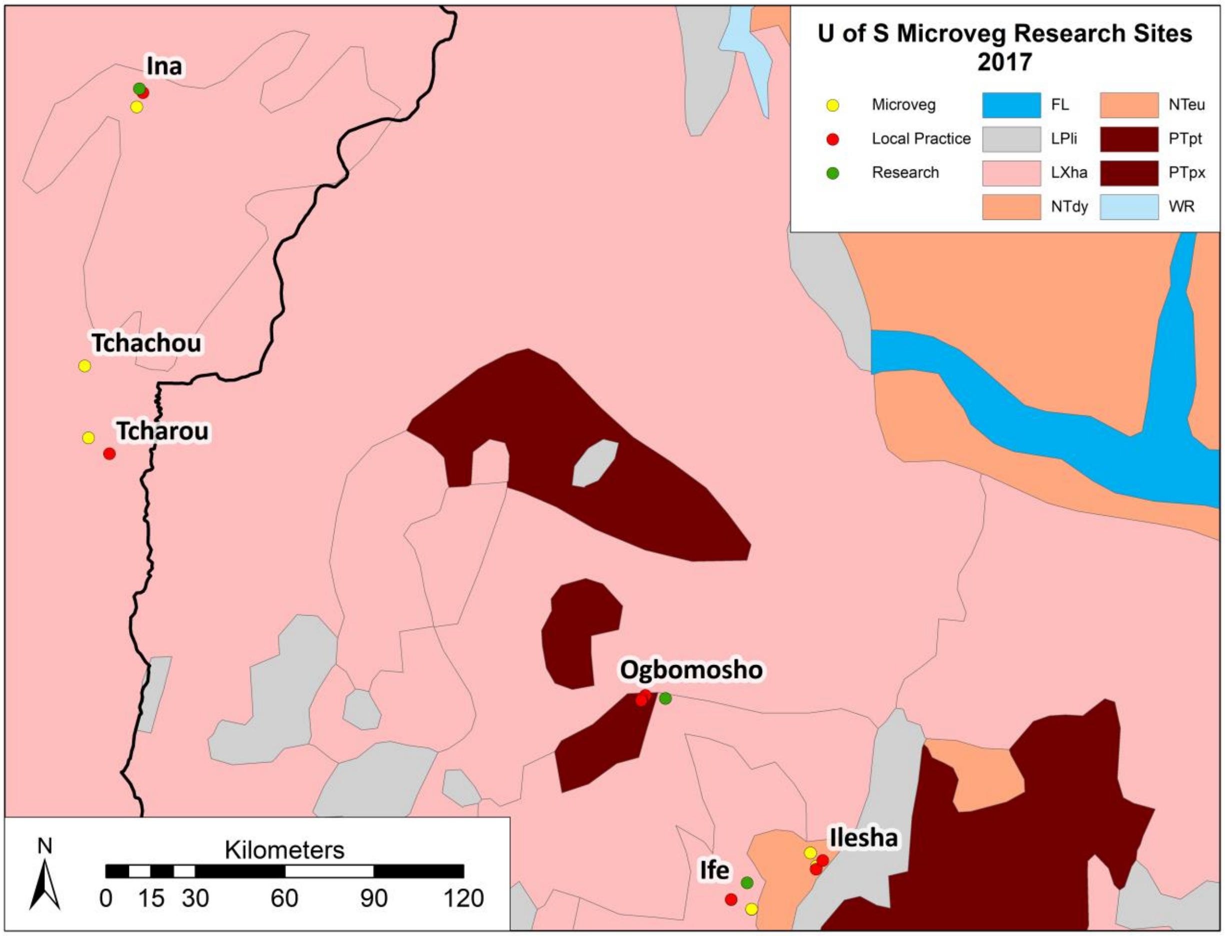


Fig. 3.2 MicroVeg and Local Practice sites

3.4.2. Experimental Design

The field experimental design was a completely randomized design comparing two farming management systems; traditional or local management practices and MicroVeg practices. The MicroVeg practices (Table 3.2) recommend specific organic and inorganic fertilizer rates, seeding densities, seed varieties, harvest intervals, and seedbed formation for three indigenous vegetables; Tete, Ugu, Igbagba. The local practices varied with each farmer, and Table 3.2 reports the range of different rates used by farmers. Perhaps the only common thread for local practices is that there was no set way to produce Tete. Generally, local practices used a lower quality Tete seed than MV farmers, and farmers tended broadcast their fertilizer and seeds without much regard for rates, placement, or timing. They did not follow a stringent schedule as to when they should harvest their plots but followed the same pattern as MV farmers by harvesting leaves three times before uprooting the plant and reseeding and reapplying fertilizer to start a new cycle (Table 3.2).

The design called for the sampling of three seedbeds representing each vegetable at each farm. Each individual farm would act as a replication allowing for statistical analysis to be performed for each vegetable under MV and LP practices. The study had some complications as farmers of both MV and LP grew vegetables they felt most comfortable with and often grew only Tete. As a result of these unexpected circumstances Tete was the only vegetable that could be statistically analyzed. Tete seedbeds were used as replications and sampling numbers range from 3-11 per eco-region, and Igbagba and Ugu were dropped from the study.

A) B)

Fig. 3.3 A) MicroVeg farm in the Savanna B) Local farm in the Rainforest.

Table. 3.2 MicroVeg recommendations for 6 m^2 seedbed.

	MicroVeg†	**Traditional/Local**
Seed Variety	Tete Atetedaye	Tete Olowo Njeja
Mineral Fertilizer Rate (kg ha^{-1})	20‡,40§	0-500‡
Organic Fertilizer Rate (kg ha^{-1})	5,000§¶	0-1,666‡
Fertilizer Application Method	Microdose	Broadcast
Fertilizer Application	0-7 days after seeding	Random
Plant Density (Nigeria)	550#	Random
Plant Density (Benin)	186††	Random
Seedbed Formation	Yes	Weakly formed or not at all
Weeding	Weekly	Weekly
Harvest per Cycle	3	3
Cycles Per Dry season	2-4‡‡	2-4

† Farmers who have been using the MV recommendations have been doing so for at least one year
‡ MV recommendations call for 40 kg ha^{-1}, but farmers in Benin did their own trials and decided 20 kg ha^{-1} provided the same benefits as 40 kg ha^{-1}. For a 6 m^2 seedbed the farmer would apply 0.012 kg or 0.024 kg for a rate of 20 and 40 kg ha^{-1}
§ These rates are reapplied after every cycle
¶ For a 6 m^2 seedbed the rate is 3.0 kg
# 10 cm row intervals
†† 20 x 20 cm spacing
‡‡ The dry season is between November to April in Nigeria, and October to May in Benin

Farms involved in the MV project used urea-N (46-0-0) fertilizer at a rate of 20 kg ha^{-1} in Benin, and 40 kg ha^{-1} in Nigeria. Fertilizer rates varied substantially for LP farms, and rates from extension agents differed significantly from rates reported in interviews. For the Rainforest eco-region, LP farms used 63, 111, and 88 kg ha^{-1}, in the Savanna rates were 4, 56, 0, and 138 kg ha^{-1}, and in the Sudano Savanna rates were 500 kg ha^{-1}. Rates from the extension agent were broader and described LP farmers using five "milk peak tins" per seedbed. Milk peak tins are 150 ml tins that contained evaporated milk. How much these tins weighed and how full they were when used to apply fertilizer was not specified but was more than the 0.024 kg of Urea used per seedbed on MV farms. Poultry or cow manure were applied to MV seedbeds and worked prior to seeding at a rate of 5,000 kg ha^{-1}, while LP farmers used anywhere from 0-1,666 kg ha^{-1}. Analysis of poultry manure had an average nutrient content of 2.27 N, 19.95 C, 1.38 P, 1.12 K, and 0.22% S, while cow manure averaged 0.3 N, 4.5 C, 0.21 P, 0.9 K, 0.13% S. Soil samples were taken at a depth of 0-20 cm from three different 6 m^2 seedbeds between the second and third harvest of Tete leaves at each farm during the third cycle of production. Samples were collected via consolidation of 8 sub-samples taken from each bed. Each sample was wrapped in aluminum foil, placed in Ziploc bags, and stored in Tupperware containers for transport. The containers were then transported to either Obamfemi Awolowo University for samples collected in Nigeria, or Université de Parakou for samples collected in Benin. Samples were air dried, passed through a 2-mm sieve, repackaged, and shipped to the University of Saskatchewan for analysis.

3.4.3. Yields

Yield data from harvested Tete leaves were collected from extension agents working with the MicroVeg project who have regular contact with MV and LP farmers. Leaves were harvested at the stalk three times during a cycle, and on the final harvest the entire Tete plant was removed from the seedbed. In addition to EA records, data collected from on-site interviews with farmers using a questionnaire (Appendix A) developed by graduate students from the Agricultural Economics Department at Obafemi Awolowo University were used in combination with EA records. Correspondence to clarify yield data with the EA and graduate students who accompanied the site visits has continued through-out the process of data analysis. The yield data from each eco-region was averaged for MV and LP farms to determine yields for one seedbed during the dry season cycle.

3.4.4. Soil Chemical Analysis

Soils were analyzed for pH, soil organic carbon (SOC), cation exchange capacity (CEC), total nitrogen (N) and phosphorus (P), available N and P, and particle size. All samples were measured in triplicate using standard methods for tropical soils. All measurements were subject to quality control by measuring a standard soil with a known amount of OC, N, or P depending on the test to ensure accuracy. Soil pH was measured using a glass electrode and 2:1 water to soil solution using 5 grams of soil and 10 ml of water (Henderson et al., 2008). Organic carbon was measured using the LECO C-632 carbon analyzer (LECO© Corporation, St. Joseph, MI, USA) following a pre-treatment of HCl (12M) to remove inorganic C (Skjemstad and Baldock, 2008). Available N (NO_3^- and NH_4^+) was determined using the KCl extraction method (Maynard et al., 2008) and analyzed using Folio AutoAnalyzer 3. Available P and CEC were determined using the Mehlich-3 extraction method (Ziadi and Tran, 2008). Available P (PO_4^{-2}) was analyzed using Folio AA3, and CEC was determined using the Microwave Plasma Atomic Absorption Spectrometer (MP-AES 4100 Agilent Technologies) for Al^{3+}, Ca^{2+}, Mg^{2+}, K^+, and Na^+. Total N and P were measured using the acid block digestion method (Thomas et al. 1967) and measured on Folio AutoAnalyzer 3. Particle size was determined using the hydrometer method (Day, 1965).

3.4.5. X-ray Absorption Near Edge Structure Spectroscopy

Carbon and nitrogen speciation was determined using XANES at the C and N *K-edges* using the Spherical Grating Monochromator (SGM) beamline 11ID-1 at the Canadian Light Source in Saskatoon, Saskatchewan, Canada. The beamline delivers 10^{11} photons s^{-1} at the C and N *K-edges* with a resolving power of $(E/\Delta E) > 10{,}000$ (Regier et al., 2007b; a). Two samples, representing MV and LP farms, were selected from each of the three eco-regions. Soil samples within the same eco-region were selected based on similar soil classification and textural properties. Samples were finely ground, suspended in water and pipetted onto Au-coated Si wafers. The wafers were attached to sample holders using double sided carbon tape and left to air dry. The slew scanning method was used to collect data at the C and N *K-edge*, averaging 60 scans per sample. The energy range for C was set to 270 to 320 eV, and for N between 380 and 430 eV, and the beam exit slit was set to 25 µm. Partial fluorescence yield was collected using a silicon drift detector (AmpTek). Citric acid and solid-state ammonium sulphate were used to calibrate C and N *K-edge* respectively.

The C and N XANES spectra were normalized to an edge step of one using Athena (ver. 0.9.26; Ravel and Newville, 2005), and deconvoluted using fityk software package (ver. 1.2.1; Wojdyr, 2010). Spectral deconvolution was performed by fitting a series of Gaussian curves corresponding to 1s-π^* and 1s-σ^* spectral transitions, as well as a background arctangent curve corresponding to the ionization step, following the procedure outlined in Dhillon et al. (2017). The peak areas of Gaussian curves corresponding to 1s-π^* spectral transitions were used to perform multivariate comparison among spectra using nonmetric multidimensional scaling (NMDS; described in the next section) procedure. It is important to note that no attempt was made towards the quantitative determination of C and N functional groups using peak areas or heights, or quantitative comparison of functional groups within single spectra.

The XANES spectral peak assignments for C and N were based upon the published diagnostic peaks of reference compounds. For N *K-edge* spectra, the peak assignments were as follows: (1) pyridines at 398.8 eV, (2) pyrazolic-N at 400 eV, (3) amide-N at 401.3 eV, (4) pyrrolic-N at 402.3 (5) nitroaromatics at 403.4 eV and (6) aromatic amines at 404.4 eV (Leinweber et al., 2007; Gillespie et al., 2009; Solomon et al., 2012). For C *K-edge* spectra, the peak assignment were - (1) unsaturated-C at 284.2 eV, (2) aromatic-C at 285.2 eV, (3) phenols at 286.5 eV, (4) aliphatic-C at 287.6 eV, (5) carboxylic-C at 288.6 eV, and (6) carbohydrates at 289.5 eV (Myneni, 2002; Lehmann et al., 2005; Solomon et al., 2005).

3.4.6. Statistical Analysis.

All measurement variable data were subject to analysis of variance via a completely randomized model using PROC GLIMMIX in SAS (version 9.2; SAS Institute, Cary, NC). Eco-region and MicroVeg were considered fixed factors. The SLICE statement was used to facilitate comparisons for interactions. Means comparisons were performed for significant differences between farm management practices and an interaction effect using least significant differences (LSD; equivalent to Fisher's protected LSD) at a significance level of 0.05.

The C and N K-edge XANES spectra of MV and LP sites among different eco-regions were compared using nonmetric multidimensional scaling (NMDS) technique. NMDS is a multivariate ordination technique that facilitates pattern recognition and interpretation for the multivariate objects by representing them geometrically such that their inter-point distance corresponds to the experimental similarities between them. NMDS analysis was performed with the R statistical software (R Development Core Team 2016) using the vegan package (Oksanen et al., 2017).

3.5. Results and Discussion

3.5.1. Yields

Tete yields from MV farms increased across all eco-regions during the dry season compared to local practices. Yields were highest in the Rainforest, followed by the Sudano Savanna, and Savanna eco-region (Fig. 3.4).

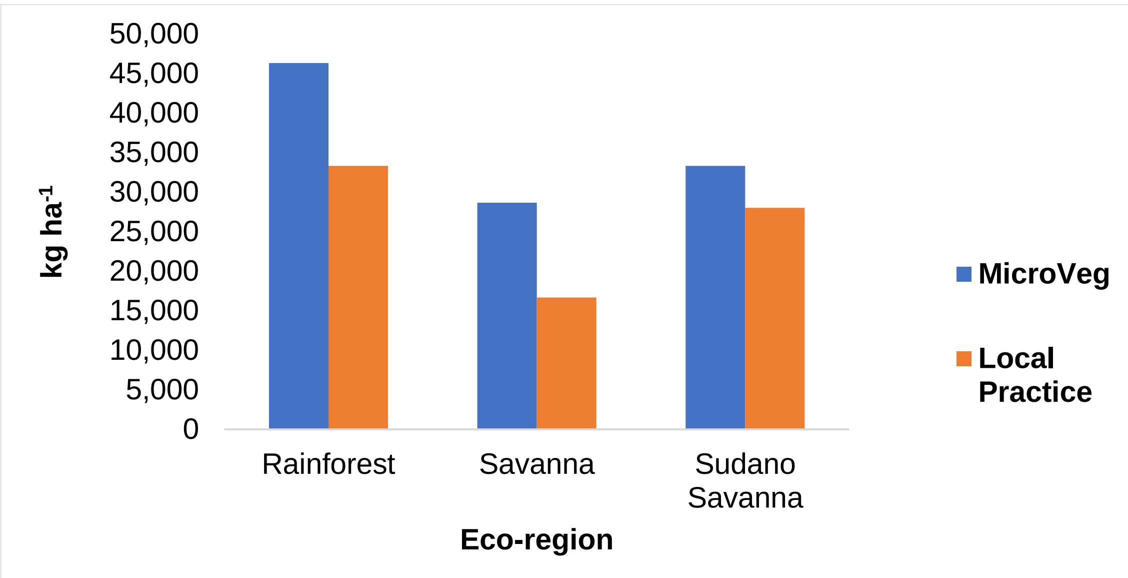


Fig. 3.4 Tete leaf yields for one cycle during the dry season for MicroVeg and local practices. These weights were recorded as fresh yields. Error bars were not included as there were not enough data points to run statistical analysis on yields.

The yield increase is comparable to other short term experiments in Africa using the microdosing method when compared to control plots receiving no mineral fertilizer (Aune et al., 2007; Hayashi et al., 2008; Twomlow et al., 2010; Camara BS et al., 2013; Ibrahim et al., 2015). Large yield differences between MV and local practices were reported for the Rainforest and Savanna eco-regions (Nigeria), while differences in the Sudano Savanna (Benin) were not as pronounced. Low soil fertility and coarser textured soil are often considered important yield limiting factors for African farmers (Bationo et al., 1998; Abdoulaye and Sanders, 2005; Aune and Bationo, 2008), yet this was not the case in our study. MicroVeg soils in the SV and SS were sandier in texture and had significantly lower nutrient levels at the time of sampling, yet still produced higher yields than LP farms (Fig. 3.5). The higher yields suggest management practices specific to MV (seeding rates, seed varieties, harvest intervals, fertilizer placement, fertilizer rates) are strongly influencing yields.

Fig. 3.5 Bundles of Tete leaves after a harvest.

The Nigeria-Canada Vegetable Project (NiCanVeg) conducted experimentation on seeding densities and methods for Tete production. Through farmer surveys, researchers found local farmers planting approximately eight spoonful's of Tete seed on a 6 m^2 plot of land. The project reported yields increased using a direct seeding method at a rate of four spoonful's for 6 m^2 (Number, 2014). The MicroVeg project further expanded on these results reporting plant spacings of 10 x 10 cm for Nigeria and 20 x 20 cm in Benin produced the highest yields while seeding at a rate of 4 spoonful's (Akponikpe et al., 2016). Larger plant spacings have proven to increase the amount of leaves, leaf area, and led to higher yields per plant, but smaller plant spacings produce higher yields per m^2 (Naghdi et al., 2004; Maboko and Plooy, 2013). The difference in seeding densities and method of application, where MV farmers plant at specific rates in a line while local farmers broadcast their seeds, is likely a contributing factor to higher yields on MV farms.

In addition to seeding densities, MV farmers used higher quality seeds (Tete Atetedaye) compared to LP farmers (Tete Olowo Njeja) and used the precise fertilizer application method known as microdosing rather than the broadcast method local farmers used, providing readily accessible N for plant growth and limiting loss via volatilization. In Benin, the smaller difference in yields between MV and LP is likely a result of the high rates of fertilizer (25x more) used on LP farms. While losses due to volatilization or leaching may be exponentially high on LP farms, enough fertilizer was applied to provide the plant with a readily accessible supply of N throughout the growing season. The increased fertilizer rates on LP farms in the SS are likely the reason the yield differences between MV and LP farms in the SS are smaller than the differences in the RF and SV regions.

3.5.2. Soil Chemical Analysis

Results from soil chemical analysis show both MV and LP soils have high levels of nutrients not characteristic of African soils (Bationo et al., 1998, 2012; Abdoulaye and Sanders, 2005; Aune and Bationo, 2008; Adams et al., 2016). These results should be understood more as a snapshot in time rather than an average depiction of soil health. Difficulty in attaining records of previous management practices and soil data provided challenges in making concrete observations. But observations can still be made between soils under MV and LP management systems, and there were significant differences between MV and LP soils primarily in the SV eco-region (Table 3.3). The pronounced difference in nutrient levels is likely a result of soil texture rather than management practices, as LP soils were higher in clay content (Table 3.1), although a general trend of higher nutrient levels in LP soils was reported. This trend was found consistently with the exception of SOC, and available and total P, which were higher in MV soils in the RF region but not significantly different.

Table. 3.3. Soil chemical analysis of MicroVeg and Local practice soils for the Rainforest (RF), Savanna (SV), and Sudano Savanna (SS) eco-regions

			pH	CEC	SOC	Total N	Avail N#	Total P	Avail P††
	n			$cmol_c\ kg^{-1}$	%		$mg\ kg^{-1}$		
RF	8	LP†	$5A^{§bc¶}$	$9.7A^{bc}$	$2.1A^{b}$	$5931A^{ab}$	$65.6A^{ab}$	$1493A^{b}$	$18.6A^{de}$
	3	MV‡	$4.7A^{bc}$	$8A^{bc}$	$2.4A^{ab}$	$5600A^{abc}$	$45.9A^{bc}$	$2306A^{ab}$	$37.3A^{e}$
SV	11	LP	$7.1A^{a}$	$32.6A^{a}$	$3.1A^{a}$	$6695A^{a}$	$72.2A^{ab}$	$3576A^{a}$	$181.2A^{a}$
	8	MV	$5.7B^{b}$	$18.5B^{b}$	$2.1B^{b}$	$4460B^{bc}$	$54.5A^{bc}$	$1955B^{b}$	$105.6B^{bc}$
SS	6	LP	$4.7A^{bc}$	$8.8A^{bc}$	$2.5A^{ab}$	$4752A^{bc}$	$85A^{a}$	$1080A^{b}$	$129.1A^{b}$
	6	MV	$4.5A^{c}$	$5.6A^{c}$	$2A^{b}$	$3142A^{c}$	$40.3B^{c}$	$964A^{b}$	$77.3B^{cd}$
						P-Value			
	Eco-region		<.0001	<.0001	0.405	0.0357	0.7757	0.0003	<0.0001
	MicroVeg		0.0149	0.0755	0.1083	0.0301	0.0014	0.3861	0.0141
	Eco-region*MV		0.0824	0.2360	0.1417	0.427	0.1402	0.0179	0.0318

† Local practice
‡ MicroVeg
§ Means within a column followed by the same letter are not significantly different ($p \geq 0.05$) using Tukey test for LSD
¶ Capital Letter represent significant differences within the eco-region and lower case letters represent differences within the variable
# Available Nitrogen in the form of NO_3^- and NH_4^+ using the KCl extraction method
†† Available Phosphorus in the form of PO_4^{-2} using the Mehlich 3 method

Aside from soil texture, difference between MV and LP nutrient levels may be a result of higher yields and a priming effect that occurs from the addition of manures and fertilizers. In the SS eco-region where soil texture was similar between MV and LP farms, the trend of lower nutrient levels in MV soils was a result of a combination of factors; yields, fallow periods, and fertilizer rates. Nutrient uptake from soils was likely greater in MV farms due to higher yields. This trend has been reported in previous studies that saw a decrease in soil nutrient levels as a result of increased yields (Kibunja et al., 2012; Ibrahim et al., 2016). In addition to lower yields the LP farmers produced Tete during the dry season only and left the land fallow during the rainy season. They informed us that during the rainy season they leave these fields to help their husbands farm cotton, as cotton is considered a cash crop and was incentivized by the Beninese government (Baffes, 2009; Honfoga, 2013). Available N was significantly higher in LP farms and was a result of the extreme amount of fertilizer being added to seedbeds. The high fertilizer rates (500 $kg\ ha^{-1}$)

were the results of using left over urea from their cotton farms as fertilizer was subsidized for growers by the government.

Manure applied to MV seedbeds may result in a priming effect, in which inputs can stimulate microbial activity into "hot spots" for organic matter decomposition (Kuzyakov et al., 2000; Kuzyakov, 2010). A concentrated application of an easily degradable energy source for microbes in the form of manure and plant residues with the addition of N fertilizer on MV seedbeds could lead to a priming effect that continues to stimulate microbial activity after the initial input is decomposed, leading to a mineralization of soil nutrients. This however is an unlikely explanation as manures and higher rates of N fertilizer were added to LP soils which would stimulate microbial activity and decomposition. As well, XANES data showed the presence of labile C and N species in MV soils, suggesting rapid decomposition of OM is not occurring.

3.5.3. Savanna Farmer Study

One particular farmer (MV4 and LP4) in the Savanna region (Ogbomosho) conducted a field trial on their own plot of land using MicroVeg recommendations. The design was similar to a completely randomized design with the land separated into two plots replicated three times with seedbeds acting as replications. The plot representing the farmers common method of producing Tete consisted of one plot measuring 6 x 18 m, and the MicroVeg treatment consisted of 12 seedbeds each 6 m^2. Since local practices do not involve formation of a seedbed, a 6 m^2 area running parallel to the MV beds was measured within the LP plot to specify sampling area (Fig. 3.6.). The local practice consisted of broadcasting 56 kg ha^{-1} of Urea and applying 1,666 kg ha^{-1} of poultry manure. Tete Olowo Njeja seed was broadcasted at an unspecified rate. Tete leaves were harvested three times in one cycle and the Tete plant was removed after the third harvest to prepare for the start of the next cycle. The MV plot consisted of all the practices record in table 3.2. Soil texture was classified as a clay loam, and sampling occurred between the second and third harvest.

(a)

(b)

Fig. 3.6 (a) Front view of the field. The red boxes represent samples taken from a 6 m^2 area in the LP plot. The area that has defined seedbeds is where the farmer was using MicroVeg practices. (b) A side view of the entire plot.

3.5.3.1. Yields and Soil Chemical Analysis in Savanna Farm Study

The Savanna farmer reported an increase of 50% using MicroVeg recommendations, increasing their Tete yields for one cycle from 20,000 kg ha^{-1} using LP methods to 30,000 kg ha^{-1} on MicroVeg plots. Similar to other MV sites in this project, sound agronomic practices implemented by farmers following MV recommendations resulted in increased yields. At this particular site, both soil texture and farmer skill are accounted for, presenting a more accurate picture of the effects of MV practices on yields.

Results from soil chemical analysis report a different pattern than the results reported for the eco-region as a whole (Table 3.4). In particular, the SV region reported MV soils having significantly lower nutrient levels compared to LP farms for all measurement except available N. At this site, variability in soil texture was accounted for and no significant differences were found except for total N and available P, which reported higher levels in MicroVeg plots. This site reported higher pH and SOC levels in LP soils and higher CEC, available N, and total P values for MV soils. The snapshot of this farm provides some evidence that farmers implementing MicroVeg at sites similar in soil texture may not lead to a depletion of nutrients.

A surprising result on this farm was available N was higher in MV soils while LP soils consistently averaged higher levels of available N in all three eco-regions. We suggested that increased yields in MV farms were leading to an increase in N uptake, lowering levels in soil (Kibunja et al., 2012; Ibrahim et al., 2016). Here, MV soils reported an increase in yields, as well as higher levels of available N and P. Unlike the other sites, the farmer at this site had more precise records, as he was performing a trial to decide whether he should implement MicroVeg or not. Local farmers rarely kept accurate reports on rates of organic fertilizer being used. Both the extension agent and farmers reported during the interview that they did not know the rates of fertilizer they used and could only make a guess. It is possible that LP farmers at other sites may have not knowingly added higher amounts of inputs than MV farmers who were keeping records leading to higher nutrient levels. At this particular site, the farmer recorded rates and MicroVeg plots received twice as much manure than the LP plot. Even though yields were higher, adequate amounts of manure was added to offset losses from nutrient uptake (Gentile et al., 2011; Adams et al., 2016; Ibrahim et al., 2016). Secondly, this site was high in clay content and classified as a clay loam. Available N in the form of nitrate is less prone to leaching in clay soils (Gentile et al., 2011). Thirdly, this study is more of a snapshot in time rather than an assessment of nutrient cycling in soils. Soil nutrient data before planting was not available, therefore it was only possible to compare between the farming systems, rather than comparing the amount of N being used during the growing season. It is possible the LP plots at the other sites had higher N levels than the MV plots to begin with.

Table 3.4 Soil chemical analysis for MV4 and LP4 in the Savanna eco-region.

		pH	**CEC**	**SOC**	**Total N**	**Avail N¶**	**Total P**	**Avail P#**
			$cmol_c\ kg^{-1}$	%		$mg\ kg^{-1}$		
SV	**LP†**	7A§	43A	3.6A	7667B	84.7A	4252A	163.5B
	MV‡	6.9A	45.2A	3.4A	8713A	89.4A	4266A	213.6A
					P-Value			
Treatment		0.6130	0.4252	0.5950	0.0041	0.7239	0.9312	0.0177

† Local practice
‡ MicroVeg
§ Means within a column followed by the same letter are not significantly different ($p \geq 0.05$) using Tukey test for LSD
¶ Available Nitrogen in the form of NO_3^- and NH_4^+ using the KCl extraction method
# Available Phosphorus in the form of PO_4^{-2} using the Mehlich 3 method

3.5.4. XANES Speciation

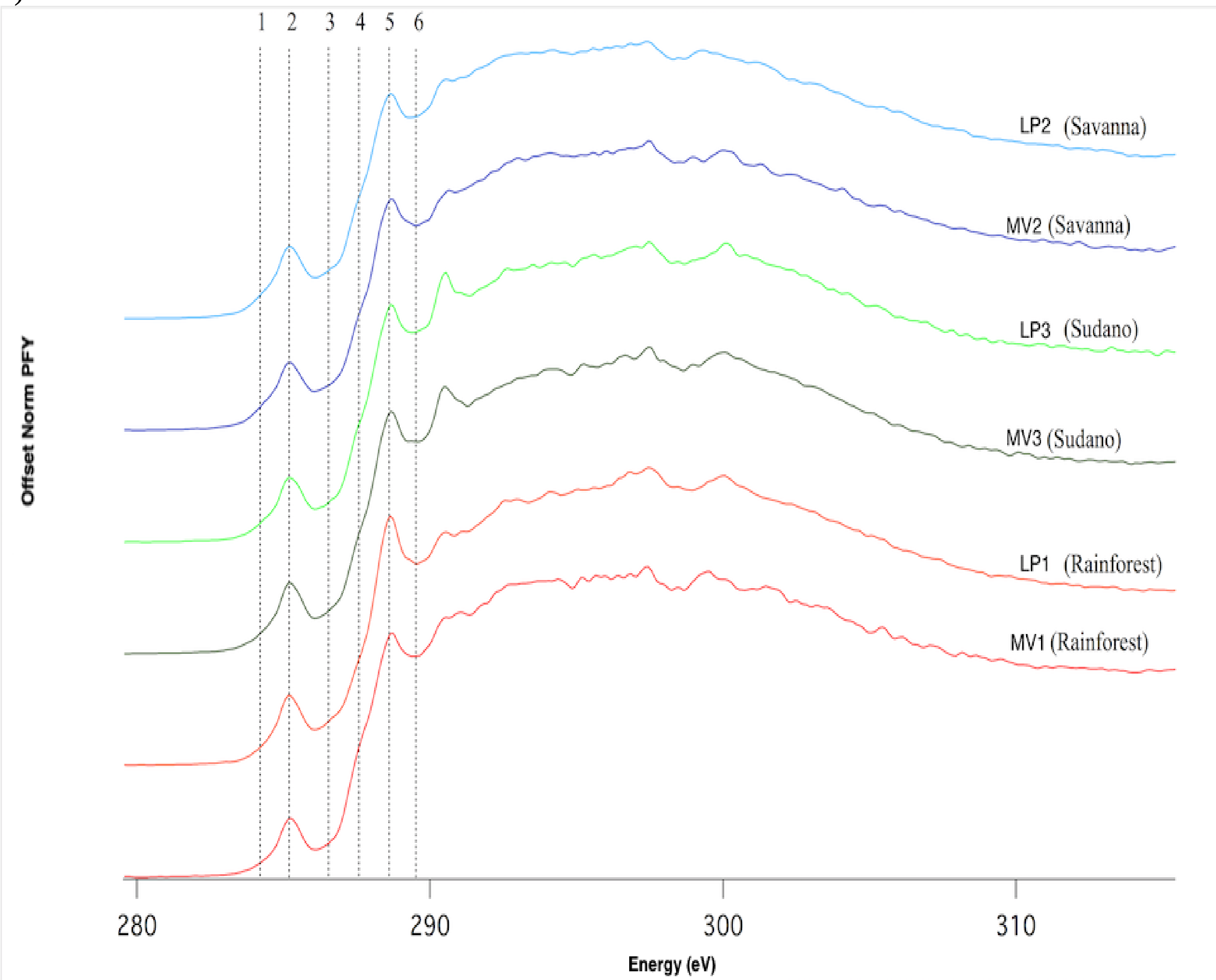
The C K-edge spectra of soil samples in this study showed strong absorbance bands for aromatic-C (285.2 eV) and carboxylic-C (288.6 eV), while also indicating the presence of phenolic (286.5 eV), aliphatic (287.6 eV) and polysaccharide-C (289.5 eV) forms (Fig. 3.7a). Identification of these organic carbon forms is consistent with other research that performed molecular characterization of SOC under temperate and tropical ecosystems (Lehmann et al., 2008; Dhillon et al., 2017). The N K-edge spectra showed the presence of amides (401.3 eV), N heterocyclic compounds (pyridines, 398.8 eV; pyrizines, 400 eV; pyrrazoles, 402.3 eV) and N-bonded aromatic compounds (including nitroaromatic-N, 403.4 eV; aromatic amines, 404.4 eV; (Fig. 3.7b). After Gaussian peak fitting to quantify C and N forms in the samples, non-metric multidimensional scaling (NMDS), was used to assess the relationship between the C and N functional group composition of soil samples under MV and LP farm systems.

For carbon, samples clustered based on their eco-regions, indicating that most of the variability in C XANES spectra of the samples could be explained based on the climatic differences in the eco-regions (Fig. 3.8a). Moreover, the samples under MV and LP methods were positioned close to each other (except for LP1 and MV1) within the ordination plot, indicating that the C functional group composition did not differ significantly among MV and LP sites. In the Rainforest eco-region (consisting of LP1 and MV1), MV soils had a higher abundance of polysaccharides and aliphatic-C compared to the LP soils. Polysaccharides are the easily decomposable C forms, and are derived from leafy crop residues rich in cellulose and hemicellulose (Krull et al., 2003; Lorenz et al., 2007). Higher abundance of polysaccharides at this MV site may be related to the higher plant productivity of the MV site compared to LP (Fig. 3.8a) leading to higher amount of plant inputs into the soil. These results provide direct evidence that the MV recommendations are not leading to higher degree of short-term (one to two-year) SOM mineralization and instead increased plant productivity in MV sites may provide soils with increased SOC inputs.

For nitrogen, the correlation vectors representing different N functional groups clustered such that amide-N appeared in the upper half of the ordination plot, heterocyclic-N compounds (including pyrazolic-N, pyridines, and pyrrolic-N) appeared in the lower left quadrant, and the N-bonded aromatic compounds (including nitroaromatics, and aromatic amines) appeared in the lower right quadrant (Fig. 3.8b). The MV soils separated in the upper half of ordination plot, thus indicating higher abundance of amide-N in the MV compared to LP soils. The LP sites (LP1 and LP2) appeared in the lower half of the ordination plot and were associated with pyrrolic-N. Amide-N is the dominant form of organic N in soils (Schulten and Schnitzer, 1997). It is primarily found in peptides and proteins and represents the proteinaceous compounds that have not been structurally altered by microbial activity (Vairavamurthy and Wang, 2002). Pyrroles are the degradation products of proteins formed through microbial activity (Corpe, 1963), and are considered to be a potential indicator of degree of microbial metabolism (Gillespie et al., 2014a). This observation is also supported by their accumulation concomitant with the depletion of amides, as observed at the LP sites in this study (Fig. 3.8b), which was identified in other studies (Knicker et al., 2002; Gillespie et al., 2014a). The higher abundance of proteinaceous substances at MV sites, and of pyrrolic compounds at LP sites, indicates that the supplemental N (in the form of mineral fertilizer and organic manure) at MV sites is less decomposed compared to the N added at LP sites, and may be more available for plant uptake and growth. The LP site at the SS eco-region (LP3) appeared in the upper half of ordination plot in contrast to the other LP sites (LP1 and LP2). However, this site (LP3) received substantially higher rates of urea fertilizer (500 kg ha^{-1}) compared to other MV (20-40 kg ha^{-1}) and LP (88-56 kg ha^{-1}) sites. Higher rate of fertilizer application may account for the abundance of labile N forms, such as amides, at LP3 site.

The MV sites also differed in the abundance of heterocyclic and N-bonded aromatic compounds (Fig. 3.8b). MV1 site had higher abundance of heterocyclic-N forms, including pyrazolic-N and pyradines, while MV2 and LP3 sites had higher abundance of N-bonded aromatic compounds. The heterocyclic-N forms are derived from the microbial and abiotic transformation of proteinaceous compounds and are considered to be relatively resistant to decomposition (Vairavamurthy and Wang, 2002). The N-bonded aromatic compounds are formed through abiotic incorporation of reactive inorganic-N compounds, into the organic molecules such as aromatic structures (Davidson et al., 2003; Schmidt-Rohr et al., 2004) (Davidson et al., 2003; Schmidt-Rohr et al., 2004). Higher abundance of bioavailable C compounds, such as polysaccharides at MV1 site (Fig. 3.8a), may enhance microbial transformation of N leading to the formation of higher amount of heterocyclic-N compounds, while the abiotic mechanisms, leading to formation of N-bonded aromatics, may dominate in the abundance of less bioavailable C and N compounds (Davidson et al., 2003). While the N-bonded aromatics are considered to be more stable than N in peptides (Verma et al., 1975; Schmidt-Rohr et al., 2004), more research is needed to determine their role in soil N cycling and stabilization.

a)



1
2
3
4
5
6
LP2 (Savanna)
MV2 (Savanna)
LP3 (Sudano)
MV3 (Sudano)
LP1 (Rainforest)
MV1 (Rainforest)
Offset Norm PFY
280
290
300
310
Energy (eV)

b)

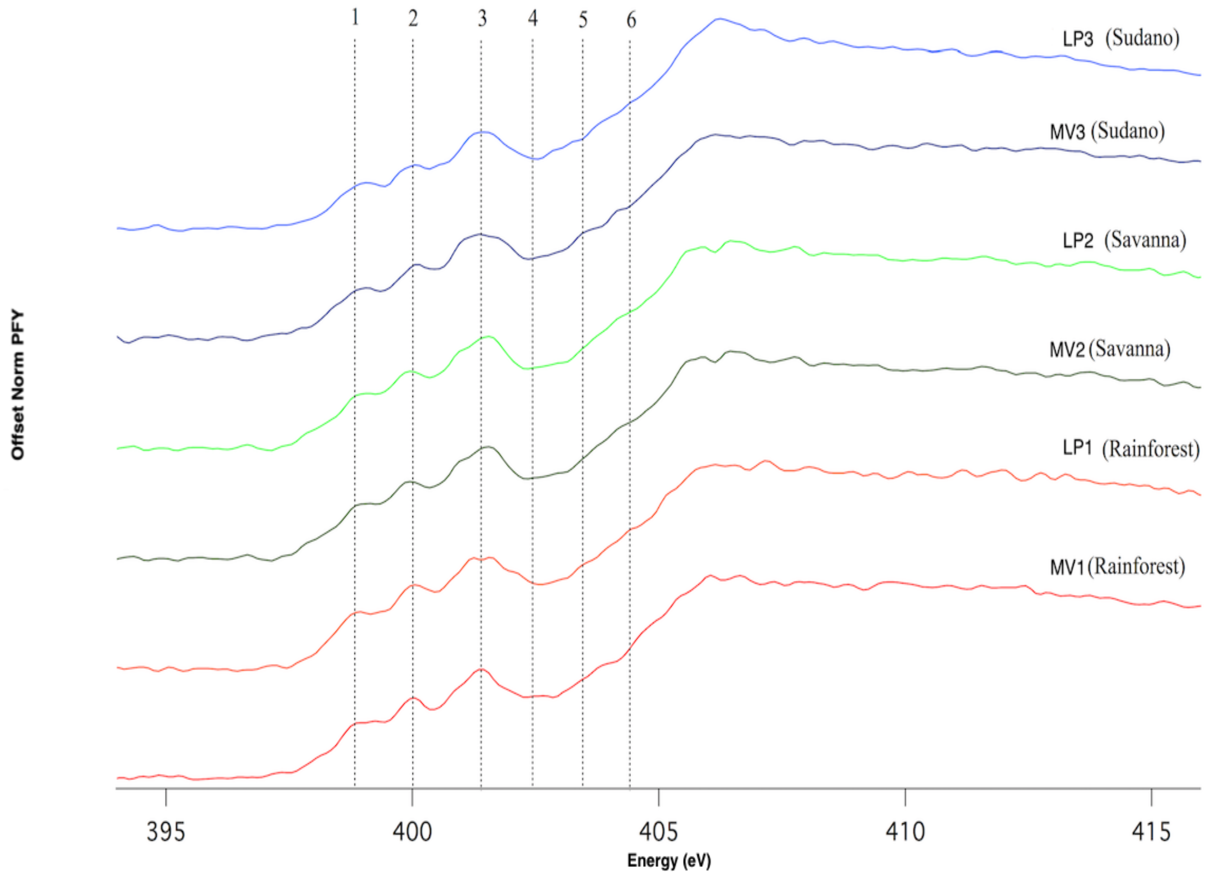
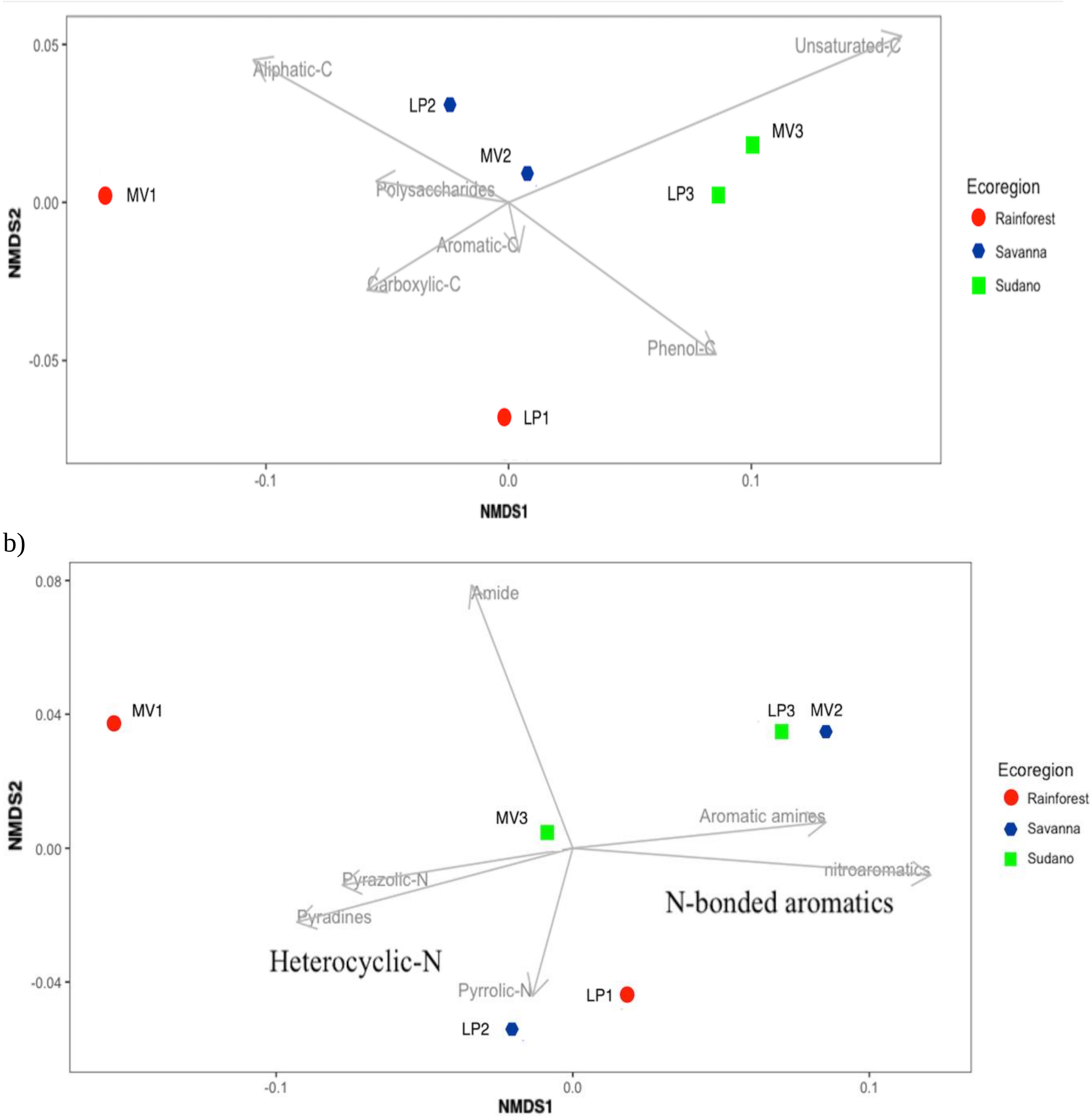


Fig. 3.7 Carbon (a) and Nitrogen (b) K-edge XANES spectra of soil samples from MV and LP soils. The eco-regions are indicated in the parenthesis. 1-unsaturated-C, 2-aromatic-C, 3-phenols, 4-aliphatic-C, 5-carboxylic-C, and 6-polysaccharides. The N K-edge spectra show the presence of 1-pryidines, 2-pyrizines, 3-amides, 4-pyrrazoles, 5-nitroaromatic-N, and 6-aromatic amines.

a)



b)

Fig. 3.8 Nonmetric multidimensional scaling of C (a) and N (b) K-edge XANES features for MV and LP soils in different eco-regions.

3.6. CONCLUSION

The goal of this research was to determine the effects of MicroVeg recommendations on soil fertility and yields. MicroVeg recommendations increased Tete yields in each eco-region regardless of soil fertility compared to local practices due to a combination of management practices such as precise fertilizer placement, seeding densities, and seed quality. Not only did these agronomic improvements lead to higher yields but also limited ecological impacts by reducing the amount of fertilizer purchased and lost through leaching and volatilization.

Soil chemical analysis showed a trend with MV soils having lower nutrient levels than LP soils. The lower nutrient levels in MV soils were likely from a combination of higher yields and lower clay and silt content in those samples. But this trend was not observed when soil texture and farmer variability were accounted for. An analysis completed on a single farm in the Savanna region implementing both MicroVeg and local practices reported no significant difference except for available P and total N, which were higher in MV soils. Analysis of XANES showed MicroVeg recommendations did not affect the degree of mineralization of SOC as indicated by similar C speciation at MV and LP sites within the same eco-regions. Additionally, XANES analysis on N indicated that the microbial degradation of supplemental N may be slower at fields following MicroVeg recommendations, as indicated by abundance of labile N forms, such as amide-N, and lack of mineralized N forms, such as pyrroles, compared to LP soils. It is difficult to assess the effect of MV on soil fertility as no data on nutrient levels was available prior to sampling. In addition to lack of data the majority of farmers did not have accurate records to confirm rates of manure applications, which can strongly influence soil quality. Nonetheless, XANES data does provide a current picture of carbon and nitrogen cycling in soils, and the data reported LP soils displayed a higher abundance of microbially degraded species than MV soils. The main findings from this study indicate that MV recommendations increased yields and may not cause further soil degradation, though longer term studies are needed.

4. The Profitability of MicroVeg Recommendations for Smallholder Vegetable Farmers in the Rainforest, Savanna, and Sudano Savanna Eco-Regions of Benin Republic and Nigeria

4.1. Preface[2]

Assessing the economic profitability of a set of recommendations is important to assess the possibility of adoption by smallholder farmers. Due to the risk averse nature of farmers, adopting new practices must come with large financial incentives. Not only does the new technique need to be profitable, it needs to be more profitable than alternative investment opportunities. This chapter compares the profitability of MicroVeg and local farmers growing the vegetable Tete using a partial budget analysis and common financial ratios used in development studies. Results from this study will shed light on whether adoption is likely to occur or not based on profitability. As well, the study includes a testimonial section that highlights the farmers reason for adopting, or not adopting the MicroVeg recommendations.

4.2. Abstract

Developing sustainable farming practices to ensure an adequate food supply is of preeminent importance for smallholder farmers in Africa. Further degradation of soils will inhibit their ability to produce enough food for a rapidly increasing population. But recommending practices that are beneficial for soil health yet provide undesirable financial returns will not be enticing for adoption. Any new technique introduced to smallholder farmers must be both agronomically sustainable and economically profitable for farmers. This study compared the economic profitability of farmers producing Tete using local practices to farmers using MicroVeg recommendations. Revenue and expense data was collected from interviews with farmers and extension agents working with the project. A partial budget was used to compare the gross profits of each farming system and financial ratios like gross profit margin, value-cost, and input-output ratios were used to determine the efficiency each system produced profits. The internal rate of return was used to estimate the return on MicroVeg practices local farmers would see if they

[2] Manuscript will be submitted to an acceptable academic journal for publication during the thesis review process. Coauthors include D. Peak and D. Natcher (financial assistance, consultation, editing, and direction), E. Bachmann (translator for interviews in Benin) D.Oyedele (PI on MicroVeg project in Nigeria), P. Akponipke (PI on MicroVeg project in Benin), C. Adebooye (PI on MicroVeg project in Nigeria).

adopted MicroVeg recommendations. Farmers using MicroVeg recommendations reported higher gross profits for all three eco-regions, and a return over 898 and 298% in the Rainforest and Savanna eco-regions. The Sudano Savanna region reported slightly higher gross profits and reported lower financial ratios and a negative return on investment. These findings suggest that MicroVeg practices are a suitable option for farmers in the Rainforest and Savanna eco-regions to increase income, but would not be a recommended option for farmers in the Sudano Savanna region.

4.3. INTRODUCTION

Profitability is essential for adoption of new practices as farmers are primarily concerned with supplying enough food for their immediate families (CIMMYT, 1988; Bachmann et al., 2016). Any new recommendation must therefore satisfy these two key aspects for farmers, it must be profitable and increase yields in a sustainable fashion. If these two criteria are not met simultaneously, then lack of profits will hinder adoption or the practice will not be a solution for sustainable production.

Although profitability is paramount in the decision to adopt new practices, it is not the only factor that influences the decisions of farmers (Foster and Rosenzweig, 2010). Farmers judge the relative profitability or net benefit of one practice to another. For example, precise placement of fertilizer may help increase yields, but farmers may not adopt this practice if they feel the labour demands outweigh the benefits (CIMMYT, 1988). Due to erratic weather patterns, limited access to credit, and impoverished conditions of African farmers, adopting practices that are considered 'risky' needs to come with large financial incentives (Yanggen et al., 1998; Aune et al., 2007; Hayashi et al., 2008). Different financial ratios have been used to predict the adoption rate of a new practice, but it is generally accepted that farmers need a minimum rate of return of at least 100% to consider an investment in a new practice worthwhile (CIMMYT, 1988; Yanggen et al., 1998). If the new practice requires the development of new skills or if the practice is more risky, the minimum return rate increases (Yanggen et al., 1998). Other factors such as farm size, farmers age, education level, labour availability, market constraints, and past experiences, all factor in the decision-making process of a farmer (Feder, 1985).

Another challenge to adoption is making recommendations based on results from controlled research plots. Research plots are well maintained and continually monitored by institutions like universities that have better access to resources (Bationo et al., 2007). Key agronomic activities that can lead to yield increases like optimal seeding, weeding, and irrigating times are more easily completed in a controlled environment. The careful monitoring and abundance of resources often inflates the results gathered on research plots and cannot be accurately used to determine potential yield increases for farmers (CIMMYT, 1988; Yanggen et al., 1998; Bielders and Gérard, 2015).

Another issue with using research stations to determine yield improvements is the comparison to a control plot (CIMMYT, 1988; Yanggen et al., 1998). Control plots are commonly low input plots (no organic or mineral fertilizers added) used as a baseline to quantify the benefit of a treatment. While it's beneficial from an experimental design standpoint to have a control plot for comparison, comparing yield increases to a baseline situation that doesn't represent local practices exaggerates yield improvements from treatments (Aune et al., 2007; Hayashi et al., 2008; Camara BS et al., 2013). A more accurate approach would be to compare results from a treatment to the local practices to determine if the treatment is more beneficial than current practices.

Using on-farm demonstration plots more closely replicates the results farmers receive, but biases leading to exaggerated results can still occur, as farmers chosen for demonstration are often better and more progressive than their peers (Yanggen et al., 1998). Thus, it is important to conduct studies involving little outside interference, aside from the initial teaching of new practices, to determine the *actual* benefits farmers receive from a certain set of recommendations. Not only will researchers be able to say with certainty a set of recommendations will benefit the end user, feedback from farmers (what parts were difficult to follow, how they overcame these struggles, etc.) can identify areas of improvement and further refinements.

The MicroVeg project was a collaborative effort started in 2014 from universities in Nigeria, Benin Republic, and Canada to sustainably increase indigenous vegetable production in Nigeria and Benin. The final phase of the project is to assess the economic benefits of MicroVeg recommendations for rural farmers. The objective of this study was to provide an economic analysis on the profitability of Tete production for MicroVeg farmers compared to local farming practices (LP) in the Rainforest, Savanna, and Sudano Savanna eco-regions of Nigeria and Benin. This was accomplished through on-site interviews with farmers and Extension Agents working with the project to gather revenue and expense data. The data was subject to various financial ratios to compare profitability. We hypothesize that MicroVeg farmers will report higher financial ratios and report an acceptable rate of return from MicroVeg recommendations. This research concludes the final phase of the MicroVeg project and highlights the importance of ensuring results from research sites are transferable to the end user.

4.4. Materials and Methods

4.4.1. Site Selection

The study involved one field season during the dry season cycle in three eco-regions spanning the countries of Nigeria and Benin Republic (refer to Fig. 3.1.), between March 20 – April 5, 2017. In each eco-region, farm sites were selected by Extension Agents (EA) working with both MicroVeg and local farmers. The Rainforest (RF) region had three MicroVeg farms and three local practice farm sites selected, the Savanna (SV) had four MV and four LP farm sites, and the Sudano Savanna (SS) had three MV and three LP farm sites. At each site interviews were conducted with the head farmer for a total of 10 MV and LP interviews.

4.4.2. Interviews and Data Collection

In Nigeria (Rainforest and Savanna eco-region), on-site interviews were conducted with farmers to determine expense and revenue data using a questionnaire developed by the Agricultural Economics Department at Obafemi Awolowo University (OAU) (Fig. 4.1) (Appendix A). After questionnaires were completed, OAU collaborators compiled the responses into a spreadsheet outlining revenues, variable expenses, and farm size for each interview conducted and emailed the information. In addition to student interviews, revenues, yields, expenses, market prices, and labour costs were gathered from Extension Agent records. Correspondence to clarify farmer responses and expense/revenue data has continued through-out the process of data analysis.

A) B)

Fig. 4.1 (a) An OAU graduate student conducting an interview with a farmer in the Rainforest eco-region. (b) Interview with a group of women farmers in the Sudano Savanna eco-region.

In Benin (Sudano Savanna eco-region), interviews with farmers were conducted with the use of a translator from the University of Saskatchewan. The student questionnaire used for Nigerian farmers was not used in Benin due to difficulty in administering the interview and understanding the units used on the questionnaire. An attempt to use the questionnaire during interviews was quickly abandoned after much confusion occurred between the farmer and translator. Instead, a list of questions used to gather revenue/expense data from the EA in Nigeria was used for farmer and EA interviews in Benin (Appendix B). Questions were asked regarding the cost to weed, plant, fertilize, irrigate, harvest, and prepare a seedbed, as well as the cost of seed, mineral, and organic fertilizers. Revenues were determined from purchasing one 50 CFA bundle at the local market, weighing the bundles, and then calculating back using harvest yields to determine the revenue per bed each farmer was receiving at market price.

Questions for expense and revenues were asked of both the farmer and EA to determine accurate pricings for labour and revenues. Records of expenses and revenues for rural farmers are non-existent, hence all expense and revenue data recorded was the result of memory recollection. The price for labour, such as weeding, harvesting, and planting was difficult for farmers to calculate since they do the labour themselves and could not put a “cost” to these jobs. Other expenses such as the cost of manure was difficult to grasp as they used the manure produced by livestock and was therefore “free”. All prices were reported in the local currency, in Nigeria the currency was the Nigerian Naira (360 Naira = 1 USD during the field season, March 20-April 5) and in Benin the CFA franc (543 CFA Franc = 1 USD).

In addition to difficulties estimating expense costs, data from farmers may have at times been purposely misleading. During some interviews, it was evident that farmers were exaggerating the cost of expenses and reporting lower revenues. This was made clear when the EA that accompanied us started to question the numbers reported by the farmer during our interview. At other sites, the farmers would ask for a financial gift and tell us they needed it to cover the costs incurred during farming, as well as to pay them for time spent talking to us.

4.4.3. Partial Budget and Financial Ratios

A partial budget analysis was used to calculate gross profit for MV and LP farmers using an average between EA and farmer expense/revenue data. A partial budget does not include all costs incurred by the farmer, but is used to highlight the differences in costs and benefits between various treatments (Table 4.1.) As well, fixed costs like tools, depreciation, taxes, and interest are not included in the analysis (CIMMYT, 1988). In this study, the term gross profit does not include all variable costs incurred to produce Tete, only those that differed between farming systems, and is therefore more representative of each farming systems gross margins rather than their “true” gross profit.

Table. 4.1 Partial budget analysis for Tete production for one 6 m^2 seedbed in the Rainforest eco- region of Nigeria.

Expenses	Average LP	Average MV
Organic Manures	0.04†	0.09
Urea Fert	0.14	0.02
Seedbed	0.15	0.52
Fert application	0.01	0.01
Weeding	0.03	0.03
Planting/Seeding	0.16	0.30
Harvesting	0.02	0.02
Insecticides	0.02	0
Irrigation	0.04	0.08
First Harvest	0.62	1.08
Second Harvest	0.11	0.14
Third Harvest	0.11	0.14
Total Expenses	0.84	1.36
Total Revenues	7.60	13.33
Net Income	**$6.76**	**$11.97**

† Currency recorded in USD

Financial ratios were used to highlight the difference between the two farming systems, and to determine whether the returns from MV are a profitable investment for rural farmers. The value cost (V/C) ratio, gross profit margin (GPM), and internal rate of return (IRR) were used to determine profitability, and the input-output price (I/O) was used to compare the cost of each farming system (Table 4.2). These ratios were chosen based upon previous development work with rural farmers and capability of comparing ratios among different crops (Yanggen et al., 1998; Aune et al., 2007; Hayashi et al., 2008). A V/C ratio is a basic profit marker that measures the profit earned as a result of input costs, and is used as a rough indicator to gauge the adoption potential of new farming practices by African farmers (Yanggen et al., 1998; Hayashi et al., 2008; Twomlow et al., 2010; Sime and Aune, 2014). A V/C ratio of two means that if a farmer spent $100 on inputs, they would earn a revenue of $200 from those inputs. Gross profit margin is an important metric for determining the efficiency at which a business turns a profit and is used to compare the financial health and business models of organizations (Maverick, 2018). The GPM measures how much of each dollar generated in revenues results in gross profit. A GPM of 0.60 means that $0.60 of each dollar made in revenue goes to gross profit, while the other $0.40 goes to cover the cost of goods sold.

Table. 4.2 Financial ratios.

Gross Profit	Gross Profit margin	Value/Cost	Input/Output	Internal Rate of Return
Revenue – Expense†	Net Income / Revenue	Yield * Market Price / Expense	Expense / Price of 1 kg of Crop	$P_t / (1+r)^t - P_0$

†All expenses are categorized as variable expenses

P_t = Difference in net cash flow between MV and LP farms for one cycle

t = Number of time periods, and is 1 for this study

P_0 =Difference in expenses between MV and LP farms for once cycle

r = Discount Rate

The internal rate of return was used to determine the annual rate of return of MicroVeg recommendations. The IRR is a metric used to determine the profitability of a potential investment. A minimal rate of return around 100% is often the benchmark number needed for farmers to consider the new practice/technology a worthwhile investment (CIMMYT, 1988; Yanggen et al., 1998). For example, if the rate of return is calculated at 200% for a particular investment, a $1.00 investment would generate $3.00 worth in revenue ($1.00 to cover the cost of investment and $2.00 as net profit). To calculate the IRR for this study, the difference in cost between the two farming systems (MV and LP) was considered the cost of investment, the cashflow was the difference in gross profits, and the time period was set at one, representing one cycle.

The I/O is a cost ratio that determines the breakeven point of a product; how much product needs to be sold at market price to cover the cost of producing that product (Yanggen et al., 1998). One kilogram of Tete in Nigeria cost $ 0.69 USD (250 Naira) and in Benin was $0.45 USD (250 FCFA) to buy. All prices were converted to USD at an exchange rate of 543 FCFA per 1 USD in Benin, and 360 Naira per 1 USD in Nigeria.

4.5. Results and Discussion

The results from the analysis reported a wide range of outcomes for MV and LP farmers. Gross profits and revenues were higher for MV farmers across all eco-regions, showing farmers using MicroVeg recommendations produced higher yields than LP farmers (Table 4.3). Although MV farmers had higher gross profits across all eco-regions, LP farms had higher GPM and V/C values, and lower I/O ratios in the Savanna, and Sudano Savanna regions, suggesting local practices were more efficient at generating profits in those regions (Table 4.4).

Table. 4.3 Gross profit for a 6 m^2 seedbed for one cycle during the dry season.

	Rainforest		**Savanna**		**Sudano Savanna**	
	MV	LP	MV	LP	MV	LP
Expenses†	$1.36§	$0.84	$1.00	$0.50	$3.37	$2.14
Revenues	$13.33	$7.60	$6.16	$3.65	$9.21	$7.73
Gross Profit‡	**$11.97**	**$6.76**	**$5.16**	**$3.15**	**$5.64**	**$5.60**

† Variable expenses

‡ Gross profit is the average variable expenses and revenue data from extension agents and farmer interview for each eco-region. It represents the gross profit of one seedbed for one cycle during the dry season

§ All numbers were converted from Naira in the Rainforest and Savanna, and the CFA Franc in the Sudano Savanna to the American Dollar

4.5.1. Gross Profit Margin

Averaging the EA and farmers data together, MV had a higher GPM than LP farms at the RF sites, but lower at the SV and SS sites (Table 4.4). Both farming systems reported high margins with the majority of revenues staying within the farm either as income or to pay off other expenses involved with farming (fixed costs, loans, etc). The higher GPM in the SV and SS sites may be a result of factors related to soil fertility and texture rather than management practices. Nitrogen and phosphorus deficient soils are considered one of the main yield limiting factors for African farmers, but in both the Savanna and Sudano Savanna eco-regions LP soils were higher in nutrients and more fertile (refer to table 3.3) (Buresh et al., 1997; Sanchez, 2002; Abdoulaye and Sanders, 2005). With fertile soils abundant in available N and P, LP farmers had conditions conducive to producing adequate yields without the addition of labour-intensive agronomic work that can increase yields like specific fertilizer placement and planting optimal plant populations, lowering their costs.

Table. 4.4 Financial ratios for MicroVeg and Local farmers in the Rainforest, Savanna, and Sudano Savanna eco-regions.

		GPM§	V/C#	IRR††	I/O‡‡
Rainforest	MV†	0.90¶	9.79	898%	1.96
	LP‡	0.89	9.05		1.21
Savanna	MV	0.84	6.14	298%	1.44
	LP	0.90	7.30		0.72
Sudano Savanna	MV	0.64	2.74	(96%)	7.03
	LP	0.72	3.62		4.65

† MicroVeg
‡ Local Practice
§ Gross Profit Margin
¶ To calculate financial ratios, an average was determined for revenue and expense costs by combining data from extension agent records and on-site farmer interviews.
# Value-Cost Ratio
†† Internal Rate of Return
‡‡ Input-Output Ratio

4.5.2. Value-cost and Input-Output

The V/C and I/O ratio are commonly used metrics for determining the potential adoption of new farming practices for rural farmers in Africa (Yanggen et al., 1998; Hayashi et al., 2008; Twomlow et al., 2010; Sime and Aune, 2014). Previous studies have reported that a ratio above two is required for farmers to consider the financial gain worthwhile for adopting a new farming practice, and a value of four or higher is needed if the recommendation is considered more risky or involves learning new skills (Yanggen et al., 1998). For the I/O ratio, there is no benchmark number that is used to gauge the likelihood of adoption, but the lower the number the more appealing the investment will be for farmers. (Yanggen et al., 1998).

Value-cost ratios in the RF, SV, and SS eco-region are high, suggesting adoption of Tete farming using either MV or local practices would be enticing for rural farmers not currently producing Tete. In the RF region, MV had a higher V/C than LP, but the difference may not be large enough to justify the additional capital needed to cover the expenses of MicroVeg recommendations. Farmers not only consider the profitability of an investment, but the relative profitability between alternative investments. With a slightly lower V/C ratio, LP farmers may determine alternative investments in livestock, education, or off-farm activities to be a more profitable option (Yanggen et al., 1998). Adoption of MicroVeg by local farmers in the Savanna and Sudano Savanna is unlikely as LP farms reported higher V/C than MV farms (Table 4.4).

At all sites, the I/O ratio was higher for MV farmers (Table 4.4). This was expected, as MV recommendations are more labour intensive (precise fertilizer placement, specific seeding densities, and seedbed formation) and more expensive (Tete Atetedaye seed) than local practices (broadcasting seed and fertilizer on weakly formed seedbeds and using lower quality Tete Olowo Njeja seed). Prices for inputs like fertilizers and manures were relatively the same for farmers in Nigeria and Benin, but labour costs, such as seedbed preparation, planting, weeding, and harvesting, were more expensive for MV farmers.

4.5.3. Internal Rate of Return

The internal rate of return for an investment in MicroVeg practices was positive for the Rainforest and Savanna regions but negative at the Sudano Savanna sites (Table 4.4). The term investment in this study represents the agronomic practices recommended by the MircoVeg package. For farmers considering adopting MicroVeg, a return that is roughly double that of what it costs to implement these recommendations is expected, reflecting a type of insurance policy against perceived risks (CIMMYT, 1988; Yanggen et al., 1998). The rates of return for MV in the RF (898%) and SV (298%) would generally be considered a worthwhile investment by farmers. In the Sudano region, however, IRR was negative and adoption in the Sudano is highly unlikely given the poor returns.

Although investment in MicroVeg in the RF and SV region is a sound financial investment for LP farmers, factors such as financial constraints, success/failures of past agricultural projects, risk diversification, and relative profitability will strongly influence the decision of adoption (Foster and Rosenzweig, 2010; Bachmann et al., 2016). Investment in off-farm activities or livestock, even at lower returns, may be more enticing as a means to diversify risk. Another hindrance to adoption may be the farmers perception of market accessibility. Investment in ‘cash crops’ or staple crops that have a fixed price, guaranteed buyers, and easy access to markets will influence investment decisions (Yanggen et al., 1998).

4.5.4. MicroVeg compared to other farming investments

For the RF and SV eco-regions, MV recommendations can be considered a worthwhile investment as returns are above the standard minimum rate of return and are above the 2-4 ratio for V/C values (Table 4.4). Although vegetable farming is profitable, production is significantly less than cereal and tuber crops like maize and cassava (Glazebrook and Kola-Olusanya, 2014). Farmers may be deterred from investing in MicroVeg because Tete has a small market and poor storage capacity compared to staple crops that have defined markets and can be stored and sold when market prices are more favourable. In addition to competition as a result of crops, livestock and off-farm investments in small business start-ups and education compete for investment dollars.

Although difficult to make direct comparisons to other crops evaluated over large geographical areas, Tete produced using MicroVeg recommendations is an economically viable option for smallholder farmers (SHF) (Table 4.5). An abundance of literature exists on the benefits to yields the technologies MicroVeg recommends (seeding densities, high quality seeds, manure application, microdose fertilizer placement), but few studies present an economic analysis comparing the opportunity costs to smallholder farmers for implementing those technologies. Studies that do include an economic analysis, compare the benefits to control plots that do not accurately portray rural farmers, or only include a single cost like fertilizer, neglecting other variable costs like weeding, planting, irrigating, and harvesting (Yanggen et al., 1998; Twomlow et al., 2010; Bachmann et al., 2016).

Tete produced using MV recommendations reported better GPM and V/C values than cereals, tubers, and legumes (Table 4.5). In Kenya, legumes like beans, soybeans, and groundnuts reported values lower than that of Tete in RF, SV, and SS (Onyango et al., 2016). In Niger, millet production under microdosed conditions reported a GPM and V/C as high as 0.61 and 2.6, and as low as 0.52 and 2.1 (Hayashi et al., 2008), while maize production in Nigeria averaged a GPM of 0.64 and V/C of 2.78 (Oladejo and Adetunji, 2012). Cassava that was intercropped with beans reported the highest GPM and V/C at 0.75 and 4.06 (Pypers et al., 2011). Table 3.5 shows Tete to be a profitable option for SHF in Africa. Tete can be used as a break in crop rotation for farmers struggling with insect and disease issues while simultaneously increasing profits.

Table. 4.5 GPM and V/C for various crops in Africa.

	MV (RF)	MV (SV)	MV (SS)	Beans†	Ground-nuts†	Soybeans†	Cowpeas†	Millet‡	Maize§	Cassava¶
GPM	0.90	0.84	0.64	0.49	0.30	0.07	0.31	0.61	0.64	0.75
V/C	9.79	6.14	2.74	1.95	1.44	1.08	1.45	2.6	2.78	4.06

† (Onyango et al., 2016)

‡(Hayashi et al., 2008)

§(Oladejo and Adetunji, 2012)

¶(Pypers et al., 2011)

Though Tete provides strong financial incentives for adoption, the crops used in this comparison provide benefits beyond financial returns. For those growing legume plants, potential benefits to soil health through the plants ability to fix nitrogen is a valuable return not measured through financial analysis. Cassava, maize, and millet are staple crops that are easy to sell and are in high demand at the local markets. In addition to these benefits, Tete is sold for its leaves rather than seeds. This can be problematic for farmers as leaves can wilt and rot and cannot be stored for long periods of time, while seeds can be stored for longer periods of time giving farmers the ability to sell when market prices are favourable or re-used for next year's crop.

4.6. TESTIMONIES

Part of the interview process involved asking farmers why they did or did not adopt MV recommendations. The responses varied, but the majority of farmers who adopted the practices did so because they saw a yield increase when they tested the recommendations or observed neighbouring farms implement these practices. Though the recommendations were more labour intensive, they were satisfied with the increased yields. For those that did not adopt, they cited prior failed experimentation with other projects, or stated an unwillingness to experiment with new interventions. In the Rainforest eco-region, farmers who adopted MicroVeg recommendations tended to have more land and a larger labour force (judging by the number of people that were at the site during visitation) and may have had access to more resources (as one MV farmer owned cattle). Farmers that did not adopt MicroVeg tended to have a smaller work force and less access to resources. In particular, two local farmers had a workforce limited to only a wife as their children were away at school.

In the SV region, three of the four MV farmers were part of a village in which the chief of the village agreed to start using MV recommendations, which seemed to have led to the adoption by other farmers in the area. This may have been influenced by the university research plots that were located within that village, and results from the research plots may have encouraged farmers to adopt. For LP farms located within Ogbomosho, they felt their soil was fertile enough and would continue to produce adequate yields. They were hesitant to use MV as they have experienced other encounters with groups of people making recommendations that will help them, only to be abandoned later on in the project, which they felt would happen again with MicroVeg. One farmer in Ogbomosho had both MV and LP plots on his field and was conducting his own trials. He informed us that the seedbeds using MV recommendations produced 6 kg a harvest, while LP produced 4 kg, and was therefore going to switch all his land to MV recommendations.

In the SS, MicroVeg farmers had conducted tests and determined that 20 kg ha^{-1} of urea was the most efficient means to increase Tete yields. They conducted their own research comparing yields at their regular fertilizer rates (roughly 90 kg ha^{-1} broadcasted) as well as rates of 20, 40, and 60 kg ha^{-1} using the microdosing application method. They found yields increased using the microdosing method, and reported yields using the 20 kg ha^{-1} rate were just as high as the 40 and 60 kg ha^{-1} rates. Not only did these farmers adopt MicroVeg when they saw the yield increases, they tweaked the practices to better suit their needs.

Though there are many factors that lead to adoption, the reasons the farmers adopted are similar to those reported in the literature: Adopting farmers tended to have larger farms and more available labour, or were strongly influenced by adoption of a chief, or were influenced by presence of university plots near their farms. Additionally, in the SS, the farmers adopting had conducted small trials on their farms comparing their current method to MV and saw positive benefits from MicroVeg practices. For farmers that did not adopt MV practices, they cited reasons that were described in the literature to be factors that hinder adoption. They were often smaller farmers who had less labour available for help, less wealth, and had experienced past failures with adopting agronomic innovations.

Fig. 4.2 The field used by a farmer conducting a trial using MicroVeg recommendations. The two farming practices can be distinguished by the organized seedbeds representing MicroVeg practices, while the large green patch behind the organized seedbeds represents the farmers normal practice for growing Tete.

4.7. CONCLUSION

MicroVeg recommendations increased gross profits at all sites and reported an acceptable rate of return for farmers in the Rainforest and Savanna eco-regions. At each site, higher revenues were reported for MicroVeg farmers, suggesting the practices recommended by MicroVeg like seeding densities, harvest intervals, and precise fertilizer placement led to an increase in yields. But these practices are more labour intensive, increasing costs and reducing income. MicroVeg farmers recorded higher V/C and GPM in the Rainforest region, but lower in the Savanna and Sudano Savanna region. At these sites in particular, higher financial margins may be tied more closely to factors like soil fertility rather than management practices. The natural growing conditions can produce adequate yields while using little agronomic work. Since soil fertility is not an inhibiting factor in yields for LP farmers, particularly in the SV eco-region, adopting MV practices would likely increase yields. The findings from this study show that MicroVeg is an economically viable option for rural farmers in the Rainforest and Savanna regions but should not be recommended for Sudano Savanna farmers.

5. LIMITATIONS

The study undertaken provided valuable insight on the profitability and likelihood of adoption of MicroVeg practices, as well as the sustainability of the project through soil chemical and synchrotron analysis. The study compared the results from MicroVeg and local farmers fields to determine how transferable the results on research sites are to *real-world* farmers. However, many limitations presented themselves while conducting such *real-world* research.

The data for the research project was gathered over a relatively short period of time (three weeks) making it difficult to make strong inferences about sustainability when the data is more representative of a snapshot in time. Farmers also did what was best for them, which at times meant not following specific recommendations. For example, MV farmers in Benin applied 20 kg ha^{-1} of urea instead of the recommended 40 kg ha^{-1} rate. They conducted experiments on their own plots and found yields were no different when using 20 kg ha^{-1}. These farmers were also unable to apply manure to their plots as the manure had not decomposed enough and were concerned that application may burn Tete seeds.

Another difficulty working with rural farmers is their lack of recorded data. Each farmer interviewed reported yields/earnings/expenses based on memory, which made it difficult to gather precise data. Farmers not involved in the project had less recollection of specific agronomic practices (rates of organic and mineral fertilizers) as they had no need to keep these records. Hence, it was difficult to determine which factors may have a potential effect on soil fertility. Without knowing the exact rates of fertilization, it is difficult to make any concrete conclusions about how management practices were influencing soil fertility.

The most challenging aspect of the project was determining the financial profitability of both types of farming systems. As mentioned, both MV and LP farmers relied on memory rather than written records for expense and revenue data. The data the farmers reported during interviews was recorded by graduate students and extension agents assisting in the process in Nigeria and was directly recorded with help from a translator in Benin. During correspondence with the graduate students and extension agents over perceived discrepancies in the data, I often received a response that smallholder farmers do not keep records and therefore it was impossible to know the exact rates and expenses for each farmer. Compounding these issues was at times farmers inflated numbers or told us numbers they thought we wanted to hear. Purposeful misleading, especially for expense and revenue data, occurred at multiple sites as a means to get some financial gift from us. This made it difficult to accurately assess how profitable MV and LP farming systems were. It was also apparent that the questions asked were prone to miscommunication through translation. At times, multiple dialects (English to French, French to Dittamari, Dittamari to local language) were spoken during the interview and inevitably some information was lost in translation.

Similar to the soil fertility analysis in Chapter 3, the results from the financial analysis in Chapter 4 should be considered with caution. Rather than concrete conclusions this study should be used to make broader assumptions about the sustainability and profitability of MicroVeg. I believe the data reported does support MicroVeg being a sustainable farming and economically viable option for smallholder farmers, but I cannot say with complete certainty that is the case. I believe the soil data, especially from the field that was implementing both farming systems, along with the synchrotron analysis, provides some evidence that MicroVeg recommendations are not detrimental to soil quality, though further research is needed to confirm this. I believe the yield, revenue, and expense data from extension agents, as well as testimonies from farmers provides evidence that MicroVeg increased yields and income for rural farmers.

Though this study would recommend MicroVeg as a crop rotation option in RF and SS, it should be taken with a degree of caution. The numbers reported had large variations due to the limitations discussed above, and the benefits received by farmers may not be entirely accurate. The study does not include every variable cost associated with producing Tete, and fixed costs were not included either, which will lower the profitability of MicroVeg, and comparison to other crops should be taken as an estimation opposed to hard fact.

6. Synthesis and Conclusions

The thesis research undertaken in this project investigated the benefits of MicroVeg recommendations for smallholder farmers in three eco-regions of Nigeria and Benin Republic. Though this study would not fall under the category of "rigorous science" it did provide a number of valuable insights that add to the vast literature of development work and soil fertility. The project focused on both the sustainability and profitability of MicroVeg recommendations compared to local practices. If development work is aimed at increasing the livelihoods of the poorest citizens, it seems useful then to determine the *actual* benefits these citizens are receiving. Too often results are published for development research conducted in controlled environments under the resourcefulness and care of institutions like universities and non-governmental organizations (Aune et al., 2007; Hayashi et al., 2008; ICRISAT, 2009; Twomlow et al., 2010; Bationo et al., 2012; Camara BS et al., 2013). These results often exaggerate the results local farmers would receive as these institutions have access to more resources than local farmers, and certain practices that can increase yields (weeding times, seed quality, harvest times) are easier to perform under constant care and supervision at these institutions. These results are often compared to a control, that involves minimal inputs and does not accurately portray local practices (Bielders and Gérard, 2015). While these results are important and provide information on whether a new technology is beneficial, they need to be verified once in practice. This project sought to "ground truth" MicroVeg recommendations to determine the benefit of this project for smallholder farmers.

This project had some inherent difficulties as mentioned in the Limitations section, and it was only when we arrived in Nigeria and Benin to conduct research that we realized the struggle of conducting such *real-world* research. We were under the impression each MV farmer would grow all three vegetables recommended by the project, while in reality, farmers chose vegetables based on their comfort level and expected profitability. Tete was the most common vegetable grown as it was the least labour intensive, and could be replaced after three harvests, while Igbagba and Ugu required more attention and were longer in duration, being harvested six to twelve times per cycle. With the knowledge that Tete is the most common vegetable grown, more research fine tuning agronomic practices for Tete production rather than the other two vegetable should be undertaken. Though research on Ugu is important, it was grown by only one MV farmer, and resources directed away from Ugu research and towards Tete may prove more profitable for the end user.

This research reported important findings that have implications for smallholder farmers in Nigeria and Benin Republic. MicroVeg increased yields and revenues across all eco-regions, regardless of soil texture, soil fertility, climate, and farmer skill. I believe this is a result of specific agronomic practices MV recommends such as using higher quality seeds, specific planting densities, precise fertilizer placement, and the addition of manures. These practices have proven beneficial for increasing yields in previous research with soils in Africa and our research provides further evidence of the importance of management practices to increase yields. Soil chemical analysis reported a trend of LP soils displaying higher nutrient levels than MV soils. This was pronounced in the Savanna region but was due to a difference in soil texture between MV and LP soils. From the chemical analysis it seems that MV soils are experiencing a nutrient mining effect as a result of increased yields, and higher rates of fertilizers are needed to replenish soils. Though this trend is consistent for all three eco-regions, there was contradictory evidence from one farmers field that used both MV and LP on the same plot of land in the Savanna region. Yields followed the similar trend, with MV producing 50% higher yields, but no significant differences were found except for total N and available P, which reported higher levels in MicroVeg plots. This provides some evidence that nutrient mining does not occur in MV soils when variability in texture, location, and farmer is accounted for.

The XANES data provided different results than the chemical analysis, as MV soils were more abundant in labile C and N species than LP soils. Carbon species tended to cluster based on eco-region as both MV and LP samples within the same eco-region displayed similar carbon species, with the exception of the Rainforest region. In the Rainforest, MV soils displayed a higher abundance of easily decomposable C, like polysaccharides, suggesting MV is not leading to a high degree of OC mineralization over the short term. MV soils were more abundant in amide-N which signify lower levels of decomposition, while LP soils were more deplete of amide-N and more abundant in molecules like pyrrolic-N indicating higher microbial decomposition. The higher abundance of proteinaceous substances at MV sites, and of pyrrolic compounds at LP sites, indicates that the supplemental N (in the form of mineral fertilizer and organic manure) at MV sites is less humified compared to the N added at LP sites, and may be more available for plant uptake and growth. From XANES analysis the presence of labile C and N species in MV soils provides evidence that MV recommendations are not leading to a greater amount of nutrient turnover and organic matter decomposition compared to local farming practices.

Another important finding from this research was the profitability of MicroVeg and likelihood of further adoption by smallholder farmers. MicroVeg increased gross profits in all three eco-regions and reported an acceptable return in the Rainforest and Savanna eco-region. The findings suggest that farmers not currently using MicroVeg to produce Tete would benefit financially from adopting these practices. In the Savanna, LP farmers were able to generate profits more efficiently, and were receiving a higher return from input expenses with the methods they were using. For these farmers, fertile soils provided conducive growing conditions without the use of much labour or inputs. Unfortunately, these farmers are missing out on potential profits by not implementing yield increasing practices like seed quality and planting densities that would increase revenues while only slightly increasing expenses. In the Sudano, a negative return for MicroVeg practices were reported and only increased gross profit by $0.04; MicroVeg should not be a recommended set of practices for farmers in that eco-region.

6.1. The Way Forward

The research provided valuable insight in to the real benefits farmers are receiving from the MicroVeg project and continual encouragement to farmers in Nigeria to adopt these practices will be crucial for income increases and food security. From my thesis work, I believe there are areas of improvement that will be practical for farmers to implement, and beneficial for research exploration. First, I would encourage a more thorough investigation on the profitability of MicroVeg in Benin. According to this study, farmers who adopted MV received a negative return on their investment. A more detailed analysis should be done to either confirm or reject these findings. If these findings are confirmed, MicroVeg should not be recommended to farmers in Benin.

Holding informational sessions for farmers may prove beneficial, and educating them on the importance of fertilizer placement, seeding densities, and management of manures will help increase yields while limiting soil degradation. Two of the farms visited did not add poultry manure to the seedbeds as they were afraid of seed burning. Though this shows farmers had some education on manure management, they may not understand the importance of manures for fertilizer use efficiency and organic matter build up. As well, the fertilizer used on all farms was Urea, which provides only N for plant growth. This may eventually be an issue as the only source of P and K that are being added are from manures, which may be of low quality and inadequate quantity. Phosphorus deficient soils is considered the most limiting nutrient for yield increases in Africa, and continual harvest of high yields may deplete soils of P and K (Bationo and Mokwunye, 1991; Bationo and Buerkert, 2001). Combining a P fertilizer such as Diammonium Phosphate (18-46-0) or NPK (15-15-15) with Urea may be an option for farmers to ensure nutrient mining does not occur at a rapid pace.

Research should be done on the benefits of a split application of Urea during the growing season. Half of the soils sampled had over 70% sand content with a high potential for leaching of fertilizer N in the form of nitrate. Adding half (20 kg ha^{-1}) of the recommended 40 kg ha^{-1} at sowing and again between the first and second harvest may limit nitrogen lost early in the season and can add an available source of N for continual production of Tete leaves. Adding fertilizers, and particularly ammonium fertilizer, can cause acidification of soils. MicroVeg soils were generally acidic and adding fertilizers will exacerbate this problem. Recommendations should be added for MV farmers to add residues to seedbeds as residues have proven beneficial in buffering pH from acidifying N fertilizers (Kibunja et al., 2012; Kihanda and Warren, 2012; Adams et al., 2016). If this is not an option, universities should continue experimentation on different vegetables that are more suited for growth in acidic soils.

Data from this study was used to produce a "profit calculator" available at www.microveg.ca that farmers can access on their mobile devices. They can input the type of crop, eco-region, currency, plot size, input costs, fertilizer rates, market prices, and labour costs and the calculator will give an estimation of the profit the farmer can expect. The profit calculator is a novel creation that has the potential to help farmers assess the risks and rewards of certain agronomic practices.

The end goal of this project and of development work in general, is to improve the livelihood of a country's poorest citizens. This project set out to prove the results from experimental plots and give an idea of the benefits the end user *actually* received. It would be beneficial for institutions and organizations to continue this type of proof of concept study, to ensure the end user is benefiting and resources are not being wasted. The study found MicroVeg to be both profitable and sustainable for farmers in the Rainforest and Savanna eco-regions, and is a potential solution to help rural farmers become more food secure.

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APPENDIX

Appendix A

13. What is the total size of your farm (in hectares)? ……………………………………………………
14. Land area used for indigenous vegetables?

Vegetable	Local unit*	no	Land size (m^2)	Remark (intercropped with what?
Tete				
Ugu				
Igbagba				
Others				

*bed=1, plot=2, others=3 (specify)

15. Are you visited by extension agents? (a) Yes [ ] (b) No [ ], if yes, how many times in the last production season?

SECTION B: FIXED AND VARIABLE INPUTS

Item	Qty	Unit price	Year of Procurement	Ownership	Number of owners
Pumping machine					
Water tank					
Hoes					
Cutlasses					
Wheel barrow					
Head pan/pail					
Shovel/ spade/file					
knifes					
Watering Can					
Knapsack sprayer					
Others					
Others					

VARIABLE INPUTS

Activity	Quantity of materials used					Labour for the activity					
	Local Unit*	No	Price/ unit	Source**	Dist	Source		No	Hrs/day	No of days	Cost
Land preparation						Family	M F CH				
						Hired: M…… F………					
						Others(specify): ………					
Planting						Family	M F CH				
						Hired: M…… F………					
						Others(specify): ………					

Weeding						Family M …… F…… CH….. Hired: M…… F……… Others (specify): ……..				
Fertilizer Organic (TYPE) METHOD OF APPLICATION Inorganic (TYPE) METHOD OF APPLICATION						Family M F CH Hired: M…… F……… Others (specify): ……..				
Herbi cide Application						Family M F…. CH… Hired: M…… F……… Others (specify): ……..				
Insecticide Application						Family M F CH.. Hired: M…… F……… Others (specify): ……..				
Pesticide Application						Family M F…. CH. Hired: M…… F……… Others(specify): ……..				
Wetting						Family M F CH Hired: M…… F……… Othersl.(specify): ……..				

Harvesting						Family	M F:.. CH				
						Hired: M…… F………					
						Others(specify): ……...					
Marketing						Family	M F… CH				
						Hired: M…… F………					
						Others(specify): ……...					

*Spoon=1 milk tin=2, congo=3, bag=4, stem=5, Units=6, sachet=7, liter= 8, bottle=9 others=10
**purchased from market=1 purchased from stockist=2, purchased from other farmers=3, received from NICANVEG=4, from own farm=5, others=6(specify)

SECTION C: FARM OUTPUT

	Types of vegetable	Dry season	Rainy season
How many production cycles do you have annually?	**Tete**		
	Igbagba		
	Ugu		
	others		
How many months does a single production cycle last before another production begin?	**Tete**		
	Igbagba		
	Ugu		
	others		
In a production, how many times do you harvest?	**Tete**		
	Igbagba		
	Ugu		
	others		
How many bundles will the harvest be?	**Tete**		
	Igbagba		
	Ugu		
	others		
How many ₦50 worth bunches will be in a single bundle?	**Tete**		
	Igbagba		
	Ugu		
	others		
How many ₦50 worth bunches do you consume?	**Tete**		
	Igbagba		
	Ugu		
	others		
How many ₦50 worth bunches do you give as gift?			

What costs do you incur on vegetable marketing per day/week/month?	**Tete**		
	Igbagba		
	Ugu		
	others		
Where do you sell?* (you can have multiple option, but state the percentage of each)	**Tete**		
	Igbagba		
	Ugu		
	others		
Who do you sell to?** (you can have multiple option, but state the percentage of each)	**Tete**		
	Igbagba		
	Ugu		
	others		

*On farm= 1 Farm gate=2 Market=3 Neighbourhood=4 others=5 (specify)

**wholesaler=1, Retailers=2, Hawkers=3, Restaurants=4, Consumers=5, Eateries=6, Others=7 (specify) ....

SECTION D: IRRIGATION

1. Source of water? (a)river/stream (b)pond/reservoir (c)tube well (d) open well (e) residual moisture
2. Mode of conveyance? (a)solar (b)electric pump (c)manual pump (d)bucket (e)watering can
3. Types of reservoir if any? (a)barrels (b)concrete (c)reservoir (d)overhead tank
4. Ownership (a) Individuals (b) Group

MANUAL					
	Litre	No of times(day/week)	How many hours per time?	Who does it?	Payment?
Bucket					
Watering can					
PUMPING MACHINE					
	How long	payment per hr/day/week/month	Fuel per use	Transportation cost	Times used during production cycle
HIRING					
OWNED					

Are you a microveg farmer? Yes ( ), No ( ). If no.
Have you heard of microveg project? Yes ( ), No ( )
Describe what you have learnt from the project...
....
....
Have you applied it on your farm? Yes ( ), No ( ), what area in acre/sq metre..........................
Which of the technology have you taught/told others?....................
Who is the person being taught/told to you?............................ (relationship to you)
How far do they live to you?......................................

SECTION E: TRANSACTION COSTS

Search costs:

5. Do you source for buyers through what medium (i) farmer group ( ) (ii) marketers association ( )(iii) family and relatives ( ) (iv) phones ( )(v)others (specify)
6. How long does it take to get a buyer______________ (hrs/days/week)
7. Do your buyers receive enough information about the quality of your vegetables that they can place an accurate bid? 1=yes, 2=no, 3= uncertain
8. Are there enough buyers to ensure the market is competitive? 1=yes, 2= no, 3= uncertain
9. Do you call your buyers? Yes () No ()
10. If yes, how much do you spend in calling them ____________(minutes)
11. How many times in a week do you call them ____________
12. Value of vegetable loss due to lack of customer ______________(market size bunch)

Bargaining costs

13. How much time do you spend negotiating the price with the buyer? _________ (minutes)_
14. How many negotiation rounds did you have before agreeing on the price? ____________
15. How many times do you present your goods for sale to warrant this negitiation?..............................

Enforcement costs

Fig. A. 1 Questionnaire developed by graduate students from the Agricultural Economics Department at Obafemi Awolowo University.

Table. A. 1 Soil chemical analysis of MicroVeg and Local practice soils growing Tete in the Rainforest (RF), Savanna (SV), and Sudano Savanna (SS) eco-regions.

		pH	**CEC**	**SOC**	**Total N**	**Available N¶**	**Total P**	**Available P#**	**Ca**	**K**	**Mg**	**Na**	**Al^{3+}**
			$cmol_c$ kg^{-1}	%					mg kg^{-1}				
RF	LP†	5bc§	9.7bc	2.1b	5931.1ab	65.6ab	1492.6b	186de	141.6bc	9.9b	24.8ab	6.5b	47.2b
	MV‡	4.7bc	8bc	2.4ab	5600abc	45.9bc	2306ab	373e	129.9bc	9.3b	13.7b	2.5b	58.9a
SV	LP	7.1a	32.6a	3.1a	6694.6a	72.2ab	3575.6a	1812a	582.9a	31a	33.6a	17a	38.8c
	MV	5.7b	18.5b	2.1b	4460bc	54.5bc	1954.6b	1056.4bc	327.5b	12b	17.6b	8.6b	33.7c
SS	LP	4.7bc	8.8bc	2.5ab	4751.7bc	85a	1080.2b	1290.7b	116.7c	20.6ab	25.6ab	7.7b	33.2cd
	MV	4.5c	5.6c	2b	3141.7c	40.3c	964.2b	773.3cd	74.7c	12.1b	14.9b	7.3b	25.9d
							P-Value						
Eco-region		<.0001	<.0001	0.405	0.0357	0.7757	0.0003	0.0063	<.0001	<.0001	0.0322	0.2276	0.002
MicroVeg		0.0149	0.0755	0.1083	0.0301	0.0014	0.3861	0.007	0.0149	0.1107	0.0124	0.0009	0.0284
Eco-Region*MV		0.0824	0.2360	0.1417	0.427	0.1402	0.0179	0.7924	0.0824	0.1851	0.1009	0.7444	0.17

† Local practice

‡ MicroVeg

§ Means within a column followed by the same letter are not significantly different ($p \geq 0.05$) using Tukey test for LSD

¶Available Nitrogen in the form of NO_3^-

Available Phosphorus in the form of PO_4^{-2}

Table. A. 2 Soil chemical analysis of MicroVeg and Local practice soils growing Tete, Igbagba, and Ugu in teh Rainforest (RF), Savanna (SV), and Sudano Savanna (SS) eco-regions

		pH	**CEC**	**SOC**	**Total N**	**Available N¶**	**Total P**	**Available P#**	**Ca**	**K**	**Mg**	**Na**	**Al^{3+}**
			$cmol_c$ kg^{-1}	%				mg kg^{-1}					
RF	LP†	5bc§	9.1b	2.1b	6532.2a	65.6abc	1492.6bc	186d	141.6b†	9.9b	24.8ab	6.4b	47.3ab
	MV‡	4.9bc	8.8b	2.4ab	5931.1ab	77.2a	2211.3b	335.9cd	143.5b	11.1b	16.1bc	4.5b	54.5a
SV	LP	7.1a	32a	2.9a	6329.2a	70.1abc	3422.8a	1847a	559.3a	29.5a	32.2a	16.1a	37.5cd
	MV	5.4b	13.1b	1.85b	3889.2c	48.8bc	1446.4bc	722.6bc	231.7b	9.9b	14c	6.5b	32.5de
SS	LP	4.5c	7.4b	2.3ab	4434.4bc	72.3ab	914.1c	908.3b	101.5b	16.7b	22.6bc	8b	39.9bc
	MV	4.7c	5.6b	2b	3538.9c	45.6c	895.9c	577bcd	77.4b	12.5b	14.4c	7.7b	29.1e
							P-Value						
Eco-region		<.0001	<.0001	0.6971	0.0054	0.3051	0.0001	<0.0001	<.0001	<.0163	0.3429	0.0034	<0.0001
MicroVeg		0.0165	0.0106	0.1368	0.0836	0.0990	0.1266	0.0254	0.0151	0.0056	0.0001	0.0062	0.1951
Eco-Region*MV		0.0016	0.0077	0.0353	0.0559	0.0852	0.0003	<0.0001	0.0057	0.0037	0.1961	0.0138	0.0063

† Local practice

‡ MicroVeg

§ Means within a column followed by the same letter are not significantly different ($p \geq 0.05$) using Tukey test for LSD

¶Available Nitrogen in the form of NO_3^-

Available Phosphorus in the form of PO_4^{-2}

Appendix B

Questions asked during interview with Beninese farmers

1. Rate of fertilizer used on MV and LP farms
2. Rates of organic fertilizer
3. Cost of labour to create seedbeds
4. Cost of labour to plant, weed, harvest, apply fertilizer, and irrigate one seedbed
5. Cost of fertilizer
6. Cost of seed and type of seed used
7. Number of harvests that occur during the dry season
8. Yield per harvest per seedbed

Table. B. 1 Financial ratios for the Rainforest eco-region from extension agent, farmer, and technical report data

		GPM†	**V/C‡**	**I/O§**	**IRR**
EA	MV	0.91	11.36	2.45	610%
	LP	0.93	13.48	1.48	
Farmer	MV	0.86	7.19	1.47	1450%
	LP	0.50	2.02	0.93	
Tech Report	MV	0.69	3.17	5.16	(42%)
	LP	0.76	4.24	3.10	

† Gross Profit Margin
‡ Value-Cost Ratio
§ Input-Output Ratio

Table. B. 2 Financial ratios for the Savanna eco-region from extension agent, farmer, and technical report data.

		GPM†	**V/C‡**	**I/O§**	**IRR**
EA	MV	0.86	7.03	2.45	664%

	LP	0.91	7.91	1.26	
Farmer	MV	0.17	1.21	0.44	(98%)
	LP	0.74	2.98	0.18	
Tech Report	MV	0.70	3.31	4.71	257%
	LP	0.80	3.18	3.10	

† Gross Profit Margin
‡ Value-Cost Ratio
§ Input-Output Ratio

Table. B. 3 Financial ratios for the Sudano Savanna eco-region from extension agent and farmer data.

		GPM†	**V/C‡**	**I/O§**	**IRR**
EA	MV	0.74	3.91	5.12	8%
	LP	0.79	4.68	3.59	
Farmer	MV	0.52	2.10	9.53	(200%)
	LP	0.66	2.94	5.71	

† Gross Profit Margin
‡ Value-Cost Ratio
§ Input-Output Ratio

Table. B. 4 Financial ratios for Igbagba in the Sudano Savanna eco-region from extension agent and farmer data.

		GPM†	**V/C‡**	**I/O§**	**IRR**
EA	MV	0.75	3.99	3.72	379%
	LP	0.63	2.69	2.16	
Farmer	MV	0.15	1.18	12.58	(72%)
	LP	0.05	1.05	5.55	

† Gross Profit Margin
‡ Value-Cost Ratio
§ Input-Output Ratio