MODELING PARASITIC WEED EMERGENCE ACROSS SMALLHOLDER FARMING SYSTEMS: THE CASE OF CENTRAL MALAWI

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ABSTRACT

MODELING PARASITIC WEED EMERGENCE ACROSS SMALLHOLDER FARMING SYSTEMS: THE CASE OF CENTRAL MALAWI

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Four out of five households in Malawi rely on farming as a primary source of income, most of whom cultivate maize (*Zea mays*). Disconcertingly, 63-80% of maize yield losses among these households are attributed to the emergence of invasive and parasitic weeds such as Striga (*Striga spp.*). A plethora of Striga-control practices (SCPs) have been developed and disseminated to smallholder farmers (cultivating < 2 ha). These SCPs are commonly evaluated at agricultural research stations prior to dissemination. Mixed results often arise later when they are implemented across the diverse agroecological and socioeconomic landscapes of smallholders. Many agree research will need to assess how SCPs perform under smallholder-conditions, and ultimately, how their uptake will affect emergence. The following dissertation is divided into three empirical studies. In the first essay, discrete choice experiments (DCEs) are used to estimate the percent of maize yield farmers are willing to sacrifice for different SCP attributes (e.g., labor, soil fertility). In the second essay, a seed bank stock and flow model (SB-SFM) is developed to assess emergence rates across different SCPs. In the final essay, results from the DCEs and SB-SFM are integrated within a system dynamics model (SDM) to simulate how environmental and socioeconomic parameters affect emergence across space and time. DCE findings highlight farmers are willing to sacrifice significant tradeoffs to implement SCPs that increase soil fertility and provide legumes. SB-SFM findings indicate the attachment phase and seed bank must

simultaneously be addressed with multiple SCPs to suppress emergence over three to five years. Finally, alteration of different climate, farm-management and adoption parameters in the SDM underline that nutrient input subsidies and agricultural extension must be included in an aggregated effort to suppress the spread of Striga across the region.

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To Mom.
The woman that put me in the garden first.
I love you.

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CHAPTER 1: INTRODUCTION

In much of sub-Saharan Africa (SSA), farming is a primary livelihood for rural society (Garrity et al., 2010). The agrarian population is mainly comprised of smallholders (those cultivating less than two hectares), representing 80% of the farms across the region (Altieri et al., 2012). Approximately 33 million farmers commonly cultivate crops such as maize, millet and sorghum (Tafirenyika, 2014). Thus, cereal production is commonly viewed as an indicator for rural food security and wealth, especially in countries like Malawi (UNICEF, 2013).

Cereal production has been supported by a number of policies and institutions in SSA, particularly in Malawi. For example, many times fertilizer subsidies are made available to farmers who cultivate hybrid maize as opposed to other food crops (Garrity et al., 2010). In addition, dietary norms have long-encouraged the cultivation of soil-erosive crops like maize. In conjunction with these policies and institutions, population growth and unequal distribution of land have obligated smallholders to intensify their monocultures of maize (Bezner Kerr, 2005; Gilbert, 2004; Hockett & Richardson, 2016). As these maize-based systems are intensified, application rates of synthetic fertilizers and sowing rates per hectare are increased. As a result, more soil organic matter and soil-N are removed than can be replaced (Heinrichs et al. 1995). Under such conditions, competition is increased for nutrients and maize is susceptible to invasion by weeds (Gigou, 1992).

In southern Africa, it is estimated that 63 to 80% of maize yields are lost due to competition for nutrients and the removal of water by parasitic weeds (Parker, 2012). One of the most prevalent parasitics in the region is commonly known as witchweed or Striga (*Striga spp.*). As an obligate hermiparasitic angiosperm, witchweed is unable to fully access minerals, photosynthates and water by individual growth, therefore, requiring a host (e.g., maize) to obtain these resources (Midega et al., 2013). After maize develops a well-established root system (4-6 weeks after sowing), witchweed will attach to the rootstock and cause a phytotoxic effect, removing nutrients and water taken up by maize. In addition, *Striga spp*. will compete for nutrients in the soil later when fully grown (30-40 days after emerging from the soil). As a consequence, maize plant height, biomass and grain yield are drastically reduced (Frost et al., 1997; Gurney et al., 1999).

Copious seed production and a long-lived seed-bank allows witchweed to rapidly invade and remain in farmers' fields for extended periods of time. Seeds can remain viable in the soil for ten years, waiting for sorghum or maize to be planted under favorable soil conditions for germination (e.g., sandy acidic soil, 30-35C^{o}) (Khan et al., 2010). After emerging from the soil, one plant can produce thousands of seeds, spreading by wind, water, and/or cultural practices (Khan et al., 2002). Much of these infestations can be deterred when lands are left to fallow, but arable-land scarcity and a long history of cultivating and consuming maize has made such methods impractical to smallholders (Bezner Kerr, 2005; Kureh et al., 2006).

Other agricultural practices such as crop rotation with green manure legumes have been proposed to reduce *Striga spp.* infestations. Unfortunately, some of these legumes can attract pests that consume maize leaves or are associated with bad luck, making them difficult to adopt (Forsythe et al., 2015; Sileshi et al., 2000). Based on the aforementioned cases, it appears then, without including input from smallholders to develop weed control strategies, parasitic weed emergence and land abandonment will likely ensue (Berner, 1995; Connelly, 1994). In addition to gaining smallholder-input to reduce witchweed emergence, the social, environment and financial context parasitic weeds proliferate in must be understood. Given the vulnerability of smallholder farms to witchweed, a large consensus agrees research is needed to develop adaptive strategies that provide food and/or revenue to farmers and control parasitic weeds under resource-limited conditions (Debra, 1994; Johnson, 1996; Khan et al., 2010; Orr et al., 2002; Orr et al., 2009; Riches et al., 2005).

The dissertation explores the implications technological attributes have on farmer choices for practices and how the choice of implementing one or several practices affect the lifecycle of *Striga asiatica* in a Malawian smallholder setting. The study is carried out in a consecutive manner, investigating Striga emergence across three successive dimensions: control preferences, control simulation (via crop modeling) and control diffusion based on the two aforementioned dimensions. The dissertation is split into three empirical essays. Each essay investigates parasitic weed emergence differently and are intended to be published as three separate manuscripts. Findings from one essay often informs the instrumentation or findings of the following essay. For these reasons, the description of one study or its data may appear partially repetitive across chapters.

Chapter 2*, Maize Farmer Preferences for Striga Control Practices in Malawi,* explores the primary traits of Striga control practices (SCPs) smallholders consider prior to implementation. Thereafter, the study determines which tradeoffs smallholders are willing (or not willing) to make to implement a SCP (e.g., increased labor for reduced Striga emergence). While numerous studies have documented the inputs required to execute several parasitic controls strategies, little research has investigated the socioeconomic drivers behind their use or the barriers that impede their implementation. The study employs focus groups to identify SCP attributes (e.g., labor days, maize yield) and conducts discrete choice experiments (DCEs) to quantify the percent of maize yield farmers are willing sacrifice for these attributes. Findings indicate that lower Striga emergence and labor requirements as well as increased soil fertility and legume yield significantly influenced the decision to select a SCP across 215 participants. Female and male farmers were willing to sacrifice different percentages of their maize yield for higher legume yield and increased soil fertility. Understanding these tradeoffs informs researchers how to better align SCPs with desired outcomes and ensure they are implemented once they are disseminated.

Chapter 3, *Systems Modeling: An Integrated Approach to Simulating Emergence and Persistence of S. asiatica*, investigates the underlying feedback behavior in the *S. asiatica* lifecycle. Uncovering which stages of the lifecycle drive emergence and the accumulation of the seed bank inform when, where and how to address the weed with various farming practices.

The study develops a cropping systems model (CSM) from previous *Striga spp*. models found in the literature. Interviews with Malawian scientists confirm the parameterization of the model. Local climatic data and findings from previous *S. asiatica* studies apply values and equations to model parameters. Emergence rates in farmer soils are used to calibrate the output of the model. Results from model runs reveal that an integrated approach is needed to manage the parasitic weed under smallholder conditions. In addition, the bottleneck behavior in the model highlights the importance of focusing control efforts on attachment rather than germination, emergence or flowering. Given the devastating effects witchweed has had in Malawi, it is imperative to develop parasitic weed modules for low-cost crop simulators to better evaluate smallholder technologies (Ejeta, 2007). Models that do not capture underlying mechanisms in the weed lifecycle, risk informing extension agents with potentially misleading or ineffective practices to deliver to farmers.

Chapter 4, *System Dynamics: Combining Choice Experiments and Crop Simulation to Model Parasitic Weed Emergence*, studies the dynamic behavior of *S. asiatica* emergence based on the implementation of its control strategies. The implementation of SCPs is influenced by an interlinked natural, financial and social environment, making them dynamic as well (Debra, 1994). Feedback behavior between SCP implementation and *S. asiatica* emergence is studied using survey questionnaires, mediated modeling and system dynamics. A system dynamics model (SDM) is parameterized from several adoption models found in the literature as well as input from various stakeholders collected at a mediated modeling workshop (Bass et al., 2000; Kopainsky et al., 2012). Parameters in the SDM are applied with values and equations from summary statistics gathered from survey questionnaires, utility coefficients calculated from DCM data and weed emergence readings from the CSM. The potential for SCP implementation is reduced largely by the stochasticity of maize yields across seasons combined with significant social pressure to abandon these practices. Low yields suppress implementation and increase abandonment due to the dynamics of utility in SCPs. A critical factor in explaining low implementation rates of agricultural technologies is the stochasticity in their performance (and in this case- yield) (Bahmanziari et al., 2003). Understanding how that stochasticity interacts with the social dynamics of learning and communicating about the performance among users and protentional users is critical to successfully disseminate SCPs.

The objective of this dissertation is to highlight the processes behind parasitic weed emergence in Malawi based on interlinked biophysical and socioeconomic factors. These processes and other findings generated from the dissertation are valuable to farmers, development and extension practitioners, policy makers and other stakeholders in the smallholder cereal production sector. The findings are intended to highlight critical areas to address the growing problem of *Striga spp.* as well as guide policy of how to do so. More specifically, findings from Chapter 2 provides technology disseminators knowledge regarding tradeoffs farmers are willing (or not willing) to make to implement various Striga control practices. With this information, extension agents can better diffuse agricultural practices to farmers. Second, Chapter 3 findings will highlight the degree of each practice required to suppress Striga. The results will be most valuable to farmers given the limited capital they have to carry out a limited number of practices. In addition, the development of a weed module will be the first of its kind, benefiting crop modelers across the globe that use systems models. Third, results from various climatic, farmer management and policy scenarios shown in Chapter 4 may shed light on when, where and how long interventions will need to be implemented to significantly reduce Striga. Such information will offer key insights to policy makers wishing to know which programs to fund in order reduce weed prevalence and subsequent food insecurity.

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CHAPTER 2: MAIZE FARMER PREFERENCES FOR STRIGA CONTROL PRACTICES IN MALAWI

2.1 Introduction

In southern Africa, it is estimated that 63-80% of maize (*Zea mays*) cropping systems are parasitized by witchweed (*Striga spp.*) (Parker, 2012). As a hemiparasite[1], the weed attaches to the maize rootstock, removing water and nutrients, and consequently devastating yields (Frost et al., 1997). In Malawi, maize is widely cultivated by smallholder farmers (cultivating less than two hectares), many of whom rely on the crop as a staple food and primary source of income (Garrity et al., 2010). Over time, the repeated cultivation of this cereal as a monoculture can reduce soil organic matter (SOM), augment soil-nitrogen (N) loss and create conditions for parasitic weeds to proliferate (Hakansson, 1982; Gigou, 1992). In addition, rapid population growth, abandonment of traditional fallow periods and minimal organic inputs application have exacerbated soil erosion, allowing parasitic weeds to become ubiquitous (Franke et al., 2004; Kureh et al., 2006; United Nations, 2014).

In the savannas of Southern Africa, *Striga spp*. is found in association with sorghum (*Sorghum bicolor*), millet (*Pennisetum glaucum*), and maize (Akobundu, 1980). As an obligate parasite[2], the weed is unable to fully access minerals, photosynthates and water from individual growth, requiring a host to facilitate its development. There is no light requirement for the plant, but germination is more prevalent in less-fertile sandy acidic soils, hence their omnipresence across the intensely cultivated soils of Africa (Singh et al., 1997). Seeds generally require a ~2-week

[1] A parasite that is capable of photosynthesis, but relies on host plants for a significant portion of their carbon supply, sequestering water and nutrients (Rich & Ejeta, 2008)

[2] An organism that cannot complete its life-cycle without exploiting a suitable host

wet-conditioning period. Optimum day/night temperatures for germination and attachment are 15 and 20°C, respectively (Baskin & Baskin, 1998). According to temperature and water conditions, the weed can thrive in vast number of low-altitude agricultural ecosystems, for instance in rainfed fields or in rice paddies. As the soils of such regions become more degraded, cereals excrete leachates, signaling mycorrhizal fungi to assimilate phosphorous in exchange for carbohydrates (Hudu & Gworgwor, 1998). Unfortunately, these leachates also catalyze *Striga* germination. Thus, as fields become more degraded, more leachates are excreted, increasing parasitization.

Numerous parasitic control practices have been developed and disseminated to smallholders cultivating cereal-cropping systems (CCS) (Dugje et al., 2008). Some of these practices include applying pre-emergent herbicides, planting weed-resistant crop varieties and/or micro-dosing crops with fertilizer (Oswald, 2002). Wealthier farmers tend to benefit from these strategies given their capital, yet poorer farmers who make up the primary population in Malawi, have little opportunity to benefit. When parasitic weeds germinate in high-input systems, their effects are less devastating (Doggett, 1984). In low-input systems however, 30-100% loss can occur, leaving 50 million hectares and 300 million African farmers with annual losses of $7USD billion per year (Parker, 2009). Given the vulnerability of such a large population to these losses, research will need to develop more adaptive strategies to control weeds under resource-limited conditions while simultaneously providing food and/or revenue to the smallholder (Debrah, 1994). One *Striga* control strategy that has been proposed to address these needs is the incorporation of legumes in combination with mulching and/or minimum tillage.

The combination of mulching, minimum tillage and intercropping/rotating legumes in CCS has not only drawn attention as a *Striga* control strategy, but also as a means to improve soil fertility, provide food or fodder and supplement farm income (Kumwenda et al., 1996). Employing these practices controls *Striga* in several ways. First, certain legumes have the ability to chemically inhibit germination by exuding substances from their roots. In the presence of legumes, some parasitic seeds will germinate absent of a host, dying and consequently depleting their soil seed bank over several growing seasons (Khan et al., 2010). Second, the seeds of parasitic weeds lose viability each season by rotating cereals with non-hosts (e.g., legumes) (Ransom 2000). Some rotation crops and their mulches immobilize soil-phosphorous (P), reduce soil erosion and increase overall soil fertility, all of which are negatively associated with *Striga* emergence (Cechin & Press, 1993; Schultz et al., 2003). Finally, minimum tillage decreases incidences of bringing dormant seeds to soil depths where they can germinate. Despite the numerous benefits parasitic weed controls provide, their use has been minimal in Malawi. Many were once widely practiced across Malawi in the past. For instance, maize was commonly intercropped with pulses until the late 1960s (Heisey & Smale, 1995). Reasons for why farmers have abandoned or continued traditional practices involving legumes are difficult to ascertain, as they have rarely been studied. Therefore, it is essential to understand what practice or practices farmers prefer which can control *Striga* and why they would implement them (if at all).

Prior to disseminating parasitic weed control practices to farmers, researchers must first consider number of questions. First, what attributes are farmers most concerned with when selecting a parasitic weed control practice? Then, which attributes and levels most significantly influence their selection of a control practice against others (particularly those without legumes)? More specifically, among the significant attributes, which ones are associated with specific farmer types (e.g., wealthy, larger landholders)? Based on these questions, researchers can assess an unbiased estimation of individual preferences while enhancing the accuracy of farmer needs to implement these practices. By understanding heterogeneous preferences among heterogeneous farmers, better recommendations can be made to policy makers regarding which attributes to invest in for purposes of encouraging *Striga* control. This study employs discrete choice experiments to assess the attributes specific farmers are most concerned with when implementing a *Striga* control practice. The objective of the study, therefore, is to determine which tradeoffs farmers were willing (or not willing) to make to implement a *Striga* control practice versus continuing their current practices.

2.2 Background

To explain the drivers behind implementing *Striga* control practices, current practices and their decision-making contexts must be identified, especially barriers to their implementation. Before discussing these three points, it should be noted that long-term *Striga* control practices, in many cases, entail one or a combination of soil fertility management (SFM) practices (Ransom, 2000). SFM practices aim to improve soil structure and input use efficiency. In the process, they reduce soil erosion and improve soil structure, which, in turn, create less-favorable conditions for *Striga* (Esilaba et al., 2000). Conversely, conditions favoring *Striga* germination are characterized as nutrient poor soils exhibiting low productivity, many of which receive low inputs of fertilizer and/or improved management practices (Oswald & Ransom, 2001)

SFM practices include (but are not limited to) the "…the use of soil amendments, organic materials and mineral fertilizer to replenish soil nutrients…" (Vanlauwe et al., 2010, p. 18).

Among the most promising organic SFM inputs and practices are "…animal manure, compost, incorporation of crop residues, natural fallowing, improved fallows, relay or intercropping of legumes" (Place et al., 2003 p., 367). Many of these inputs and practices, especially the integration of legumes, keep seed production from increasing significantly over a four-year time period (Ransom, 2000; Reda et al., 2005). A vast body of literature has discussed the drivers and barriers of these practices. Likewise, the drivers and barriers of *Striga* control practices, while not documented at great length, are assumed to be similar to that of SFM practices.

2.2.1 Context specific weeding practices in Malawi

Fairly little is known about smallholder weeding practices and their efficacy across sub-Saharan Africa (Dimes et al., 2004). Without understanding the farming systems managed by farmers, the technologies they implement, soil conditions they cultivate under, and/or recurring weed populations (just to list a few), it is difficult to provide agricultural extension recommendations to control *Striga* (Collinson, 1997). Many weeding recommendations are based on fixed or predetermined designs conducted at agricultural experiment stations (Orr et al., 2002). In addition, management at these stations is relatively unaffected by the financial and labor constraints smallholders face at the field level. Therefore, the utility and relevance of these fixed weeding recommendations is limited and potentially erroneous.

Rural farmers are well aware of the repercussions of not weeding effectively, but much of the challenge to weed completely or in a timely manner arises from labor and financial constraints (Kumwenda, 1997). One of the most critical times for smallholders to weed their cereal cropping systems is three to four weeks after sowing. Unfortunately, this period coincides with the time when food supply and finances have dwindled from last season. During that time, available labor is typically allocated for off-farm employment (e.g., wage labor) to supplement finances for food before harvest (Giller et al., 2011). Thus, farmers become stuck in a vicious cycle of receiving poor yields and allocating more human capital to wealthier farmers' lands rather than their own.

Malawi is one of the few African countries where weeding practices have been documented in great detail (e.g., illustrations, applications) (Orr and Ritchie, 2004). In several studies, researchers have found Malawians employ a complex set of weeding practices[3] according to specific contexts (Orr et al., 2002). The local language, Chichewa, has no fewer than 36 different words that describe weeding actions such as 'hoeing'. Much of the variation in weeding is attributed to the natural, financial and/or social circumstances farmers face (Tafirenyika, 2014). Several researchers have compiled reports detailing descriptions of these manual techniques, many of which agree are highly advanced, but lack punctuality, allowing weeds like *Striga* to flower, reproduce, and reemerge (Orr et al., 2002; Orr et al., 2009; Riches et al., 1993; Sileshi et al., 2008). Based on these findings, it would seem frivolous to advise farmers with limited time, income and labor to weed timelier and more often. Rather, it may be more useful to offer alternative techniques that require less labor and coincide with current management practices, crops and agroecological/financial conditions.

2.2.2 Determinants of practice

The decision to implement an agricultural practice is contingent upon the social, physical and financial resources available to a farmer (Mugwe et al., 2009). Resources such as food, land,

[3] Kupalira is exclusively for first weeding and kubandira (i.e., banking) for second weeding. Kukwazira (or kupala) is used on compacted soils instead of kubandira. Following kubandira kukwazir is conducted on fields where weeds have re-established. In addition, kukwazira is used for relay-crops (mbwera) such as beans (*Phaseolus vulgaris*), green pea (*Pisum sativum*) and sweet potato (*Solanum tuberosum*) (Orr et al., 2002)

labor and cash are constrained at different times of the year for smallholder farming households. Household decisions to allocate these limited resources, therefore, will be influenced by their resilience against risk and the costs and benefits a technology offers (Ajayi et al., 2003). Smallholders are often considered to be risk-averse, but when the incentives of a practice reduce risk, empirical evidence has shown they will increase expenditures and time devoted to such technologies as a strategy to cope with climatic shocks (Shiferaw & Bantilan, 2004). Social scientists must also consider the context of when and where a practice is implemented; thus, farming decisions are often time and space-specific (Feder, 1993). In addition, scientists must consider the motivations behind these decisions, including preferences for one or multiple attributes of a practice such as "legume intercropping" (e.g., weed control, soil nitrogen additions, provision of protein rich food) (Silberg et al., 2017; Waldman et al., 2016). There are several socioeconomic, institutional and cultural factors that affect the implementation of *Striga* control practices commonly mentioned in literature.

<u>2.2.2.1 Socioeconomic</u>

Food security is often considered as a primary driver (or hindrance) of farming practice implementation. Literature suggests that households with fewer members are unable to grow enough food to satisfy caloric needs, making them more likely to seek out practices to improve food security (Mugwe et al., 2009). Larger households, on the other hand, are sometimes less likely to implement new agricultural practices (e.g., a *Striga* control) for several reasons. For example, in less productive agricultural ecosystems, household labor and finances tend to be allocated for supplementing caloric needs, rather than for investing in new practices (Ajayi et al., 2007). Less food-secure households have shown a reluctance to employ new agricultural practices as well when they believe they will negatively affect staple food crop yields (Adato & Meinzen-Dick, 2002).

Field size or total land holdings are typically used to estimate the determinants of SFM decisions (Marenya & Barrett, 2007). It has been argued that farmers who cultivate larger areas of land are able to experiment with new cropping systems and integrate them later if positive outcomes transpire (Feder et al., 1985; Feder & Umali, 1993). In Malawi specifically, farmers cite that larger landholdings (or more fields) are needed to experiment with new SFM practices (Hockett & Richardson, 2016). Others add that smallholders with more land to cultivate crops will experiment with new agricultural practices frequently on marginalized or highly degraded lands, resulting in modest short-term yield improvements (Oluoch-Kosura et al., 2001). With little improvement, larger landowners are less likely to continue using these practices. Decisions made by farmers with other trait preferences may be less affected by the timeliness of a benefit being received. For instance, farmer-decisions for perennial legume technologies in Malawi were found to be driven by long-term objectives such as higher soil fertility (Waldman et al., 2017).

Income streams that support household wealth, including off-farm income, affect farming decisions. If a smallholder household receives their primary income from off-farm activities, farm-level decisions can be influenced in several ways. Some researchers argue that off-farm incomes encourage implementation of SFM technologies such as the integration of leguminous hedgerow species in cereal systems (Adesina et al., 2000). Implementation of these technologies are encouraged by the ability to purchase seed from supplementary incomes and experimenting with the new technology. Still, without off-farm income, households may be motivated to diversify their farms with new practices, such as maize-legume intercropping, to reduce risk. Without knowing the motivation of smallholder farmers, it is difficult to assess how off-farm earnings affect their decisions to implement a yield-maximizing technology. This is one factor that seems to be missing in many quantitative assessments about *Striga* control implementation.

Beyond off-farm income streams, overall wealth index scores are often used to assess practice implementation. In lower-income households, family labor fulfills much of the on-farm tasks because little, if any, contract labor can be hired (Marenya & Barrett, 2007). Thus, when a new practice demands more labor relative to current practices, uptake rates usually remain low among poorer or labor-constrained families. When labor markets are available, wealthier families are able to practice more labor-intensive agricultural technologies by hiring contract labor as needed (Pender & Kerr, 1998).

Distance to towns or urban centers providing agricultural extension and markets are often considered as an important factor in practice implementation. Exposure to agricultural extension and subsequent farmer training has shown to increase the speed at which new practices are learned and implemented (Nkonya et al., 1997). In addition, the existence of markets near communities can affect their access and sales of production from new technologies (Place et al., 2003). Much literature has covered distance to or contact with extension, but little has studied farmer perceptions or trust with recommendations made by extension. Some researchers claim that this is an important factor to consider when assessing practice implementation because farmers will be less likely to integrate new innovations in their fields diffused by extension agents they believe are not-versed in farming or knowledgeable about their circumstances (Anderson & Feder, 2004)

2.2.2.2 Institutional

Institutions are defined as prevalent social rules that structure social interactions (Hodgson, 1989). Hodgson (1989) adds that institutions are often referred to as the rules of the game in society that structure incentives in human exchange. In addition, organizations of people are often considered as institutions because they are groups of individuals bound together by some common purpose to achieve a given set of objectives. As such, these rules and organizations are important factors to consider when assessing practice implementation.

Practices aimed to improve soil fertility, for example, are affected by land tenure and/or property rights. In African rural communities, many times village headsmen allocate land to smallholders but do not offer formal ownership (Otsuka & Place, 2001). Without ownership, there is little incentive to implement technologies that will improve the fertility and monetary value of these lands (Kalaba et al., 2010). This finding highlights the importance of not only considering land tenure institutions but gender institutions as well. Others argue, however, 'formal land titles' or 'ownership' are still relatively new concepts to rural African communities (Adesina et al., 2000).

Other gendered institutions such as the markets each sex is permitted (or not) to participate in must be considered. In East Africa several studies have found that women have more control over profits gained from selling milk in the evening compared to the morning because morning milk is often sold to cooperatives and chilling plants where men are registered members (Njuke et al., 2011). Female participation was excluded from these cooperatives. Therefore, women will sell milk in the evening to neighbors and local traders. Thus, these studies conclude that the longer the distance between the output of a new technology (e.g., legume) and market for its output (e.g., grain), the less control women have over the income generated from the technology (Njuke et al., 2011). Researchers add though, the further women participate in the supply chain with the yield gained from a new technology, the more likely they are to receive profit from and implement the technology.

Blackie (1994) discovered that farmer coops increased access to inputs, markets and extension agents for new technologies and practices. Affiliation with such institutions might then influence practice implementation. In addition, he highlighted the fact that better-off famers preferred more independent modes of operation rather than joining groups. This may be attributed in some part due to credit access. For these reasons, institutional support for certain practices needs considerable attention when assessing drivers and barriers to implementing *Striga* control practices.

<u>2.2.2.3 Cultural</u>

Household head or field manager characteristics such as gender, are often emphasized as determinants of agricultural practices. For example, in Uganda and Malawi, many times men are more knowledgeable about cash or commodity crops while women have more experience with low market value crops (Njuki et al., 2011). In this respect, tobacco or cotton are often referred to as men’s crops. Consequently, female-headed households are more likely to implement practices such as legume rotation that provide ample and diverse diets for their families (Ferguson & Mkandawire, 1993).

2.2.3 Understanding smallholder decisions under resource-poor conditions

Researchers have identified numerous barriers to conduct Striga control practices. Drechsel et al. (2005) note the biophysical barriers that limit integrating legumes are not as great as the barriers presented by poor socioeconomic conditions. Perceptions about the costs and benefits associated with a certain practice must first be understood before assessing why households choose to invest their scarce resources into one method over another. Smallholders tend to have seasonal perspectives of 'factor scarcity', where returns on investment fluctuate during the year. As such, different amounts of land, labor and finances are more constrained during specific times of the year (Kunze, 2000). Given the fluctuation of a given resource (e.g., labor), farmers frequently are unable to dedicate a sufficient amount of one resource (in a timely manner) when it is most needed (Mbaga-Semgalawe & Folmer, 2000).

Many times, it is assumed that household labor is readily available during critical times of the growing season; however, its availability hinges on a range of factors. For instance, during planting and weeding times, household members will often leave the farm to seek temporary contract work (Graves *et al*., 2004). While this may seem counterintuitive, income from off-farm labor is needed to purchase food to supplement last season's dwindling stock (Barrett *et al*., 2001). When labor is available, decisions to implement new practices are further truncated when members are not skilled enough to fulfill the complex tasks of a *Striga* control practice (Bartel & Lichtenberg, 1987; Bonaban-Wabbi & Taylor, 2012).

While highly beneficial, many times the tradeoffs between a *Striga* control practices' short-term losses and long-term benefits are too great to bear. To elaborate, one of the largest barriers for smallholders to implementing an SFM practice lies in its delayed returns on investment

(Andersson & D'souza, 2014). For example, when higher yields for maize (which is a primary crop in Malawi) cannot be delivered during the first or second year, farmers that rely on short-term gains (from annual cropping systems) are less likely to implement SFM practices (Nowak, 1987). Barriers to implement *Striga* practices can also be compounded when rights to land ownership are restricted (Fenske, 2011). For example, household heads often show little interest to invest in practices promising long-term soil fertility benefits when their children are not permitted to inherit matrilineal lands (Amsalu & De Graaff, 2007). In some instances, researchers have observed village headsman appropriating lands from widows once they were improved (Bezner Kerr et al., 2007).

Not only does the timing of benefits place barriers for some smallholders to implement *Striga* control practices, but also the extent to which they provide these benefits. For example, some suggest that an SFM method would need to provide at least 50-100% higher yields relative to current practices for smallholders to consider adoption (Baum et al., 1999). Unfortunately, not all *Striga* control practices can deliver these outcomes, and for the ones that do, access to agricultural extension (e.g., external agent visits, demonstration trials) must be provided as well (Ntege-Nanyeenya et al., 1997). Although, due to inconsistent funding and training, developing countries face difficulties in providing effective extension about these practices (Kassie et al., 2013).

Many *Striga* control practices involve rotating or intercropping legumes. When new plants such as legumes are introduced to traditional cropping systems, food security can be reduced in several ways. Farmers who believe that legumes will reduce their staple crop yields are often dissuaded from intercropping. A smallholder's risk-averse tendency will also deter him or her from investing in unfamiliar green manure legumes where no food is provided for one or more seasons (Pengelly *et al*., 2003). Legumes (e.g., *Vigna uguiculate*, or cowpea) that do provide food still run the risk of attracting new pests to staple crops, further reducing chances of adoption (Ndove *et al*., 2004).

Often funding and support for the agricultural sector is limited in developing countries. When support is given, all too often subsidies and export markets are allocated to crops which erode soils such as maize. These subsidies and/or markets contradict the promotion of practices and their associated crops that rehabilitate unproductive soils (FAO Land and Water Development Division, 2001). When fertilizer and markets are provided environmentally beneficial crops, they still may not be taken-up by households when they do not coincide with taste or cooking norms (Drechsel *et al*., 2005).

This study contributes to the determinants of *Striga*-control practices in Malawi. There are numerous gaps mentioned in this subsection, such as where farmers receive information about *Striga* and the extent they trust this information, from an agricultural extension officer, for example. Results from this study address these gaps using a number of analyses. In addition, the study contributes to the body of research evaluating tradeoffs farmers are willing to make for more *Striga* control. Finally, findings reveal which attributes farmers are most concerned with when implementing the *Striga* control practices in their fields.

2.3. Empirical Model

It is unlikely that any one *Striga* control practice will work effectively across the diverse biophysical and socio-economic landscape of Malawi. Instead, it may be more beneficial to offer farmers a basket of choices to choose from, allowing them to select a practice adapted to their local conditions and livelihood strategies (Orr et al., 2002). To examine these choices, I employ a theoretical framework that is grounded in choice modeling, which is based on consumer theory (Lancaster, 1966). The study employs discrete choice experiments to estimate the marginal value of various attributes for agricultural practices.

2.3.1 Random utility theory

Discrete choice experiments entail a controlled experiment where hypothetical scenarios are constructed and respondents choose one out of two or more alternatives. In each scenario, a respondent will choose an alternative that is characterized in terms of the levels of several attributes. By presenting multiple attributes that comprise the alternative, researchers can understand how respondents value certain attributes and confront tradeoffs between their levels. For example, instead of presenting several varieties of maize for a respondent to choose from, a researcher may present the crop in a picture indicating the price of the seed, if it can be purchased using credit and whether the variety is resistant to pests or not (Birol et al., 2012). In this respect, respondents are obligated to make a choice based on their valuation of the three specified attributes. Valuation of attributes is consistent with choice theory, whereby farmers do not select the agricultural technologies themselves, but the characteristics they embody (Ortega et al., 2014).

Since there is uncertainty about which alternative will be chosen by an individual from a sample, researchers can assess the probability of him or her choosing a specific alternative (Lancsar & Savage, 2003). Hence, discrete choice experiments are rooted in random utility theory (RUT) because of its probabilistic nature. The framework proposes that utility is divided into two components- an explainable (or rather observable) and a stochastic component. That is,

$$U_{ij} = V_{ij} + \varepsilon_{ij} \quad \textbf{(1)}$$

where U_{ij} is the utility derived from choice *j* chosen by individual *i*, V_{ij} is the observable component and ε_{ij} is the random component. Eq. (2) explains the assumption that an individual would select alternative *j* if the utility derived from that alternative is greater than the utility derived from another alternative in choice set *j.* Such that,

$$V^*_{njs} = \int {}^{1\ if\ V^*_{njs} = \max V^*_{n1s,}\ V^*_{n2s},\ldots,V^*_{nKs}}_{0\ Otherwise} \quad \textbf{(2)}$$

In this equation, smallholder *n* will choose alternative *j* so long as $V_{njs}^* > V_{nks}^* \forall k \neq j$. In **Eq. (2)**, actual utility (V_{njs}) is observed, but indirect utility (V^*_{njs}) is not. In this study, a farmer is assumed to maximize his or her utility derived from choosing a *Striga* control practice. In econometric terms, farmer *n* faces *K* alternatives contained in choice set *s*. I define an underlying latent variable V_{njs}^* that denotes the value function associated with smallholder *n* choosing option *j* in a given choice task (Waldman et al. 2017).

2.3.2 Random parameter logistic regression

Given that smallholders are socioeconomically heterogeneous, their preferences for *Striga* control practices may be as well. One analysis often employed to evaluate preference heterogeneity is random parameters logistic regression (RPL), commonly referred to as mixed logistic regression. In this regression, indirect utility is assumed to be linear whereas marginal utility is monotonic (i.e., not increasing nor decreasing), yielding corner solutions where one choice is selected (Useche et al., 2013). Based on this assumption, farmer *i*'s utility function is written as

$$X_{ij} = \beta' X_{ij} + \gamma' Z_i + \varepsilon_{ij} \quad \textbf{(3)}$$

where X_{ij} represents the vector of attributes for the *j*th choice observed by the *i*th individual; Z_i represents the vector of personal characteristics for that individual (i); β and γ are vectors of parameters that explain the influence each alternative's attribute (e.g., price of seed) and each individual's characteristic (e.g., wealth) has over the observable component (e.g., choosing a corvette); and ε_{ij} is the unobserved (or rather stochastic) component of utility, independent from the observed components (i.e., *X* and *Z*) and equally distributed across individuals and alternative choices. The unobserved component acknowledges that unobserved variations and errors are present in farmer preferences for a given alternative in a scenario.

As Train (2009) outlines, the probability that a smallholder *n* chooses alternative *j* in choice task *s* is assumed to be-

$$\frac{Prob\left(V_{njs} = 1 \left|(X'_{i1s}, \left(X'_{i2s}, \ldots, (X'_{iks}, \wedge)\right)\right)\right)}{\exp(X'_{ijs}\beta)}$$

$$\int = \sum_{k=1}^{K} \frac{\exp(X\prime_{ijs}\beta)}{\exp(X'_{iks}\beta)} f(\beta | \wedge) \mathrm{d}\beta \quad \textbf{(4)}$$

where $X'_{njs}\beta$ represents the marginal utility parameters and various attribute levels. Λ refers to the parameters characterizing the distribution of random parameters such as mean and covariance of β (Waldman et al., 2017). In this study, we specify the parameters (i.e., the attributes of *Striga* control practices) and their respective attribute levels (e.g., low, medium and high labor). In **Eq. (4)**, the probability is approximated numerically through maximum likelihood simulation. In the analysis, we allow coefficients corresponding to each attribute take a normal distribution. In doing so, their sign can either be positive or negative, indicating preferences for each of the attributes.

Due to the non-cardinal nature of utility, the coefficients generated by an RPL regression have limited economic interpretation. To gain insights about the behavior of a given sample of individuals, economic tradeoffs are calculated by dividing attributes that do not necessarily have monetary values (e.g., soil fertility) with ones that do (e.g., maize yield). Discrete choice experiments can explicitly account for zero, positive and negative willingness to pay (WTP) ratios. As Train (2009) explains, rather than assigning individuals with the same value associated across different attributes, RPLs indicate whether a statistically significant distribution exists between coefficients across individuals. In the sample, the sign of the random coefficient can be positive or negative. Nahuelhual et al. (2004) estimates-

$$WTP = \frac{MU}{MUI} \quad \textbf{(5)}$$

where MU is the marginal utility gained from a various productive attribute and MUI is the marginal utility of income gained from a monetary attribute (i.e., profit). MUI is used as a proxy for the premium/discount coefficient. When there is a negative ratio for an attribute parameter, it is not strictly correct, but indicates the amount individuals are willing to accept in compensation to suffer a utility reducing attribute change (Rigby & Burton, 2005). In this study, a negative and statistically significant WTP ratio indicates individuals would demand a certain amount of maize grain for higher soil fertility, for example. Oppositely, if the sign is positive and statistically significant, the individuals would be willing to sacrifice or accept (WTA) maize grain for higher soil fertility.

2.4 Methods

2.4.1 Discrete choice experiments

Discrete choice experiments have been used as a method in research to assess tradeoffs farmers face when choosing alternative practices (Vaiknoras et al., 2014). Discrete choice experiments present respondents with scenarios having two or more alternatives to choose from. In the case of *Striga* weed control, these alternatives may be different practices (e.g., hand-weeding, herbicide) with the same attributes (e.g., time in field, yield received) but at different levels (e.g., 4 hours/day + 500 kg/ha vs 8 hours/day + 1000 kg/ha). In these scenarios, many times, respondents may pick an alternative they are not familiar with or opt-out (i.e., continue what they were already doing). By selecting one alternative over another, farmers reveal what tradeoffs they are (or not) willing to make to make. Then, by estimating marginal values of attributes, researchers can quantify these tradeoffs (Knowler et al., 2009). In this section, the strengths and limitations of discrete choice experiments are disused as well as the choice design and its implementation.

2.4.1.1 Strengths and limitations of method

There are several advantages and limitations to using discrete choice experiments in the context of examining the implementation of an agricultural practice. First, RPL has moved beyond earlier methods of analysis (e.g., conjoint analysis) that assessed practice implementation by assuming homogenous preference across respondents (Birol et al., 2009). By assuming heterogeneity of preferences, discrete choice experiments enable unbiased estimation of individual preferences to accurately assess their needs for implementing a farming practice. In accounting for heterogeneous preferences across a population, better policy recommendations can be made for which attributes to invest in for which groups to encourage implementation (Boxall & Adamowicz, 2002). Second, discrete choice experiments allow researchers to examine the willingness of farmers to confront tradeoffs among technologies with which they may not be familiar. Third, following mixed logistic regression, matrix correlations can show which attributes are correlated and affect implementation (Ortega et al., 2016). These correlations are important to be cognizant of when assessing which attributes are of most concern to the smallholder. For example, a positive correlation found between two attributes of an SFM technology, such as soil fertility and time in field, would indicate that respondents were motivated by increased soil fertility were also motived by increased time in the field (Waldman et al., 2016).

Discrete choice experiments assume several limitations. One of the largest drawbacks of using discrete choice experiments is that they are susceptible to hypothetical bias (Hensher, 2010). That is, the stated responses of farmers in the experiment may not reflect their actual behavior in the field. Also, discrete choice experiments are prone to researcher bias. In this instance, farmers could be selecting alternatives in the choice sets they believe researchers want them to make in hopes of receiving compensation (e.g., seeds, extension). Second, farmers anchor their choice base on only one attribute rather than all attributes of the technology presented in the experiment (Árvai et al., 2014). If they do not confront tradeoffs, the experiment has little process validity. Third, attributes may have weights applied to them that are not congruent with the realities of smallholders. Later, when results are analyzed, conclusions made about tradeoffs do not reflect tradeoffs made in reality (Árvai & Gregory, 2003). To address the three aforementioned concerns, researchers can first explain to participants that their decisions will have no influence over inputs disseminated by the organization their affiliated with. Second, researchers can survey participants prior to the experiment to determine what is the average time they spend fulfilling a SCP, for example, and apply these averages as appropriate weights. Third, researchers can ask participants during each choice scenario for participants to explain what the tradeoffs are between each choice set.

2.4.2 Choice design

The discrete choice experiment in the study was designed to compare farmers' current management practices against hypothetical *Striga* control practices. To make this comparison, control (i.e., alternative) attributes were discussed with farmers, but more specifically, their corresponding levels according to each practice. Literature and supporting data were later used to confirm the levels identified by farmers for each attribute.

<u>2.4.2.1 Identification of choice attributes via focus group discussion</u>

Three focus group discussions were held in May-June 2017 across three EPAs to determine the practices (i.e., alternatives) farmers were aware of that control *Striga* and the attributes they were most concerned with when implementing them. The manner in which focus groups were conducted such as the number of participants selected per discussion, participant recruitment and settings where focus groups took place are explained in **section 2.4.4** (Sampling procedures).

The study took a Feminist-Political Ecology (FPE) perspective to inform its methodology for analyzing focus group data. There are many definitions of FPE, but this study drew from Hovorka's (2006) explanation, whereby the perspective views gendered experiences as a result of political-economic environments. In turn, these environments govern how livelihoods are affected in terms of institutions of property, social relations, etc. Livelihoods also inform how farmers value different attributes of new technologies. The valuation of attributes is influenced by the control that farmers have over resources in their households, thus, gendering his or her choices about new technologies (Adato & Meinzen- Dick, 2002; Dinh et al., 2014).

Prior to asking questions about *Striga*, results from a preliminary study conducted in 2013 were reported back to farmers at the beginning of the focus group discussions. Results from the study estimated the drivers of legume-maize intercropping and described the implications for AEDOs and policy makers. Afterward, the researcher stated that the objective of the study was to identify which *Striga* control practices participants had heard about or used, and what attributes they considered before implementing them.

The reason for reporting results back to farmers was to gain trust prior to data collection (Creswell & Miller, 2000). For example, the researcher explained that in 2015-16, over 50% of the participants in the study had reported *Striga* as a primary challenge to production; hence, the study was being conducted to address their voiced concerns. Afterwards a series of open-ended questions were asked in a specific sequence so that attributes of locally implemented *Striga* control practices emerged (refer to **Appendix 1** for further detail). First, participants were asked about their familiarity with *Striga* (lifecycle, identification, effect on yield, seed transport), then about the history and extent of its effects in their field (e.g., when *Striga* first appeared in their fields, what yield losses occurred).

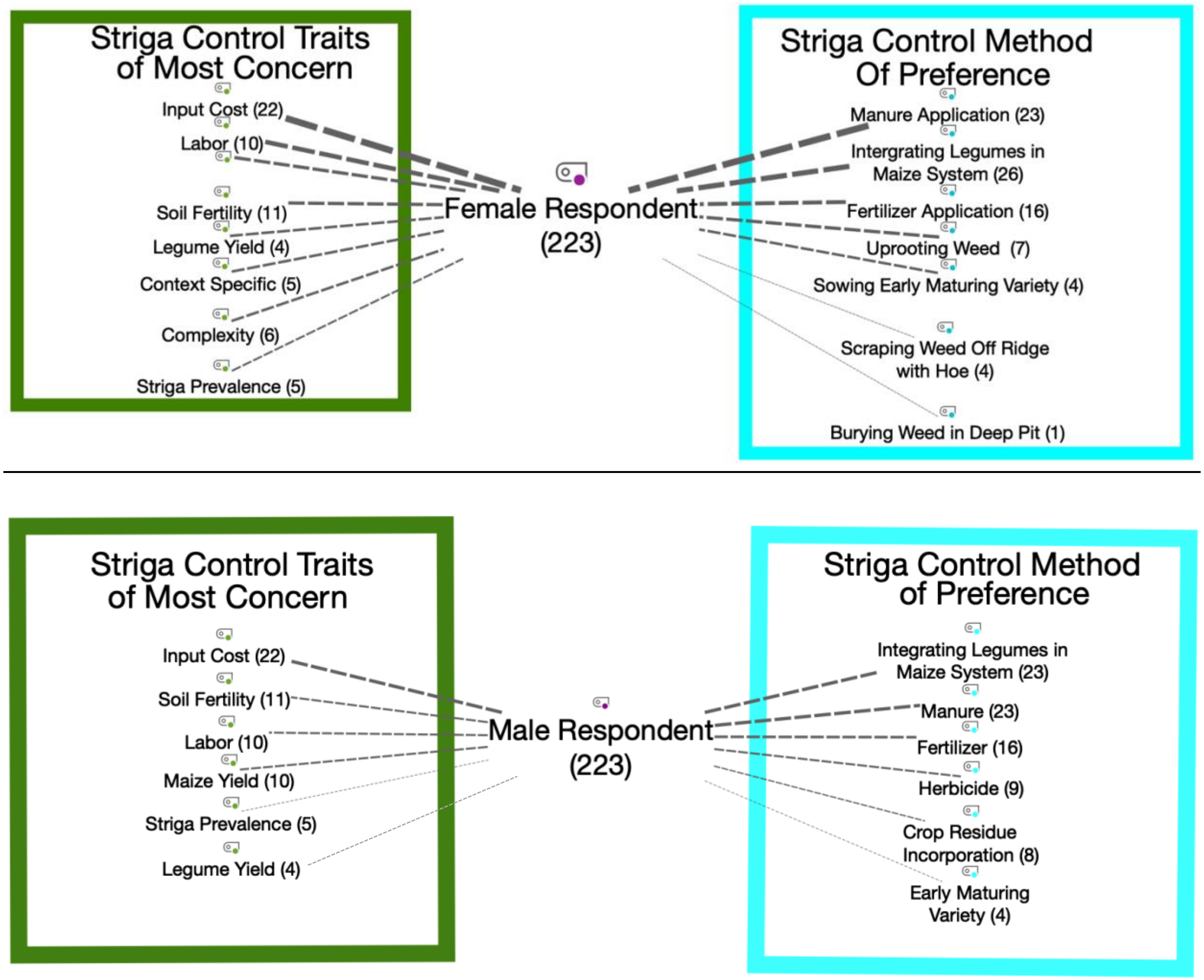
After the preliminary questions were asked, farmers were asked to state any treatment and/or preventative practices they had heard of. Treatment practices are employed when *Striga* is observed in the field and removed by a famer. In some instances, after the weed is removed, a treatment practice may also entail applying an input where it emerged. Oppositely, preventative practices are employed before *Striga* is observed in the field in an effort to create less favorable conditions for germination. The treatment practices mentioned by focus group participants included timely weeding, disposal in a deep pit and micro-dosing the affected area with maize bran, ash, fertilizer and/or manure. The preventative practices mentioned by focus group participants included mulching, minimum tillage and/or crop rotation/intercropping with legumes. The participants from each EPA mentioned different treatment and preventative control practices, but the intention of the focus groups was to gather and compose a list of all practices farmers had heard about or implemented. Afterward, participants were asked to identify the source they learned or heard about the practice. Then, what was required to carry out the practice (e.g., timing, required inputs) if they had implemented it in their field/s.

The third part of the focus group discussion inquired about the goals or objectives farmers took into account before choosing and implementing a *Striga* control practice. Before they answered, an example was given. “If you chose a legume seed, perhaps you would look at taste, yield, cooking time, etc.” In the case of *Striga* control, participants were asked what were the short- and long-term objectives they took into account before implementing the practice as well as the primary/secondary benefits they aimed to receive. By identifying these objectives and benefits, attributes of *Striga* control practices were revealed. At the closing of each focus group discussion, participants were asked to rank the attributes from most to least important as well as the practices they believe were most to least effective in controlling *Striga*. Finally, participants were asked to rank which practices they preferred (from most and least) considering the attributes mentioned.

To assess other factors that affected preferences for various *Striga* control attributes, focus group discussions were first recorded and transcribed from Chichewa to English. The enumerator who conducted the interviews assisted the researcher with translating each data from each focus group discussion. Then, transcriptions were uploaded into the qualitative data analysis software MAXQDA to analyze the data. Data was coded into nodes and sub-nodes. Nodes included farmer knowledge about the *Striga* lifecycle (e.g., germination, attachment), the type of practices mentioned (e.g., preventative, treatment), their understanding of the control mechanisms employed by each practice (e.g., suicidal germination catalyzed by legumes), the attributes they considered before implementing a practice (e.g., labor) and their preferences for each practice.

To determine the valuation of attributes between farmers, *Striga* knowledge, practice preference and practice attribute preference nodes were applied to different participant quotes. In addition, quotes were applied with gender and location nodes. Then knowledge and practice/attribute preferences were compared across gender and location. A concept map was made (see **Figure 1**) to assess if there was a qualitative relationship between gendered concerns for *Striga* control attributes, and to what extent these concerns informed preferences for *Striga* control practices. In the concept map, line thickness represented the frequency of statements according to an attribute or practice. Each attribute or practice node could be opened to view statements made about preferences for attributes or practices.

Figure 1 - Control trait preferences related to control method preferences across gender



2.4.2.1 Selection of attributes

Across eight themes, five common attributes were selected across both genders. They were later confirmed with literature. These attributes included Soil Fertility Improvement, Labor Requirement, *Striga* Emergence, Legume Yield and Maize Yield. They are reviewed below. The inputs and benefits required and received from each practice were quantified. Informal discussions with *Striga* experts and stakeholders were asked to verify these quantifications.

Literature was then referred to confirm the quantifications. From this review, many of the practices and their required inputs were based on the extent of *Striga* emergence in a field as well as number of other factors.

2.4.2.1.1 Soil fertility improvement

Many *Striga* preventative control practices have shown to increase soil fertility and long-term yields, while *Striga* treatment control practices often increase same-season yield. Thus, increased soil fertility can be a secondary benefit received from implementing many *Striga* control practices. As a result, these benefits can positively affect farmer decisions to implement a practice such as maize-legume intercropping (Place et al., 2003). Other researchers have found in choice-experiment research that farmers are willing to sacrifice maize yields for soil fertility improvements (Waldman et al., 2017). Lastly, evidence has shown farmers are more likely implement SFM practices (e.g., *Mucuna pruriens*, or velvet bean, a cover crop) when they perceive soil fertility as a primary problem to their productivity (Versteeg et al., 1998). In this study, farmers would have to perceive soil fertility as a determinant of *Striga* emergence. Many control practices aim to alter the soil fertility by increasing soil pH and soil-P, given that there is a strong correlation between higher soil-P and lower *Striga* emergence (Abdul et al., 2012). Soil fertility improvement was applied with three levels: low (sandy soil), medium (sandy-clay soil) and (dark loamy-clay) soil fertility. Smallholders were asked which fields in their community had these types of soils, and thereafter, were collected and put in sacks for them to see during the discrete choice experiment. Farmers were then asked to identify the difference between soils to ensure they agreed with the assessment that sandy soils were assumed as low soil fertility, sandy-clay soils were assumed as medium fertility, and dark-loamy-clay soils were assumed as high fertility soils. Soils in Dedza are dominated by coarse, well-drained Alfisols and a mixture of eutric Cambisols and eutric Fluvisols (primarily in Golomoti) or ferric Luvisols (primarily in Linthipe) (Lowole, 1983). Whereas in Ntcheu, fields are dominated by mixed chromic Luvisols and orthic Ferralsols (Mungai et al., 2016). Three levels of soil fertility were used: low, medium/current and high, which corresponds to a decrease in current soil fertility, no increase or decrease from current practices and a 50% increase in soil fertility.

2.4.2.1.2 Labor requirement

Different practices require different inputs to carry out in the field. For instance, some mulching practices call for 0.5-2 tons of maize stover to be applied per hectare to significantly change a field's soil profile (e.g., soil organic matter, macronutrients) (Giller et al., 2009). This requires farmers to lay stover, and in many instances, harvest supplementary biomass to reach a 0.5-2 ton/ha threshold. Other control methods, such as minimum tillage, restrict soil disturbance (e.g., making ridges, use of a plough). In doing so, farmers can reduce the time they spend preparing their fields before planting, but extend their weeding labor given that some annual weeds were not buried from tilling at sowing. Preventative methods such as cereal-legume intercropping can reduce weeding labor by shading low emerging annuals. Apart from intercropping, rotating cereals with legumes can spread labor to sow, weed and harvest to off-peak times, relieving labor burdens for households with smaller labor pools (Thierfelder & Wall, 2010). On the other hand, perennial legumes, particularly pigeon pea (*Cajanus cajun*), sometimes demand pruning during and after the growing season. In addition to these pruning activities, farmers have to de-shell pulses, adding to postharvest activities. These activities (among many others) have shown to affect farmer decisions when implementing *Striga* control practices. Three levels of labor requirement were used: low, medium/current and high, which corresponds to a 50% decrease, no increase or decrease from current practices and a 50% increase in person-day farm activities.

2.4.2.1.3 *Striga* emergence

Many farmers will determine how effective a control method is by how much *Striga* emerges the same or following season. Thus, *Striga* can be controlled in terms of prevalence and persistence. Prevalence refers to the extent a weed emerges across a given area whereas persistence refers to the extent a weed emerges across consecutive seasons. Emergence is typically not uniform across a field. Rather, weeds will emerge at various densities in different areas across a field. In other instances, under heavy infestations, a weed like *Striga* can have uniform emergence across an entire field.

One factor that is consistent across all farmer settings is the number of individual *Striga* plants that can parasitize and be supported by a single maize plant. Only a maximum of 9 juvenile parasites can attach to one maize plant, and after underground attachment, a maximum of 8 flowers can emerge given the percentage of juveniles that make it to adulthood (Kunisch et al., 1991). It is clear that *Striga* emergence, in terms of its prevalence and persistence plays a critical role in farmers' control practice decisions. In this study, the researcher tested how highly farmers consider this attribute. Three levels of *Striga* emergence are specified in the choice experiment: low emergence (0-1 flowers per plant), mild/current emergence (3-4 flowers per plant), to high emergence (6-7 flowers per plant). Flower numbers were based on average field observation and maximum attachment factors found in the literature (Kunisch et al., 1991; Smith et al., 1993).

2.4.2.1.4 Legume yield

Several preventative *Striga* control practices involve the use or integration of legumes within CCS. Apart from improving soil fertility and reducing attachment, these crops provide a protein-rich food source during the interim (Place et al., 2003). Grains delivered by the legume not only can increase food security, but also provide an alternative income source for farming households. Researchers posit that farmers who are knowledgeable about the benefits legume grain provides, as well as the secondary benefits they offer (e.g., protein-rich fodder), are more likely to implement them within their cropping systems (Bezner Kerr et al., 2007).

In this study, the researchers used groundnuts (*Arachis hypogaea*) as the representative of legumes given that farmers were more familiar with their production, processing and market price. It is important to note that not all preventative controls, such as mulching, involve legumes. Many, in fact, are absent of legumes given they can be parasitized by *Striga spp*. and/or *Alectra vogelii* (another parasitic weed). Hence, the soil is blanketed with residues completely, absent of any legumes. With these considerations, the legume yield attribute was applied with three values- no yield (i.e., removal of any legume from field to conduct mulching), average yield (300kg/ha) and high yield (600kg/ha). Farmers were presented with a smaller version of 50kg sacks filled with the aforementioned amounts during the discrete choice experiment. Thus, no sacks corresponded to the yield received from current practices, three sacks corresponded to low yield and six sacks corresponded to high yield. The attribute was applied with the aforementioned yields based on previous cereal-legume intercropping studies conducted by Kamanga et al. (2002) in Malawi. The researchers agreed, however, groundnut yields were quite variable across EPAs.

2.4.2.1.5 Maize yield

Maize is the primary crop cultivated in Malawi, "comprising 53, 38, and 51 % of total farmed land in Dedza, Ntcheu, and Zomba, respectively" (Waldman et al., 2016, p. 1088). Hence, maize yield is a critical attribute considered by farmers when implementing any new agricultural technologies. Many times, preventative *Striga* control strategies and their related SFM practices have delayed returns on investment. Hence, the short-term and long-term maize yields received from a given technology will ultimately affect a farmer's decision to employ a practice such as mulching (Nowak, 1987). Some argue that farmers' avoidance of preventative control practices (e.g., legume intercropping) stems from the fear that increased crop diversity will increase competition for resources, and consequently, reduce maize yield (Gliessman, 1992; Waldman et al., 2017).

Based on the aforementioned points, maize yield was included as an attribute. Maize is often considered as a currency in rural areas where the study was conducted. The attribute, therefore, serves as a substitute for a cost/price variable in order to evaluate the tradeoffs (Ortega et al., 2016). As Birol et al. (2009) explains, an indirect measure of cost (as opposed to a direct monetary variable) is more suited for discrete choice experiments conducted with subsistence farmers given that they may not be able to accurately assess the true value of their currency. In addition, financially insecure smallholders may not be familiar with the true value of cash given their limited access to it, making it an ineffective measure of currency for them. Maize yield (without fertilizer application) per hectare within the specified EPAs ranged from 500-2000kg/ha. Hence, the researchers agreed maize yield was quite variable across the EPAs. Four levels were applied to the maize attribute; a 50% loss (approximately 500 kg/ha); a 25%

loss (approximately 750 kg/ha); average yield (approximately 1000 kg/ha); and a 25% gain (approximately 1250 kg/ha). The following percentages were applied as values to the maize attribute based on observations in Malawi and supporting literature (Ngwira et al., 2013). In the discrete choice experiment, farmers were presented with a smaller version of 50kg sacks filled with the maize. Hence, 5 sacks corresponded to a 50% loss, 6 ½ sacks corresponded to a 25% loss, 10 sacks corresponded to current yield and 12 ½ sacks corresponded to a 25% gain. Detailed information on the selected attributes and their levels is presented in **Table 1.**

Table 1 - Striga control attributes used in choice experiments

Attribute	Variable form in equation	Levels	Definition
Soil Fertility Improvement	Hi_Soil_Fert, Low_Soil_Fert	Less, current, more	Soil fertility improvement received for applying the method. Less (sandy soil), current (sandy-clay soil) and more (dark loamy-clay) soil fertility.
Labor Requirement	Hi_Lab_Req, Low_Lab_Req	Less, current, more	Labor requirement defined as a 50% increase in labor (more), current labor or a 50% decrease in labor (less).
Striga Emergence	Hi_Strig_Emerg, Low_Strig_Emerg	Less, current, more	The extent *Striga* emerges per maize plant. Less emergence (0-1 flowers per plant), mild/current emergence (3-4 flowers per plant), to more emergence (6-7 flowers per plant).
Legume Yield	Hi_Leg_Yield, Low_Leg_Yield	None (i.e., current), low, high	Legume harvest received from *Striga* control practice. The following yields were 0kg/ha, 200kg/ha and 400kg/ha
Maize Yield	Hi_Maiz_Yield, Low_Maiz_Yield	50% loss, 25% loss, average yield, 25% gain	Maize harvest received from *Striga* control practice. The following yields were 500kg/ha, 750kg/ha, 1000kg/ha and 1250kg/ha.

Based on the attributes selected above, a choice model is regressed. The derivatives of the likelihood estimates of the coefficients yield the probability of selecting one alternative over two others. This gives a measure of explanatory power for all independent variables included in the equation. The equation used to estimate the parameters of a choice model is:

$$E(Y_{ijs}) = \beta_{i1}Hi\_Soil\_Fert_{ijs} + \beta_{i2}Low\_Soil\_Fert_{ijs} + \beta_{i3}Hi\_Lab\_Req_{ijs} + \beta_{i4}Low\_Lab\_Req_{ijs} + \beta_{i5}Hi\_Strig\_Emerg_{ijs} + \beta_{i8}Low\_Strig\_Emerg_{ijs} + \beta_{i9}Hi\_Leg\_Yield_{ijs} + \beta_{i10}Low\_Leg\_Yield_{ijs} + \beta_{i11}Maiz\_Yield_{ijs} + \varepsilon_{ijs} \quad \textbf{(6)}$$

In the choice model (**Equation 6**), Y_{ijs} is the choice as a function of the various attributes and their respective levels, *Hi_Soil_Fert/Low_Soil_Fert* are variables indicating lower/higher soil fertility received from choosing a practice relative to the status quo, *Hi_Lab_Req/Low_Lab_Req* are variables indicating the required labor required from the chosen practice relative to the status quo, *Hi_Strig_Emerg/Low_Strig_Emerg* are variables indicating lower or higher *Striga* emergence surrounding a maize plant received from a chosen practice relative to the status quo, *Hi_Leg_Yield/Low_Leg_Yield* is the amount of legumes received from a chosen practice relative to the status quo and *Maiz_Yield* is the percent of maize yield received from a chosen practice relative to the status quo. The indices *i, j* and *s* represent the farmer, the choice and the scenario, respectively; whereas β is the coefficient associated with each attribute and ε_{ij} is the random component, which is assumed to be equally distributed across individuals and choices.

The description, coding scheme and unit of measurement for each explanatory variable are listed in **Table 2**. Different coding schemes were applied to each variable, but an effect coding scheme was applied to the non-monetary random parameters. Dummy or effect coding schemes could have been applied to these attributes. Neither type of coding scheme is necessarily better, but yield different interpretations of the estimated effect an attribute has on the choice (if significant) (Kugler et al., 2012). Based on the effect found in the results, the researcher can decide whether one coding scheme yields more meaningful results to explain farmer decisions. The effects being estimated with an effect coding scheme are generally referred to as "main effects". Dummy codes do not estimate main effects (Rodgers et al., 1984). Main effects are defined as the difference between the mean response at one level of a particular attribute and the mean response at the other level, collapsing over the levels of all remaining attributes (Montgomery, 2009).

Table 2 - Definition of variables used in choice model

Short Form	Description	Coding	*Values
Random parameter			
Hi_Soil_Fert	Higher soil fertility received from a *Striga* control practice	Effect	0,0,1
Low_Soil_Fert	Lower or higher soil fertility received from a *Striga* control practice	Effect	1,0,0
Hi_Lab_Req	More labor required to carry out *Striga* control practice as compared to status quo	Effect	0,0,1
Low_Lab_Req	Less labor required to carry out *Striga* control practice as compared to status quo	Effect	1,0,0
Hi_Strig_Emerg	More or more *Striga* emergence per maize plant by carrying out a *Striga* control practice	Effect	0,0,1
Low_Strig_Emerg	Less *Striga* emergence per maize plant by carrying out a *Striga* control practice	Effect	1,0,0
Hi_Leg_Yield	High (~600kg) legume yield received from an intercropping *Striga* control practice	Effect	0,0,1
Low_Leg_Yield	Low (~300kg) legume yield received from an intercropping *Striga* control practice	Effect	1,0,0
Maiz_Yield	Percent of current maize yield received from carrying out current *Striga* control practice	Ordinal	50, 75, 100, 125
Non-random parameter			
Opt_Out	Whether or not to continue status quo practices for controlling *Striga*	Dummy	0,0,1

Note: If an attribute had had high soil fertility, then the code three cells in the column would read, 0-0-1.

When using a dummy coding scheme, row values correspond to the alternative and column values correspond to the individual making the choice (see **Table 3**). Values for the coding scheme are either 0 or 1 (Hardy, 1993). On the contrary, with an effect coding scheme, column values correspond to the alternative and row values correspond to the individual making the choice. Values for the coding scheme are either -1 or 1, with 0 referring to the status quo. When running a logistic regression, the status quo attribute level (e.g., Med_Lab_Req) is not included with the higher/more and lower/less attribute levels in the model. The status quo attribute level acts as a reference point to interpret the results from its two counterparts.

Table 3 - Example of dummy and effect coding schemes for labor requirement attributes

	Dummy Coding				Effect Coding		
Alternative	*Low_ Lab_ Req*	*Med_ Lab_ Req*	*Hi_ Lab_ Req*		*Low_ Lab_ Req*	*Med_ Lab_ Req*	*Hi_ Lab_ Req*
1	1	0	0	->	1	0	0
2	0	1	0	->	-1	-1	-1
3	0	0	1	->	0	0	1

A near-orthogonal design was made with the aforementioned attributes and levels using NGENE software. In perfectly efficient designs, each level would appear as equally often in each attribute, but in this design, each pair of levels appears equally often across all pairs of attributes with the design (Johnson et al., 2013). NGENE generated 36 choice sets blocked into 6 groups of 6 choice scenarios. Each scenario respondents were provided with three alternatives to choose from: two *Striga* control practices and an opt-out option. The opt-out option allowed participants to select neither of the two alternatives, inferring they would continue current practices (i.e., the status quo). Louviere et al. (2000) postulate that it is important to include an opt-out choice so that respondents can compare and infer what tradeoffs they will make by selecting one or neither of the alternatives. The random parameter logistic regression (outlined in **Equation 7**) was estimated using the statistical software package Stata 15.0 as well as parameter logistic regression for the willingness to pay space (outlined in **Equation 8**)**.** The following commands were imputed in Stata 15.0:

mixlogit Farmer_Choice Opt_Out, rand(Hi_Soil_Fert Low_Soil_Fert Hi_Lab_Req Low_Lab_Req Hi_Strig_Emerg Low_Strig_Emerg Hi_Leg_Yield Low_Leg_Yield Maiz_Yield) group(Group_ID) id(Hh_ID) **(7)**

and

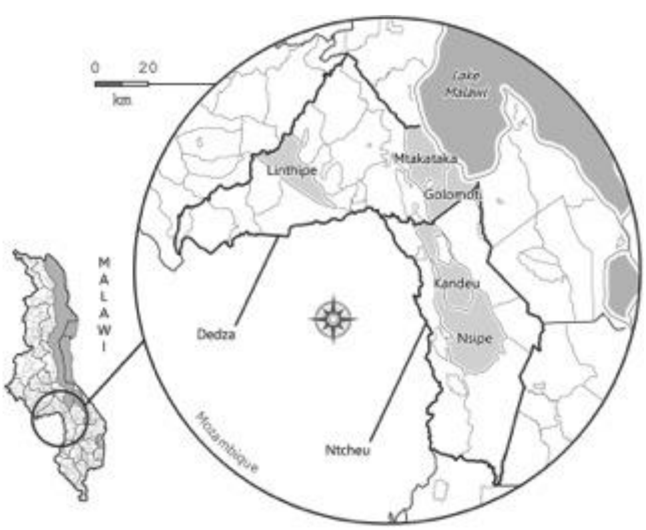
mixlogitwtp Farmer_Choice Opt_Out, rand(Hi_Soil_Fert Low_Soil_Fert Hi_Lab_Req Low_Lab_Req Hi_Strig_Emerg Low_Strig_Emerg Hi_Leg_Yield Low_Leg_Yield) price(Maiz_Yield) group(Group_ID) id(Hh_ID) **(8)**

where *Farmer_Choice* is specified as the dependent variable, *Opt_Out* is specified as a non-random parameter, *Hi_Soil_Fert Low_Soil_Fert Hi_Lab_Req Low_Lab_Req Hi_Strig_Emerg Low_Strig_Emerg Hi_Leg_Yield Low_Leg_Yield Maiz_Yield* are specified as random parameters, *Group_ID* specifies the choice set where an alternative (out of three) was selected and *Hh_ID* specifies who made the decision (i.e., the participant identification number). In equation/command **(8)** *Maiz_Yield* is specified as the price variable to estimate how attributes are valued by participants in terms of percent maize yield. In some instances, random parameter logistic regressions specify the price attribute as a non-random parameter. Meijer and Rouwendal (2006) postulate though, it is difficult to assume all individuals receive the same marginal utility from the monetary attribute. Alternatively, researchers can specify preference for Maiz_Yield to be heterogeneous and argue the coefficient for this monetary attribute is log-normally distributed; hence, the Maiz_Yield is specified as a random parameter (Hole & Kolstad, 2012). Similar to price, Opt_Out can be specified as a random parameter, but other regression logistic regressions have specified Opt_Out as a non-random parameter (Waldman & Richardson, 2018).

2.4.3 Site description

Household surveys were conducted over a 3-week period from August-September 2017 using questionnaires and discrete choice experiments in two central districts of Malawi- Dedza and Ntcheu. Dedza and Ntcheu are located in the Kasungu Lilongwe Plain (14.1667°S, 34.3333°E) and Rift Valley Escarpment (14.7500°S, 34.7500°E), respectively. Within these districts, four extension-planning areas (EPAs) were selected for data collection, namely Linthipe, Kandeu, Nsipe and Golomoti (**See Figure 2).** These EPAs were specifically chosen based on the growing challenge of *Striga* reported by farmers in recent years (Atera et al., 2012). Hence, the study was highly relevant to the region and its current farming population.

Figure 2 - Data collection sites



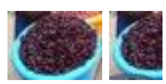
Malawi has a unimodal rainy season occurring from November to April, and a dry season from

May to October (Jury & Mwafulirwa, 2002). The sites in this study provide a gradient of biophysical potential as described in depth by Mungai et al. (2016). The marginal environment of Golomoti has a high evapotranspiration and erratic rainfall, compared to the medium potential sites of Kandeu and Nsipe. The high potential agricultural site of Linthipe has a medium-high elevation and generally receives well-distributed rainfall (Smith et al., 2016; Tamene et al., 2015).

2.4.3.1 Choice experiment setting

Demonstrative choice sets were created for each block, each containing 6 choice sets (see **Figure 3**). To increase comprehension of each choice task and reduce cognitive burdens, actual soil, maize grain and unshelled-peanuts were used. In addition, actual hand-hoes and life-sized photos of *Striga* flowers were used. This design was pre-tested in the field to ensure the props were relevant. Each choice task AEDOs asked participants to indicate what difference/s in attribute levels were present between the alternatives and the status quo (i.e., opt-out option). Stating differences between alternatives for each choice task ensured that farmers understood the tradeoffs they were making by selecting one alternative over another.

Figure 3 - Sample choice task

Attribute	Option A	Option C	Status Quo
Striga emergence	High 	Low 	
Labor requirement			Neither
Soil fertility benefits	Medium 	High 	
Legume yield			
Maize yield (kg/ha)			

Enumerators introduced one block of the discrete choice experiment to 10 respondents at a time. Each group of respondents had an enumerator explain the purpose of the discrete choice experiment and clarify any questions respondents had afterwards. Respondents were then given a card with a blue, green and orange circle corresponding to alternative 1, alternative 2 and opt out, respectively. Each choice task respondents would indicate which choice participants made by pointing to the circle behind their back so as not to influence others' decisions.

2.4.4 Sampling procedures

Data used to run the mixed logistic regression was collected at two different time-periods. First, in March of 2016 (Maize Harvest Questionnaire) then June-September 2017 (Striga Questionnaire Survey). The program Africa Research In Sustainable Intensification for the Next Generation (RISING) conducted the Maize Harvest Questionnaire using questionnaires to investigate how various sustainable intensification methods affect food security, farming livelihoods and agroecological system health. The program has been conducting action-based research with the farmers since 2013. Farmers who participated or were surveyed by the Africa RISING program (treatment, local-control and distant-control) were selected to participate in the Striga Emergence Questionnaire. Socioeconomic data from the Maize Harvest Questionnaire were used to avoid re-collecting the same data and prevent respondent fatigue. The data from this survey were not collected by the researcher, but he had access to the instrument, data, its investigators and enumerators to clarify any questions regarding clarity and validity.

A stratified sample of 215 households (n=215) was taken from the Africa RISING's farmer roster (N = 298) across four EPAs (Linthipe, Golomoti, Nsipe, Kandeu) to determine who would be surveyed in the Striga Emergence Questionnaire and discrete choice experiments. First, a stratum of 125 participants were purposefully selected consisting of households that expressed *Striga* as primary challenge to productivity (see **Table 4**). After these households were removed from the roster, famer names were segregated into their respective EPAs. Given the budget constraints of this study, only 50-60 Striga Emergence Questionnaires and discrete choice experiments were carried out per EPA. Taking this budget into account, the first names of the household heads were put in ascending order alphabetically and the remaining balance was taken to fill a quota of 50-60 questionnaires per EPA. For example, in Linthipe, 36 farmers were purposefully selected and removed from the EPA's roster, then households were alphabetized, and the first 24 names were selected to make a total of 60 famers. After eliminating households for which data were missing or incomplete, 51 households were selected from Linthipe, 59 from Golomoti, 52 from Nsipe and 53 from Kandeu.

Table 4 - Farmers expressed *Striga* as a primary challenge in 2016 (out of a list of 15 productivity challenges)

EPA	No Striga challenge	Striga challenge	TOTAL Farming HHs
Linthipe	31	36 (54%)	67
Golomoti	32	26 (45%)	58
Kandeu	51	27 (35%)	78
Nsipe	39	36 (48%)	75
TOTAL	153	125 (45%)	278

**Striga frequencies were sourced from an Africa RISING database where a maize harvest-questionnaire collected information about productivity challenges in the 2016 growing season. No manuscript has been published with this data.*

Data was available from a Maize Harvest Questionnaire conducted in March 2017, but the roster could not be used to inform which participants to sample for several reasons. A question in the 2016 questionnaire asked, "*What challenges did you face in production ON THIS PLOT this growing season? List up to 3".* The 2017 questionnaire assessed *Striga* challenges based on field observations. That is, enumerators would randomly select seven areas in two primary fields of production to see if *Striga* was present. This question may have not yielded a good representative of the farmers facing *Striga* challenges for two reasons. First, enumerators may have missed identifying juvenile plants given their small nature, and second, farmers could have removed the weed prior to observation.

The plot mentioned in the 2016 questionnaire was referring to one of two fields the Africa RISING program has been monitoring over the course of five years. These two plots are considered as the two primary fields of production for the household. Thus, if the farmer indicated that *Striga* was a challenge in one or both plots, they were considered as a household that face a "*Striga* Challenge". It is important to note in the question, farmers selected *Striga* out of a list of 16 choices related to primary challenges (e.g., not enough fertilizer, drought, low soil fertility). Hence, the data gathered from this question (as indicated by **Table 4**) was a strong indicator that a household was facing *Striga* challenges. The researcher acknowledges farmers may have been suffering yield losses unknowingly to *Striga* parasitism, thus table frequencies may be underestimated. Apart from using the 2016 Maize Harvest Questionnaire to indicate which farmers to participate in the study, no other data was used.

For focus group selection, Agriculture Extension Development Officers (AEDOs) were given lists of farmers from the Africa RISING program and participants were randomly selected from each gender. AEDOs purposefully selected 6-8 men and 6-8 women per focus group to avoid one gender from dominating the discussion and to capture a diverse dialogue. The focus group quota was set to 12-15 participants to ensure each participant had ample opportunity to share his or her opinion (Fern, 1982). Each discussion lasted between 60-80 minutes, was recorded and transcribed after. Discussions took place in or near an extension office. Participants were compensated with a soda and bread to discuss *Striga* control practices with the researcher and his enumerator.

2.4.5 Instrument calibration and protocol

Three enumerators and the researcher held focus groups, conducted surveys and administered discrete choice experiments (i.e., the second time-period). All instruments were pretested to assess the comprehension and suitability of questions used in the focus groups/questionnaires as well as the attributes used in the discrete choice experiments. The researcher trained all enumerators prior to data collection. For example, enumerators would hold mock-focus groups or conduct mock-questionnaires/choice experiments with non-participants prior to collecting data for the study. During each of these instances, the researcher observed how questions were asked, respondents answered and made critiques to instruments as well as suggestions to enumerators about their data collection techniques (e.g., probing). The March 2017 questionnaire went through a similar process whereby the instrument was tested in the field prior to data collection. All enumerators that participated in the researcher's study (August-September 2017) had also fielded questionnaires in March 2016.

The researcher's questionnaire consisted of inquiries regarding *Striga* knowledge, current and past agricultural practices, and the effects the weed has had on their farms. Please refer to the instrument in **Appendix 2** and **3** for further clarification about questions and responses. Once the questionnaire was completed, farmers participated in a discrete choice experiment. The survey and discrete choice experiment took approximately 40 to 70 minutes. Farmers were compensated with 5 blocks of laundry soap for completing the questionnaire and one bottle of soda for completing the discrete choice experiment. Survey-respondents primarily consisted of those charged with making farm decisions for their household.

Focus group questions were discussed in the previous sub-section "Identification of choice attributes via focus group discussion". Refer to **Appendix 1** for further clarification about questions. The discussion took approximately 40 to 70 minutes. Farmers were compensated with one loaf of bread and one bottle of soda for participating in the discussion. Survey-respondents primarily consisted of those charged with making farm decisions for their household.

2.5 Results & Discussion

2.5.1 Descriptive statistics

Table 5 explains the sample characteristics by gender using summary statistics. Almost three quarters of the participants were female. The average respondent age was 45 years old with a little more than some secondary education completed (Mean Education = 2.65). Male participants were slightly older and received more education than female participants. Households had about two members participating on their farms regularly, varying little across gender. As an indicator of wealth, annual income ranged between 33,000 MKW to 55,000 MKW, and among that income, 10.7% was derived from casual labor (i.e., ganyu labor). Male participants received slightly higher incomes (21.5% more) than female participants. Women, however, seemed to engage in more ganyu labor than men.

Table 5 - Sample characteristics

	Full sample n = 215	Women n = 160	Men n = 55
Mean Age	45.62	45.30	46.53
Mean Education (1-7 levels)[1]	2.21	2.06	2.65
Mean Maize Yield/Ha (2016)	1,523	1,471	1,574
Mean Household Labor	2.82	2.79	2.88
Mean Income	27,583	24,264	30,902
Mean Total Land Ownership	2.33	2.17	2.79
Mean # of SFM Practices Employed	2.33	2.2	2.38

Table 5 (cont'd)

% Intercrop Maize in Past or Currently	79.17	79.14	79.17
% Engaged in Ganyu Labor During the 2016-17 Season	46.98	56.9	35.6
% Consider Ganyu Labor as Primary Income	10.72	12.50	5.54
% Have One or More Fields with Low Soil Fertility	53.86	52.72	55.00
% Mention Soil Fertility as a Primary Production Challenge	19.63	15.00	14.50
% Mention *Striga* as a Primary Production Challenge	53.87	55.00	52.73
Mean % Fields with *Striga*	57.71	57.48	58.49
Mean *Striga* Knowledge (0-11)	5.10	5.14	5.00

[1]Schooling levels: 1 - No School, 2 - some primary, 3 - complete primary, 4 - some secondary, 5 - complete secondary, 6 – some post-secondary, 7 – complete post-secondary)

As an indicator of household food security, maize yield (per hectare) varied dramatically, ranging from 400 kg/ha to 4000 kg/ha, but the average was approximately 1500kg/ha. The mean yield seemed to exceed farmer yields (approximately 1000 kg/ha) from the 2016 season. This commonly occurs when yield cuts are extrapolated into kg/ha, which is what the study did. Still, yield cuts are effective in determining which participants received higher or lower yields, and consequently, higher or lower food security. Male and female participants received very similar yields. Participants owned on average 2.33 ha of land and cultivated 76% (1.76ha) of their farms with maize as a primary crop. In terms of *Striga* prevention, both male and female participants overwhelmingly (approximately 80%) had cultivated legumes as an intercrop or rotator crop with their maize in the past or currently. Excluding legumes from SFM practices, both men and women conducted between 1 and 3 soil SFM practices that directly or indirectly prevented *Striga* (e.g., minimum tillage, manure application).

We asked farmers a series of questions related to their knowledge of *Striga*. Approximately 53% of the sample (115 farmers) had expressed *Striga* as a primary challenge to their farm production (see **Table 5).** Women expressed slightly (3%) more concern over Striga than men as a primary challenge to production. Women also seemed to know slightly more about *Striga* than their male counterparts. "*Striga* Knowledge" was a scale calculated by the number of questions farmers answered correctly regarding the identity of *Striga* and the mechanisms behind its parasitism (Refer to **Appendix 2**, Questions 1-5, 10 for further clarification). Both genders assumed virtually the same percentage of fields having *Striga* (57% vs 58%). Apart from *Striga*, equivalent percentages of men and women mentioned soil fertility as a primary challenge to production; however, men characterized marginally more fields as having low soil fertility than women (55% vs 53%).

2.5.2 Marginal value of Striga control attributes

Results from the discrete choice experiments are displayed in **Table 6**. Being that *Striga* emergence, labor requirements and soil fertility improvement are all coded either as a -1, 1 or 0, a positive coefficient indicates decisions to select a *Striga* control practice were encouraged by the attribute. A negative coefficient indicates decisions to choose a *Striga* control practice were discouraged by the attribute. Since legume yield is coded with a zero, one or two, a positive coefficient indicates the valuation from a low to high level. The same assumption can be made for the maize yield attribute.

Table 6 - Random parameters logit model and willingness to pay space for *Striga* control practices

Variable	Preference Space		WTP-space	
	Coefficient	Std. error	Coefficient	Std. error
Random parameter means				
Hi_Soil_Fert	0.166***	0.055	11.158***	4.200
Low_Soil_Fert	-0.152**	0.063	-9.134*	5.037
Hi_Lab_Req	-0.122*	0.065	-9.273*	4.955
Low_Lab_Req	0.091	0.067	7.844	5.292

Table 6 (cont'd)

Hi_Strig_Emerg	-0.229***	0.061	-16.844***	4.790
Low_Strig_Emerg	0.141***	0.063	10.288**	4.887
Hi_Leg_Yield	0.367***	0.066	27.792***	5.841
Low_Leg_Yield	0.173***	0.061	13.165***	4.961
Maiz_Yield	0.012***	0.002	-4.378***	0.131
Non-random parameter means				
Opt_Out	-0.126	0.174	8.779	11.934
Random parameter standard deviations				
Hi_Soil_Fert	0.022	0.146	5.123	8.381
Low_Soil_Fert	0.195	0.140	8.662	8.862
Hi_Lab_Req	0.234**	0.117	6.429	9.303
Low_Lab_Req	0.085	0.196	18.696**	9.294
Hi_Strig_Emerg	0.085	0.093	7.162	6.517
Low_Strig_Emerg	0.101	0.119	12.019	8.698
Hi_Leg_Yield	0.261***	0.119	30.206***	7.351
Low_Leg_Yield	0.066	0.090	7.890	7.998
Maiz_Yield	0.011***	0.002	0.311***	0.098
N	3870		3870	
LR chi2(9)	42.75		4200.150	
Log-Likelihood	-1221.2861		-1232.357	
Prob > chi2	<0.01		<0.01	

Note: ***, **, * represent significance at the 1%, 5%, and 10% levels. Random parameters logit model estimated using Stata 15.

The coefficients of high soil fertility improvement, Low_Strig_Emerg, Hi_Leg_Yield and Low_Leg_Yield are positively significant at the 1% level in the RPL. Hi_Leg_Yield was valued twice as much as any of the other positively significant attribute. These findings suggest that all attributes were strong determinants of farmer decisions, but Hi_Leg_Yield may be an overarching factor. As expected, Maiz_Yield coefficient (i.e., the monetary attribute) was both positive and highly significant. Low_Soil_Fert, Low_Lab_Req and Hi_Strig_Emerg were negatively significant, implying all attributes deterred the selection of *Striga* control practices with the following attributes. Hi_Strig_Emerg assumed the highest coefficient and was significant at the 1% level (as compared to Low_Soil_Fert [5%] and Hi_Lab_Req [10%]). While these values are relative, they indicate practices that require higher labor requirements and result in lower soil fertility or higher *Striga* are unlikely to be implemented.

Low_Lab_Req was negative but not significant, indicating decreases in labor requirements were not necessarily an important determinant of choice for a *Striga* control practice. Only 5% (200/3870) of decisions were Opt_Out; hence, the non-random parameter was not found to be significant, but the coefficient was negative. The Wald chi-square statistic allows us to reject the null hypothesis whereby no attributes significantly influence respondent decisions at the 1% level. Significant standard deviation estimates indicate preference heterogeneity for high labor requirements, high legume yield and maize yield across participants. Their significance suggests that a subset of farmers value attributes differently when compared to their counterparts.

Results from the estimation in WTP-space model capture participants' valuation of *Striga* control attributes. The maize yield attribute is used to calculate the marginal rate of substitution; thus, the coefficient of an attribute can be interpreted as the percent of maize yield a participant is willing to sacrifice or be compensated for by choosing a *Striga* control practice. Positive valuation (i.e., a positive coefficient) should be interpreted as how much yield a participant is willing to sacrifice to receive or have higher levels of that attribute. Negative valuation (i.e., a negative coefficient) should be interpreted as how much yield a participant must be compensated to receive or have higher levels of that attribute. The coefficient of willingness to pay estimates should be considered as relative values, not exact magnitudes (Rocker et al., 2012). The coefficient is negative because in a willingness to pay space attribute values for the price attribute (i.e., Maiz_Yield) are multiplied by -1 to run the regression in Stata 15 (Hole & Kolstad, 2011).

In a willingness to pay space, participants were willing to sacrifice the largest percentage of maize to receive a high legume yield (27.8%) or low legume yield (13.2%), followed by high soil fertility improvement (11.2%) and low *Striga* emergence (10.3%). Based on the value of the negatively significant coefficients, participants would need to be compensated with the highest percent of maize yield for *Striga* control practices that were associated with high *Striga* emergence (16.8%), followed by high labor requirements (9.3%) and lower soil fertility improvement (9.1%). The marginal utility of the monetary attribute (Maiz_Yield) is negative and significant, as expected, because the attribute was multiplied by -1.

Table 7 - Correlation matrix for random parameters logit model in Table 6

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
Maize (1)	1.000								
Hi_Soil_Fert (2)	-0.004	1.000							
Low_Soil_Fert (3)	-0.007	0.496	1.000						
Hi_Lab_Req (4)	-0.010	0.025	-0.005	1.000					
Low_Lab_Req (5)	-0.019	-0.006	-0.019	0.502	1.000				
Hi_Strig_Emerg (6)	0.011	0.017	0.016	-0.029	0.028	1.000			
Low_Strig_Emerg (7)	0.014	-0.001	0.013	0.013	0.014	0.496	1.000		
Hi_Leg_Yield (8)	0.001	-0.052	-0.004	0.015	0.001	0.012	-0.012	1.000	
Low_Leg_Yield (9)	-0.016	-0.016	-0.014	-0.012	-0.004	0.001	0.011	0.507	1.000

Table 7 is a matrix correlation which indicated whether respondents were motivated by the choice of certain attribute based on the value another. Under this premise, the attributes can be positively or negatively correlated. No negative or positive correlation could be found

between two attributes (**Table 7**), implying respondents were not motivated by an increase of legume yield and an increase in soil fertility improvement, for example. These assumptions were based on conventional levels of statistical significance. The highest negative correlation found among the attributes was between high and low labor requirements as well as high and low *Striga* emergence whereas the highest positive correlations were found between high and low legume yield. This analysis indicates farmers do not necessarily find an association between attributes when choosing a *Striga* control practice.

Results from the experiment agree with findings from similar studies that evaluated soil fertility management practices using choice experiments (Silberg et al., 2017). For example, the negative association found between *Striga* control practices and high labor requirements coincides with the counterfactual finding presented by Vaiknoras et al. (2015), where Ugandan smallholder preferences for soil conservation practices were positively associated with lower labor requirements. Choice experiments that evaluated legume intercropping decisions in Malawi (Waldman et al., 2017) analogously found smallholders were willing to sacrifice a large percent of their maize yield (36.5%) for soil fertility improvement. Unlike Waldman et al. (2017), labor requirements and soil fertility improvement attributes were not correlated. Their study, however, included two different attributes (e.g., biomass, pigeon pea yield) in their choice experiment, which may be a reason why no correlation was found in our study. Farmers were only willing to sacrifice a marginal percent of their maize yield for legumes (perennial pigeon pea grain) in the Waldman et al. (2017) experiment. Our experiment conversely found farmers were willing to sacrifice willing to sacrifice large percentages of maize yield for legumes. The species of legume (e.g., annual groundnut vs perennial pigeon pea); therefore, may be a large reason why farmer- decisions were vastly different in this experiment.

2.5.3 Gender level differences

We also estimated RPL models in a willingness to pay space for each gender (see **Table 8**). The analysis revealed that men and women farmers valued attributes differently. Female participants were not willing to pay for higher soil fertility improvement while their male counterparts were (17.12% loss in maize yield). Men were willing to sacrifice 7.57% more losses in maize yield for lower labor requirements than women would need to be compensated for control practices with higher labor. Both genders would need to be compensated for control practices that received higher *Striga* emergence, but women would need to receive more than a 20% increase in current maize yields for this burden. Furthermore, women were willing to sacrifice maize yield losses for lower *Striga* emergence while men were not. Women were also willing to sacrifice 39.4% more losses in maize yield for higher legume yield when compared to men. This is not to say men did not value legumes, but women were willing to sacrifice more maize yield losses for higher legume yield. The opt out dummy for male participants was very large and significant, indicating that they derived more utility selecting *Striga* control alternatives as opposed to continuing status quo practices. The price attribute was negatively significant for both genders. No correlation was found between attributes among either gender.

Table 8 - Willingness to pay space for *Striga* control practices across gender

	Female WTP space		Male WTP space	
	Coefficient	Std. error	Coefficient	Std. error
Random parameter means				
Hi_Soil_Fert	7.726	0.147	17.124**	7.191
Low_Soil_Fert	-9.637	0.151	-9.077	7.303
Hi_Lab_Req	-12.264*	0.161	-6.894	7.626
Low_Lab_Req	7.548	0.149	19.833***	7.374
Hi_Strig_Emerg	-21.103***	0.138	-16.209**	7.706
Low_Strig_Emerg	15.276**	0.149	3.433	8.155
Hi_Leg_Yield	36.380***	0.149	22.436***	6.799
Low_Leg_Yield	7.296	0.140	14.929**	7.702
Maiz_Yield	-4.613***	0.184	-3.978***	0.207
Non-random parameter means				
Opt_Out	-8.359	0.402	27.792*	14.449
Random parameter standard deviations				
Hi_Soil_Fert	11.036	0.179	26.240***	8.116
Low_Soil_Fert	12.801	0.201	19.313**	8.958
Hi_Lab_Req	21.896**	0.234	22.943**	9.417
Low_Lab_Req	9.004	0.202	4.175	6.236
Hi_Strig_Emerg	3.946	0.167	1.080	7.362
Low_Strig_Emerg	10.069	0.235	33.504***	12.315
Hi_Leg_Yield	26.497***	0.464	11.313	8.417
Low_Leg_Yield	1.533	0.255	6.556	10.224
Maiz_Yield	0.610***	0.125	0.662***	0.260
N	2880		990	
LR chi2(9)	2116.01		986.730	
Log-Likelihood	293.849		290.970	
Prob > chi2	0.156		<0.001	

Note: ***, **, * represent significance at the 1%, 5%, and 10% levels.

Women participated and derived more of their primary income from ganyu labor, supporting the finding whereby women were deterred by control practices with higher labor requirements whereas men were not. Opposing results between men and women in the willingness to pay space did not appear to be supported by what little socioeconomic differences were found between genders (seen in **Table 5**). Qualitative findings seemed to shed more light between these differences however. For example, focus group transcription (see **Table 9**) highlights an underlying concern for hunger and food provided by *Striga* control practices, whereas men seemed to deliberate more about the monetary costs of a practice before implementing it. These considerations are supported by the literature as well (Njuki et al., 2011). In addition, men appeared to have preferences for control practices that used synthetic inputs given their preferential access and use of them (Bezner Kerr et al., 2007). These findings may support why women were willing to pay more for legumes than men.

Table 9 - Participant quotes related to food security and financial costs and preference of Striga control practices

Female Participant	Male Participant
*"Striga is just bad. We don't harvest anything. It brings **hunger** in our villages." F1 –G*	*"If you have enough **money in your pocket**, you just buy **herbicide** and spray. That would lessen your work." M6-N*
*"With **crop rotation**, you'll get **more maize** the following season. With manure application, the maize will still grow well with Striga, but not as well with crop rotation." F6-L*	*"For **fertilizer**, for you to apply three times, you need to have enough **money** to do that." M2-N*

With respect to soil fertility improvement, men were willing to sacrifice while women were not. Women may have been less concerned about soil fertility improvement being that they generally do not own land nor are they permitted sell it once they have increased the value (Pircher et al., 2013). Rather they are willing to sacrifice more of their maize yield for lower *Striga* emergence perhaps because they are more familiar with the weed and its effects. Literature explains women may be more familiar with weeds given that they are charged with the task of hand-weeding (Andersson & Giller, 2012). Men do weed, but primarily with the use of a hoe (via scraping), as they are charged with preparing the land. Men may only see the negative effects of witchweed at harvest, which may be a reason their willingness to pay is smaller. Gendered roles, thus, may be a driver of attribute preferences (e.g., men and soil fertility improvement) (see **Table 10**).

Table 10 - Participant quotes related to gender roles and preference for *Striga* control practices

Female Participant	Male Participant
*"But when you **scrape**, you leave a cutting in the ground to grow again. So I think **uprooting** would be the best way." F1–G*	*"You can be **weeding** in the field, but you will not produce anything if there's no fertility in the field." M1-N*

Each gender was concerned about labor requirements differently. Male focus group participants were willing to pay for lower labor requirements to control *Striga* whereas female participants mentioned multiple times they would only implement a practice if they could manage it themselves. When asked which practices they preferred, the female narrative (as shown in **Table 11**) seemed to avoid any practice associated with intensive labor requirements. Concern for labor requirements may stem from previous experiences when new technologies shifted the burden of increased weeding labor to them (Giller et al., 2009).

Table 11 - Participant quotes related to labor and preference for *Striga* control practices

Golomoti Female Participant	Linthipe Female Participant	Nsipe Female Participant
*"Ah, well if one **takes a lot of hands** to fulfill it, then it's not easy." F4-G*	*"Yah, **we look at labor**. It's all about what we think we can manage in term of labor. If we can manage it, then we will choose that one." F6-L*	*"Something that **will not consume too much of our time**." F2-N*

2.6 Conclusions

The objective of the study was to learn: 1) when given a choice among *Striga* control practices, which alternative would participants choose (or remain with the status quo); 2) which attributes most significantly influenced the selection of a *Striga* control practice; and finally, 3) what tradeoffs were male and female participants willing to accept.

Few farmers opted out (5%, 200/3870), even when faced with selecting an alternative with lower maize yield. A strong inclination to select one of the two alternatives reveals one or a combination of motives. First, given the widespread emergence of *Striga* across the central region of Malawi, policies providing legumes may encourage *Striga* reduction. Second, farmers may have selected alternatives they believed researchers wanted them to select (i.e., hypothetical bias) in hopes of receiving compensation later (Hensher, 2010). Third, farmers may have been willing to sacrifice larger percentages for maize yield for various attributes given the choice experiment was conducted one month after maize harvest. Had the experiment been conducted one month prior to harvest season (when maize foodstuffs are most scarce), farmers may have been more reluctant to choose any alternative where maize yield was less than average.

Significant attributes in the RPL suggest the correct characteristics and appropriate levels were applied to hypothetical alternatives for the choice experiment. As expected, participants chose scenarios with lower *Striga* emergence as well as higher maize yield, legume yield and soil fertility improvement. Participant decisions were not influenced by scenarios that had lower labor requirements, but were negatively and significantly influenced by higher labor requirements. These findings suggest farmers will implement *Striga* control practices that integrate legumes within their maize-based systems that offer soil fertility improvements, but not ones which will increase their current labor requirements. Being that the “High Legume Yield” attribute assumed the highest coefficient of significance at the 1% level, farmers may be more concerned with a *Striga* control practices that offers more food security, as opposed to ones that provide soil fertility improvement or reductions in labor requirements.

As much as farmers expressed their concerns about *Striga* and the negative effect it has on their maize yield, the willingness to pay space suggests otherwise. Farmers were willing to sacrifice the highest maize yield loss for high legume yield (>27%), followed by low legume yield, high soil fertility improvement, and finally, lower *Striga* emergence. Strangely, farmers would need to be compensated for practices that received higher *Striga* more than any other attribute. Concern about higher *Striga* emergence may be out of fear of maize yield loss. Less concern for decreasing emergence may be that *Striga* is not viewed as a limiting factor to production as compared to input availability (e.g., fertilizer) or rainfall. That is, farmers do not believe *Striga* emergence has passed a limit (i.e., economic threshold level) where it should be controlled (Debrah, 1994). This view about the effect of *Striga* on maize may be attributed to two issues. First, *Striga* knowledge among farmers may be low. While the assessment of knowledge in the study was subjective, the majority of farmers scored very low ($\bar{x}$=5.1 out of 11). Second, farmers may not believe they have the means to control a stubborn weed such as *Striga*. In Ethiopia, smallholders abandoned fields long after they had discovered *Striga* and claimed they were well aware of the effect they pest had on their cereal crops (Tamado & Millberg, 2000). Prior to halting cultivation, numerous control practices had been disseminated for several years. The researchers found that abandonment was attributed to input availability and economic feasibility, not necessarily neglect. Malawian farmers may be faced with the same dilemma.

Further research is needed to assess barriers to *Striga* control implementation and drivers behind their decisions. These barriers may be due to any number of issues besides the obvious socioeconomic challenges cited in literature. As it became evident in this study, very few farmers were able to make the connection between the mechanism behind what increased or decreased *Striga* emergence. That is not to say farmers were not aware of *Striga* control practices, but they were unaware of *why Striga* emergence decreased when legumes were planted. Many times, creating the connection between a practice and its *effect* on a pest has shown to increase uptake of technologies (Oswald, 2005).

The study also encourages future choice experiment research to confirm findings and inform instruments with qualitative inquiry. Summary statistics and parametric tests can be limited in explaining the difference between male and female participant decisions, especially in the willingness to pay space. Many times, when qualitative and quantitative methods are used separately to analyze farmer decisions, findings are not generalizable or do not highlight the context-specific nuances, respectively. The addition of qualitative methods in the analysis unveiled different preferences between different farmer-types. Furthermore, qualitative inquiry helped determine whether quantitative findings had any internal validity (Barbour, 2001). Without focus groups and a thorough literature review, the results of this study may have been confounding. Consecutive mixed method approaches, therefore, may be valuable in explaining the tradeoffs farmers are willing to make to implement future agricultural technologies (Morse, 2005).

The following DCE allowed opportunities to present technologies to farmers they may not have seen, heard or used (e.g., *Striga*-resistant maize). Demonstration trials were not needed to elicit decisions about these relatively new or unknown control technologies. Choice experiments offer more economical avenues for researchers to evaluate technological preferences. The study also attempted to move beyond earlier methods (e.g., latent class models) that assess farming practice decisions which assume heterogeneous preferences across heterogeneous respondents (Birol et al., 2009). By assuming heterogeneity, the study enabled unbiased estimation of individual preferences while enhancing the accuracy of smallholder needs. Country-wide maize yields can be increased when the development and dissemination of agricultural practices are informed by a better understanding of smallholder preferences for specific attributes. Malawian farmers are unlikely to employ *Striga* control practices which exceed yield losses for attributes (e.g., lower labor requirements) they do not desire. With little uptake, *Striga* will likely continue to emerge and reduce maize yield in Malawi. Curtailing practices for specific smallholder groups encourages implementation, increasing maize yield and consequent food security (Boxall & Adamowicz, 2002).

APPENDICES

APPENDICES

APPENDIX 1. Focus Group Instrument

Objective: Discover traits of Striga control methods that are of most concern to smallholder farmers

Introduction: Today we are going to ask you about your knowledge and practices regarding weed management. The intention of this interview is to first, gather information so researchers can better understand Striga management strategies conducted by farmers like yourself. Then according to your description of these weed management strategies, determine reasons for your implementation and/or preference.

1. Are you familiar with Striga? If yes, what do you know about Striga (e.g., lifecycle, identification, effect on yield, seed transport)?

2. Have you ever faced challenges with Striga? When do you first notice Striga in your field (specifically at what physiological stage/height)?

3. If you've had Striga, how many years?

4. If you've seen Striga in your field, did it affect your maize yields? How much?

5. Are you <u>aware</u> of any practices used to **<u>treat</u>** Striga (e.g., manual pulling)? If so, please describe (e.g., timing, required inputs, etc.).

6. Are you <u>aware</u> of any practices used to **<u>prevent</u>** Striga (e.g., soil fertility techniques)? If so, please describe (e.g., timing, required inputs, etc.).

7. How did you hear about these practices? How did you learn about them (e.g., experimentation, extension, NGO, etc.)?

8. Would you consider any of these practices traditional? That is, agricultural extension, an NGO or an outside party did not promote them to you. They were passed on from generation to generation. Please indicate which ones.

9. Among the **treatment** practices you mentioned, do you implement any of them? If so, please describe (e.g., timing, required inputs, etc.). Among those you don't implement, why not?

10. Among the **preventative** practices you mentioned, do you implement any of them? If so, please describe (e.g., timing, required inputs, etc.). Among those you don't implement, why not?

11. What are some of the control methods you used because inputs were subsidized (or given free) to you? What were the inputs? Describe why you did them because the inputs were offered? Why wouldn't you do them without the inputs?

12. How do the treatment and preventative practices control Striga (e.g., reduce emergence the next season, remove before seeds are mature, etc.)? Essentially, what are the mechanisms or processes behind them that control Striga?

13. What goals or objectives do you take into account before choosing/implementing a Striga control practice? (Give the example of choosing a legume seed. You would perhaps look at taste, yield, cooking time, etc.)

14. Rank these traits from most important to least according to importance. Then, rank the practices you mentioned from most to least effective in controlling Striga.

15. Rank the methods you mentioned from most to least preferred. While they may be effective, we are trying to determine which ones are the practiced among farmers.

Date:____
Beginning Time:____
Ending Time:____
Location:____

Cholinga: *Kumvesesa za kaufiti ndi njira zothesera kaufiti zomwe alimi ang'onoang'ono amagwiritsa ntchito*

Mawu oyambirira: Lero timafuna tikambilane zomwe mumadziwa ndi kuchita zokhuzana ndi kasamalilidwe ka zomera zosafunika mmunda. Cholinga cha kucheza kwathu ndikufuna kupeza uthenga ofunika kuti anthu a kafufuku ngati ineyo amvesese mmene kaufiti amasamalilidwa ndi alimi ngati inuyo. Kutengera ndi zomwe mutafotokoze, ndifunsaso zifukwa zomwe munasankhira njira zomwe mukugwiritsa ntchito posamala ndi kuthana ndi zomera zomera zokha mmunda.

1. *Mukudziwapo kalikonse kokhudzana ndi kaufiti? Ngati eya, mukudziwa chani zokhuzana ndi kaufiti? (monga mayendedwe a moyo, maonekedwe ake, mmene zimakhuzira zokolola).*

2. *Mwakumanako ndi mavuto ena liwonse ndi kaufiti? Munamuzindikila ali potani mmunda mwanu? (kakulidwe, katalikidwe)*

3. *Ngati mwakumanako ndi mavuti ndi kaufiti, zachitika kwa zaka zingati?*

4. *Ngati munakhalako ndi kaufiti mmunda mwanu, anakhuzako zokolola zani? Zinakhuzika bwanji?*

5. *Mukudziwapo ndondomeko/njira ina iliyonse yomwe mungathe kuthana ndi kaufiti (monga kuzula pamanja)? ngati ilipo ifotokozeni (monga nthawi yoyenera, zipangizo zofunika)?*

6. *Mukudziwapo ndondomeko/njira ina iliyonse yomwe mumatsata poteteza kaufiti (monga njira zobwezeretsa nthaka)? ngati ilipo ifotokozeni? (monga nthawi yoyenera, zipangizo zofunika)?*

7. *Munadziwa bwanji za ndondomeko zimenezi? Munaziphunzira bwanji? (monga kuyesela, alangizi, mabungwe ndi ena otero)*

8. *Pa ndondomeko/njira zimenezi, ndi ziti zomwe zili zamakolo? Kutanthauza kuti alangizi, mabungwe kapena anthu ena obwera sanazakuphunzitseni. Izi ndi njira zomwe zakhala zikutsatidwa ndi mibadwa yonse.*

9. *Pa ndondomeko/njira zothana ndi kaufiti zomwe mwatchulazi, mukugwiritsa ntchito ziti? Chonde fotokozani zomwe mukugwiritsa ntchito (monga nthawi yoyenera, zipangizo zofunika ndi zina zotero). Pa zomwe simukugwiritsa ntchito, ndi chifukwa chani simukuzigwiritsa ntchito?*

10. *Pa ndondomeko/njira zoteteza kaufiti zomwe mwatchulazi, mukugwiritsa ntchito ziti? Chonde fotokozani zomwe mukugwiritsa ntchito (monga nthawi yoyenera, zipangizo zofunika ndi zina zotero). Pa zomwe simukugwiritsa ntchito, ndi chifukwa chani simukuzigwiritsa ntchito?*
11. *Ndi ndondomeko ziti zothana ndi kaufiti zomwe munagwiritsa ntchito chifukwa zipangizo zinali zotsika mtengo mokuthanidzani kapena zinapatsidwa mwaulele? Zinali zipangizo zanji? Fotokozni chifukwa chimene munagwiritsa ntchito njirazi chifukwa zipangizo munapatsidwa mwa ulele? Ndi chifukwa chani simukanatsatila ndondomeko/njira zi popanda zipangizo zimenezi?*

12. *Ndondomekozi/ njirazi zinathana kapena zinateteza bwanji kaufiti? (monga kuchepesa kumera kwa kaufiti mu chaka china, kuthana nazo zisanayambe njere)*

13. *Ndi zinthu ziti zomwe mumaona musane sankhe ndondomeko/ njira yothana ndi kaufiti? (pelekani chitsanzo: mukamasankha mbewu ya mtundu wa nyemba mumaona kakomedwe kake, zokolola komanso nthawi yomwe zimatenga kuti zipsye)*

14. *Ikani zinthu zomwe mumaganizira musanasankhe ndondomeko/ njira yothana ndi kaufiti mu dongosolo kuyambira yofunika kwambiri kumalizira yosafunika. Mukatero, ikani ndondomeko/ njira zomwe munatchula zothana ndi kaufiti mu dongosolo kuyambila yomwe imagwira kwambiri kumalizila yosagwira bwino*

15. *Ikani ndondomeko/ njira zothana ndi kaufiti mu dongosolo kuyambira zomwe zimakondedwa pakati pa alimi kumalizira ndi zomwe sizikondwedwa. Njira zina zitha kukhala zogwira kwambiri koma tikufuna tidziwe zomwe alimi ambiri amakonda kugwiritsa ntchito*

   Tsiku:

   Nthawi yoyambila:

   Nthawi yomalizira:

   Malo:

APPENDIX 2. Survey Instrument

Informed Consent

Enumerator (say to respondent): Today we will be asking you about your knowledge about Striga and its control practices. You can contact Timothy Silberg or the Institutional Review Board at Michigan State University and/or withdraw from the study without penalty at any time.
Wofunsa (nenani kwa wofunsidwa): Lero tikufunsani za mmene mumadziwira kaufiti komanso njira zotetezera kaufiti. Mutha Kulumikizana ndi a Timothy Silberg kapena Komiti imene imawayang'anira ku Michigan State University komanso muli ndi ufulu wosiya kuyankha mafunso ndipo palibe chilango chilichonse pochita izi.

Section A. Basic member & household characteristics

1. District:____
2. EPA: ____
3. Respondent Name, Age, Gender & Education: _________________________
4. Village: ____
5. Date: ____
6. Enumerator: ____
7. Household identification (HHID):________________________________

Section B. Perceptions and awareness of Striga

8. Are you familiar with Striga? **Y** **N**
Mumadziwa tchire la mmunda lotchedwa kaufiti?
9. Can you visibly tell the difference between annual weeds and Striga? **Y** **N**
Mungathe kusiyanitsa pakati pa tchire lina (udzu wa mmunda) ndi kaufiti?
   a. If YES, how can you identify Striga among annual weeds?
(List up to three) (**Code A)______________________________**
Ngati ndi choncho, mungamudziwe bwanji kaufiti pakati pa tchire la mtundu wina uliwonse?
10. Do you find there is a difference between the ways annual weeds affect your maize yield versus the way Striga affects your maize yield? **Y** **N**
Mumatha kusiyanitsa mmene tchire lina lonse limavutitsira chimanga kuyerekeza ndi mmene kaufiti amachitira?
   a. If YES, how so? (List up to three) (**Code B)________________________**
Ngati ndi choncho, zimasiyana bwanji?
11. Can you visibly tell where Striga is in your field before it emerges? **Y** **N**
Muli ndi kuthekera kodziwa kuti pamalo pali kaufiti ngakhale asanamere?
   a. If YES, how can you tell Striga is present before it emerges from the soil?
(List up to three) (**Code C)__________________________**
Ngati ndi choncho, mumadziwa bwanji?
12. Are you aware how Striga attacks maize? **Y** **N**
Mumadziwa mmene kaufiti amaonongera chimanga chathu?
   a. If YES, please describe (List up to three) (**Code D)________________**
Ngati ndi choncho, fotokozerani
13. What does **the enumerator** consider their general knowledge of Striga is? (Circle one)
Wofunsa akuwona kuti woyankha akumudziwa bwanji kaufiti? (zungulizani chimodzi)

0 **1** **2** **3**

(Unaware) (Little Knowledge) (Some Knowledge) (Very Knowledgeable) *Sakumudziwa* *Akumudziwa pang'ono* *Akumudziwa ndithu* *Akumudziwa kwambiri*

Section C. Striga history & impact

14. Please indicate the number of fields you cultivated this past season where maize was the primary crop (#)____
Pa minda imene munalima ndi ingati imene chimanga chinatenga gawo lalikulu m'chaka chapitachi?
   a. How many fields had Striga? (#)____________________________________
Ndi minda ingati imene munamera kaufiti?

High Fertility Plot

15. Did this plot have striga?
Munganene kuti kaufiti ndi vuto lalikulu pa ulimi wanu? **Y** **N**
***Note- If farmer responds NO, please go to #20)**
****Ngati mlimi ayankha kuti ayi, pitani ku funso #20)***
   a. If **YES**, what year did these challenges begin?__________________________
Ngati ndi choncho, vutoli linayamba m'chaka chiti?

16. Comment on Striga emergence on the plot.
Mundiuzeko za kameredwe ka kaufiti mu minda imene ili ndi vutoli?
   a. Striga emergence was patchy **Y** **N**
Kaufiti anamera patalipatali
      i. Please comment on the soil conditions of this plot
(List up to four) (**Code E**)____________________________________
Nthaka ndiyotani mmindayi?
   b. Striga emergence extended across the entire plot **Y** **N**
Kaufiti anamera m'munda wonse?
      i. Please comment on the soil conditions of this plot
(List up to four) (**Code E**)____________________________________
Nthaka ndiyotani mmindayi?

17. Now think about this season.
Mwa minda mwatchulayi, ndi chaka chiti chimene mudayamba kuonamo kaufiti?
   a. What month and week did you plant maize?__________________________
Tchulani mwezi komanso sabata imene munadzala chimanga?
   b. Did the maize plant begin to wilt before you saw Striga?
Mbewu yanu ya chimanga inayamba kufota kaufiti asanamere? **Y** **N**
      i. What month and week did the maize begin to wilt? *Ndi mwezi komanso sabata iti mmene chimanga chanu chinayamba kufota?*________________week #/month #)
      ii. At what physiological stage did the maize begin to wilt?
   (List 1) (**Code F**)____
   Chimanga chinayamba kufota chitakula bwanji/motani?

18. Now think about once Striga emerged.
Taganizani mmene kaufiti anamera.
   a. What week (#) and month (#) did you begin seeing Striga **emerge** from the soil?____
Unali mwezi uti komanso sabata iti mmene kaufiti anayamba kumela?

b. At what physiological stage was the maize when Striga emerged?
(List 1) (**Code F)**____
Chimanga chinali chitakula bwanji/motani mmene kaufiti amaonekera?
c. Please comment on the health of maize once Striga emerged
(List up to three) (**Code G)**_______________________________________
Thanzi la chimanga linali bwanji mmene kaufiti amamera?

19. Was there a cob at harvest? **Y** **N**
Chimanga chinali chili ndi tiana mmene kaufiti amamera?
a. If YES, please comment on cob size at harvest
(List up to 3) (**Code G**)____________________________________
Ngati ndi choncho, Zisononkho zinali zazikulu bwanji pa nthawi yokolola?
b. **That season,** what yield did you receive compared to others that did not have Striga (List 1) (**Code H**)________________________
Munakolola zochuluka bwanji poyerekezera ndi zaka mmbuyomu (mmene munalibe kaufiti)?

***Note – If farmer states that all fields had Striga, ask them how their yields compared to those of their neighbors**

Ngati mlimi wanena kuti minda yonse inali ndi kaufiti, afunseni za zokolola zawo poyerekeza ndi minda yoyandikana nayo.

c. In addition to Striga, did you face any other challenges on this plot related to productivity?
Panalinso mavuto ena omwe anakhudza ulimi wanu kupatulapo vuto la kaufiti?
Y **N**
I.List up to 3 (**Code I**)________________________

Low Fertility Plot

20. Did this plot have striga?
Munganene kuti kaufiti ndi vuto lalikulu pa ulimi wanu? **Y** **N**
***Note- If farmer responds NO, please go to #25)**
Ngati mlimi ayankha kuti ayi, pitani ku funso #25)
a.If **YES**, what year did these challenges begin?________________________
Ngati ndi choncho, vutoli linayamba m'chaka chiti?

21. Comment on Striga emergence on the plot.
Mundiuzeko za kameredwe ka kaufiti mu minda imene ili ndi vutoli?
a. Striga emergence was patchy **Y** **N**
Kaufiti anamera patalipatali
i.Please comment on the soil conditions of this plot
(List up to four) (**Code E**)___________________________________
Nthaka ndiyotani mmindayi?
b. Striga emergence extended across the entire plot **Y** **N**
Kaufiti anamera m'munda wonse?
i.Please comment on the soil conditions of this plot
(List up to four) (**Code E**)___________________________________
Nthaka ndiyotani mmindayi?

22. Now think about this season.
Mwa minda mwatchulayi, ndi chaka chiti chimene mudayamba kuonamo kaufiti?
a. What month and week did you plant maize?________________________

Tchulani mwezi komanso sabata imene munadzala chimanga?

b. Did the maize plant begin to wilt before you saw Striga?

Mbewu yanu ya chimanga inayamba kufota kaufiti asanamere? **Y** **N**

i. What month and week did the maize begin to wilt? *Ndi mwezi komanso sabata iti mmene chimanga chanu chinayamba kufota?*________________week #/month #)

ii. At what physiological stage did the maize begin to wilt?

(List 1) (**Code F**)____

Chimanga chinayamba kufota chitakula bwanji/motani?

23. Now think about once Striga emerged.

Taganizani mmene kaufiti anamera.

a. What week (#) and month (#) did you begin seeing Striga **emerge** from the soil?____

Unali mwezi uti komanso sabata iti mmene kaufiti anayamba kumela?

b. At what physiological stage was the maize when Striga emerged?

(List 1) (**Code F)**____

Chimanga chinali chitakula bwanji/motani mmene kaufiti amaonekera?

c. Please comment on the health of maize once Striga emerged

(List up to three) (**Code G)**____

Thanzi la chimanga linali bwanji mmene kaufiti amamera?

24. Was there a cob at harvest? **Y** **N**

Chimanga chinali chili ndi tiana mmene kaufiti amamera?

a. If YES, please comment on cob size at harvest

(List up to 3) (**Code G**)_____________________________________

Ngati ndi choncho, Zisononkho zinali zazikulu bwanji pa nthawi yokolola?

b. **That season,** what yield did you receive compared to others that did not have Striga (List 1) (**Code H**)_________________________

Munakolola zochuluka bwanji poyerekezera ndi zaka mmbuyomu (mmene munalibe kaufiti)?

***Note – If farmer states that all fields had Striga, ask them how their yields compared to those of their neighbors**

Ngati mlimi wanena kuti minda yonse inali ndi kaufiti, afunseni za zokolola zawo poyerekeza ndi minda yoyandikana nayo.

c. In addition to Striga, did you face any other challenges on this plot related to productivity?

Panalinso mavuto ena omwe anakhudza ulimi wanu kupatulapo vuto la kaufiti?

Y **N**

i. List up to 3 (**Code I**)_________________________

Section D. Methods used to address Striga

25. Enumerator (say to respondent): Now I'm going to ask you some questions about treatment practices you have heard about that control Striga. A treatment practice involves the removal of Striga once it has emerged from the soil.

25a. What treatment practices have you heard? (*Ndi njira ziti zothana ndi kaufiti zomwe munamvapo?)*	25b.When did you hear about them? (*Munazimva liti?)*	25c. How did you hear about them? (*Munazimva bwanji?)*	25d. What were the benefits you heard about? (*Munamva kuti ubwino wake ndiwotani?)*

CODE J	CODE K	CODE L	CODE M
i. 1st Practice	i. Years ago	i. (List up to 3)	i. (List up to 3)
ii. 2nd Practice	ii. Years ago	ii. (List up to 3)	ii. (List up to 3)
iii. 3rd Practice	iii. Years ago	iii. (List up to 3)	iii. (List up to 3)
iv. 4th Practice	iv. Years ago	iv. (List up to 3)	iv. (List up to 3)

Wofunsa (nenani kwa wofunsidwa): Tsopano, ndikufuna ndikufunseni mafunso okhudzana ndi njira zothana ndi kaufiti zomwe munamvapo. Njira yothana ndi kaufiti ndi iyo yomwe imatengera mlimi kuchotsa kaufiti akamera mmunda mwake.

26. Enumerator (says to respondent): Next, I would like to ask some questions about the treatment practices you have implemented. Please indicate those that you've implemented across an entire field.
Wofunsa (Nenani kwa wofunsidwa): Tsopano, ndikufuna ndikufunseni mafunso okhudzana ndi njira zothana ndi kaufiti zomwe munagwiritsapo ntchito. Muonenetsetse kuti mwatidziwitsa njira zomwe munazigwiritsa ntchito m'munda wonse.

26a. What treatment practices did you implement? *Ndi njira ziti zothana ndi kaufiti zomwe munazitsatira?* **CODE N**	26b. When did you first begin implementing them? *Munayamba kuzitsatira liti?*	26c. What did you do with the Striga? *Kaufiti amene munamuchotsayo munapanga naye chiyani?* **CODE O**	26d. What happened (in terms of Striga control and secondary benefits)? *Chinachitika n'chiyani (kumbali yoteteza kaufiti komanso ubwino wake kuposera apo)?* **CODE P**	26e. How many seasons did it take for you to see these results? *Panapita zaka zingati kuti inu muyambe kuona zotsatira?* **CODE Q**	26f.Did you stop or continue the practice after seeing these results? *Munasiya kapena kupitiriza njirazo mutaona zotsatira zakezo?*	26g. Why did you stop or continue the practice? **CODE P**
i. 1st Practice	i. Year	i. (List up to 2)	i. (List up to 3)	i.	i. Stop (0) / Continue (1)	i. (List up to 3)
ii. 2nd Practice	ii. Year	ii. (List up to 2)	ii. (List up to 3)	ii.	ii. Stop (0) / Continue (1)	i. (List up to 3)
iii. 3rd Practice	iii. Year	iii. (List up to 2)	iii. (List up to 3)	iii.	iii. Stop (0) / Continue (1)	i. (List up to 3)
iv. 4th Practice	iv. Year	iv. (List up to 2)	iv. (List up to 3)	iv.	iv. Stop (0) / Continue (1)	i. (List up to 3)

27. Enumerator (says to respondent): Also, I would like to know whom you shared the positive/negative results from implementing these practices.
Wofunsa (Nenani kwa wofunsidwa): komanso, ndimafuna nditadziwa kuti munauza ndani za zotsatira zabwino/zoipa za njira zimene munatsatirazo.

***Note - Before asking farmers who they shared results with, transcribe the control practices they mentioned and their respective outcomes from question 26a and 26b in column 27a and 27b, respectively.**
****Musanawafunse alimi za amene anawauza za zotsatira, akumbutseni za njira zothana ndi kaufiti ndi zotsatira zake zimene azitchula mu mafunso 26a ndi 26b mu ndandanda 27a ndi 27b.***

27a. Treatment practice **(Refer to 26a)** *Njira yothana ndi kaufiti (muonere funso 26a)*	27b. List of outcomes **(Refer to 26d)** *Zotsatira (muonere funso 26b)*	27c. Who did you share these results with? *Munauzako ndani za zotsatira?* **CODE R**	27d. How many? *Munawauza zotsatira zingati?* **CODE S**
i. 1st Practice	i.1.	i.1.	i.1.
	i.2.	i.2.	i.2.
	i.3.	i.3.	i.3.
ii. 2nd Practice	ii.1.	ii.1.	ii.1.
	ii.2.	ii.2.	ii.2.
	ii.3.	ii.3.	ii.3.
iii. 3rd Practice	iii.1.	iii.1.	iii.1.
	iii.2.	iii.2.	iii.2.
	iii.3.	iii.3.	iii.3.
iv. 4th Practice	iv.1.	iv.1.	iv.1.
	iv.2.	iv.2.	iv.2.
	iv.3.	iv.3.	iv.3.

28. Enumerator (says to respondent): Finally, I want to know about the practices you haven't implemented, but would have liked to in the past or in the future.
Wofunsa (Nenani kwa wofunsidwa): Pomaliza, ndimafuna nditadziwa za njira zomwe simunathe kuzitsatira koma mukanakonda mukanatsata m'mbuyomu kapena mtsogolomu

***Note – Make sure no practice listed in column 28a was listed in 27a.**
****Wonetsetsani kuti njira zotchulidwa mu mndandanda wa mayankho a 28a zisafanane ndi njira zomwe zatchulidwa kale mu mdandanda wa mayankho a 27a.***

28a. What treatment practices would you have like to have implemented in the past, but couldn't? *Ndi njira ziti zothana ndi kaufiti mukadakonda mukadatsatira mmbuyomu koma simunathe kutero?* **CODE T**	28b. What was the reason you could not implement the treatment practice? *N'chifukwa chiyani simunathe kutsatira njira yothana ndi kaufitiyi?* **CODE U**
i. 1st Practice	i. (List up to 3)
ii. 2nd Practice	ii. (List up to 3)
iii. 3rd Practice	iii. (List up to 3)
iv. 4th Practice	iv. (List up to 3)

29. Enumerator (says to respondent): Now I would like to ask you about some practices you have heard about that prevent Striga. These practices are different from the previous ones you mentioned earlier. These practices would be implemented before you see Striga so it will not emerge from the soil in the future. There are multiple ways you can prevent Striga. Some practices you may have heard of, but are not aware of or consider them as preventative practices. These include soil fertility management practices, which improve soil texture, decrease acidity and increase nitrogen/phosphorous in the soil. Essentially, these practices enhance soil fertility. In doing so, these practices make less favorable soil conditions for Striga to spread.

Wofunsa (Nenani kwa wofunsidwa): Tsopano ndikufunsani za njira zina zomwe munamva zomwe zimateteza kaufiti mminda mwanu. Njirazi ndi zosiyana ndi zomwe mwatchula kale. Njirazi zingatsatidwe kaufiti asanamere mmunda mwathu ndi cholinga chokuti kaufitiyo asamere mtsogolomu. Pali njira zosiyanasiyana zomwe mungapewere kaufiti. Pali njira zina zoti munazimvapo, koma simukuzidziwa mmene zimatsadwira kapena kuzitenga ngati njira zopewera kaufiti. Izi ndi monga kupititsa chonde patsogolo, zomwe zimathandizira kuti nthaka isakanikilike bwino, kuchepetsa michere yowononga komanso kuonjezera Michele yomwe ili yofunikira pa kakulidwe ka mbeu zathu.chachikulu n'chakuti njirazi zimapititsa patsogolo chonde mu nthaka yathu. Potero, njirazi zimapanga nthaka yathu kuti isalore kaufiti kuti afalikire mmunda mwathu.

29a. What preventative practices have you heard? *Ndi njira ziti zopewera kaufiti zomwe munazimvapo?* **CODE V**	29b. When did you hear about them? *Munazimva liti?* **CODE W**	29c. How did you hear about them? *Munazimva kudzera mu njira yanji?* **CODE X**	29d. What were the benefits you heard about? *Ndi ubwino wanji wa njirazi umene munamva?* **CODE Y**
i. 1st Practice	i. Years ago	i. (List up to 3)	i. (List up to 3)
ii. 2nd Practice	ii. Years ago	ii. (List up to 3)	ii. (List up to 3)
iii. 3rd Practice	iii. Years ago	iii. (List up to 3)	iii. (List up to 3)
iv. 4th Practice	iv. Years ago	iv. (List up to 3)	iv. (List up to 3)
v. 5th Practice	v. Years ago	v. (List up to 3)	v. (List up to 3)
vi. 6th Practice	vi. Years ago	vi. (List up to 3)	vi. (List up to 3)

30. Enumerator (says to respondent): Next, I would like to ask some questions about some preventative practices you have implemented. Please indicate those that you've implemented across an entire field.
Wofunsa (Nenani kwa wofunsidwa): Tsopano ndikufuna ndifunse mafunso okhudzana ndi zina mwa njira zopewera kaufiti zomwe munagwiritsapo ntchito. Chonde tidziwitseni njira zomwe munazitsatira m'munda wonse.

30a. What preventative practices did you implement? *Ndi njira ziti zopewera kaufiti zomwe munagwiritsapo ntchito?* **CODE Z**	30b. When did you first begin implementing them? *Munayamba kuzigwiritsa ntchito liti?*	30c. What happened (in terms of Striga control and secondary benefits)? *Chinachitika n'chiyani (kumbali yoteteza kaufiti komanso ubwino wake kuposera apo)?* **CODE AA**	30d. How many seasons did it take for you to see these results? *Zinatengera zaka zingati kuti inu muyambe kuona zotsatira?* **CODE BB**	30e.Did you stop or continue the practice after seeing these results? *Munasiya kapena kupitiriza njirazo mutaona zotsatira zakezo?*	30f. Why did you stop or continue? *Chinachitika n'chiyani (kumbali yoteteza kaufiti komanso ubwino wake kuposera apo)?* **CODE AA**
i. 1st Practice	i. Year	i. (List up to 3)	i. (List up to 1)	i. Stop (0) / Continue (1)	i. (List up to 3)
ii. 2nd Practice	ii. Year	ii. (List up to 3)	ii. (List up to 1)	ii. Stop (0) / Continue (1)	ii. (List up to 3)
iii. 3rd Practice	iii. Year	iii. (List up to 3)	iii. (List up to 1)	iii. Stop (0) / Continue (1)	iii. (List up to 3)
iv. 4th Practice	iv. Year	iv. (List up to 3)	iv. (List up to 1)	iv. Stop (0) / Continue (1)	iv. (List up to 3)
v. 5th Practice	v. Year	v. (List up to 3)	v. (List up to 1)	v. Stop (0) / Continue (1)	v. (List up to 3)
vi. 6th Practice	vi. Year	vi. (List up to 3)	vi. (List up to 1)	vi. Stop (0) / Continue (1)	vi. (List up to 3)

31. Enumerator (says to respondent): Also, I would like to know whom you shared the positive/negative results from implementing these practices.
Wofunsa (nenani kwa wofunsidwa): Komanso, ndimafuna nditadziwa kuti munauzako ndani za zotsatira zabwino/zoipa kuchokera njira zimenezi.

***Note - Before asking farmers who they shared results with, transcribe the control practices the mentioned and their respective outcomes from question 30a and 30b in column 31a and 31b, respectively.**
****Musanafunse alimi za omwe anawauza za zotsatira, akumbutseni za njira zothana ndi kaufiti ndi zotsatira zake zomwe anatchula kale mu mafunso 30a ndi 30b komanso mu ndandanda wa 31a ndi 31b.***

31a. Preventative practice **(Refer to 30a)** *Njira zopewera kaufiti (Onerani funso 30a)*	31b. List of outcomes **(Refer to 30c)** *Ndandanda wa zotsatira (onerani funso 30b)*	31c. Who did you share these results with? *Munauza ndani za zotsatirazi?* **CODE CC**	31d. How many? *zingati?* **CODE DD**
i. 1st Practice	i.1.	i.1.	i.1.
	i.2.	i.2.	i.2.
	i.3.	i.3.	i.3.
ii. 2nd Practice	ii.1.	ii.1.	ii.1.
	ii.2.	ii.2.	ii.2.
	ii.3.	ii.3.	ii.3.
iii. 3rd Practice	iii.1.	iii.1.	iii.1.
	iii.2.	iii.2.	iii.2.
	iii.3.	iii.3.	iii.3.
iv. 4th Practice	iv.1.	iv.1.	iv.1.
	iv.2.	iv.2.	iv.2.
	iv.3.	iv.3.	iv.3.
v. 5th Practice	v.1.	v.1.	v.1.
	v.2.	v.2.	v.2.
	v.3.	v.3.	v.3.
vi. 6th Practice	vi.1.	vi.1.	vi.1.
	vi.2.	vi.2.	vi.2.
	vi.3.	vi.3.	vi.3.

32. More specifically, I would like to know where you receive your inputs from to complete the preventative practices you mentioned.
Makamaka, ndimafuna nditadziwa kuti zipangizo za ulimi zomwe munagwiritsa ntchito popewa kaufiti munazipeza kuti?
***Note - Before asking farmers about the sources of their inputs, transcribe the control practices they mentioned from question 31a in column 32a.**
****Musanafunse alimi za kumene anapeza zipangizo zawo, akumbutseni za njira zopewera zimene anatchula mu mafunso 31a mu ndandanda was 32a.***

32a. Preventative practice **(Refer to 31a)** *Njira zopewera Kaufiti 31a*	32b. Week & Month *Sabata ndi mwezi*	32c. Specify crop if rotation/ intercropping listed *Tchulani mbeu ngati mwayidzala mwa kasinthasintha kapena kasakaniza* **CODE EE**	32d. Specify seed source if rotation/ intercropping listed *Mundiuze za kumene munapeza mbeu (ngati kasinthasintha/ kasakaniza zatchulidwa)* **CODE FF**	32e. Specify type of fertilizer or manure if fertilizer/ manure application was listed *Mundiuze mtundu wa fetereza kapena manyowa (ngati fetereza/manyowa zatchulidwa)* **CODE GG**	32f. Specify source of fertilizer or manure if fertilizer/ manure application was listed *Mundiuze za kumene munapeza fetereza/manyowa (ngati zinatchulidwa)* **CODE HH**	32g. How was the fertilizer/ manure incorporated? *Fetereza/ manyowa anathiridwa motani?* **CODE II**
i. 1st practice	i.1. Week # i.2. Month #	i. (List up to 3)	i. (List up to 3)	i. (List up to 3)	i. (List up to 3)	i.1. Degraded Y N i.2. (List up to 2)
ii. 2nd practice	ii.1. Week # ii.2. Month #	ii. (List up to 3)	ii. (List up to 3)	ii. (List up to 3)	ii. (List up to 3)	ii.1. Degraded? Y N ii.2. (List up to 2)
iii. 3rd practice	iii.1. Week # iii.2. Month #	iii. (List up to 3)	iii. (List up to 3)	iii. (List up to 3)	iii. (List up to 3)	iii.1. Degraded? Y N iii.2. (List up to 2)
iv. 4th practice	iv.1. Week # iv.2. Month #	iv. (List up to 3)	iv. (List up to 3)	iv. (List up to 3)	iv. (List up to 3)	iv.1. Degraded? Y N iv2. (List up to 2)
v. 5th practice	v.1. Week # v.2. Month #	v. (List up to 3)	v. (List up to 3)	v. (List up to 3)	v. (List up to 3)	v.1. Degraded? Y N v.2. (List up to 2)
vi. 6th practice	vi.1. Week # vi.2. Month #	vi. (List up to 2)	vi. (List up to 3)	vi. (List up to 3)	vi. (List up to 3)	vi.1. Degraded? Y N vi.2. (List up to 2)

33. Enumerator (says to respondent): I want to know about the practices you haven't implemented, but would have liked to in the past or in the future.
Wofunsa (Nenani kwa wofunsidwa): Pomaliza, ndimafuna nditadziwa za njira zimene simunathe kuzitsatira, koma mukanakonda mutazitsatira.
***Note – Make sure no practice listed in column 32a was listed in 33a.**
****Wonetsetsani kuti njira zatchulidwa mu ndandanda 32a zisafanane ndi zimene zatchulidwa mu 33a.***

33a. What preventative practices would you have like to have implemented in the past, but couldn't? *Ndi njira ziti zopewera kaufiti zomwe mukadakonda mutazitsata m'mbuyomu koma simunathe kutero?* **CODE JJ**	33b. Specify type of manure or fertilizer if farmer mentioned manure/ fertilizer application *Mundiuze mtundu wa fetereza kapena manyowa (ngati fetereza/manyo wa zatchulidwa)* **CODE KK**	33c. Specify seed if farmer mentioned intercropping/crop rotation *Tchulani mtundu wa mbeu (ngati mlimi watchula mbeu)* **CODE LL**	33d. What was the reason you could not implement the preventative practice? Ndi chifukwa chiyani munakanika kutsatira njira yopewera kaufiti? **CODE MM**
i. 1st Practice	i. (List up to 2)	i. (List up to 2)	i. (List up to 3)
ii. 2nd Practice	ii. (List up to 2)	ii. (List up to 2)	ii. (List up to 3)
iii. 3rd Practice	iii. (List up to 2)	iii. (List up to 2)	iii. (List up to 3)
iv. 4th Practice	iv. (List up to 2)	iv. (List up to 2)	iv. (List up to 3)
v. 5th Practice	v. (List up to 2)	v. (List up to 2)	v. (List up to 3)
vi. 6th Practice	vi. (List up to 2)	vi. (List up to 2)	vi. (List up to 3)

34. Enumerator (says to respondent): Finally, I would like to know about some soil fertility practices you implemented before Africa RISING arrived. Please indicate those that you've implemented across an entire field.
Wofunsa (Nenani kwa wofunsidwa): Tsopano ndikufuna ndifunse mafunso okhudzana ndi zina mwa njira zopewera kaufiti zomwe munagwiritsapo ntchito. Chonde tidziwitseni njira zomwe munazitsatira m'munda wonse.

34a. What soil fertility practices did you implement? *Ndi njira ziti zopewera kaufiti zomwe munagwiritsapo ntchito?* **CODE JJ**	34b. How did you hear about them? *Munazimva kudzera mu njira yanji?* **CODE X**	34c. When did you hear about them *Sabata ndi mwezi?*	34d. After hearing about them, how long did it take until you fully implemented them across an entire field?
i. 1st Practice	i. (List up to 3)	i. Year	i. Years
ii. 2nd Practice	ii. (List up to 3)	ii. Year	ii. Years
iii. 3rd Practice	iii. (List up to 3)	iii. Year	iii. Years
iv. 4th Practice	iv. (List up to 3)	iv. Year	iv. Years
v. 5th Practice	v. (List up to 3)	v. Year	v. Years
vi. 6th Practice	vi. (List up to 3)	vi. Year	vi. Years

Section E. Food and labor preferences

Enumerator (says to respondent): I'm going to present to you several scenarios where you have to choose between cultivating a monoculture of maize or another cropping system across **1 ha**.
Wofunsa (Nenani kwa wofunsidwa): Tsopano ndikuyerekezerani njira zingapo zosiyanasiyana ndipo mukuyenera kusankhapo imodzi pakati pa kalimidwe ka chimanga pachokha kapena kalimidwe ka mtundu wina pa munda wokwana hekitala imodzi.

35. Enumerator (says to respondent): Suppose you have the choice of accepting 20 (50kg) bags of traditional maize (Option A) or a less amount of early-maturing maize (Option B). There is a chance you may not be able to receive 20 bags of traditional maize. With the early maturing maize, however, you will receive the specified amount (e.g., 15 bags) without a chance of losing it to Striga.
Wofunsa (Nenani kwa wofunsidwa): Tingoyerekeza mwapatsidwa mwayi wolandira matumba 20 (a 50kg) a chimanga cha makolo (chisankho A) kapena chimanga chocheperapo koma chocha msanga (chisankho B).
***Note- Do NOT show this table to the farmer. You will present the choices in an iterative manner. State the first tradeoff (e.g., "Would you take a sure-yield of 15 bags of early maturing maize/ha or try for 20 bags/ha of traditional maize?"). If they do not select the first choice, then present T2.**
******Musaonetse zimene mukufunsazi kwa mlimi. Mudzifunsa zisankhozi polankhulana basi. Tchulani kasinthanitsa woyamba (mwachitsanzo, Mungatenge zokolola zotsimikizika zokwana matumba***

15 a chimanga chocha msanga pa hekitala kapena mungafune matumba 20 pa hekitala a chimanga cha makolo?). Ngati sasankha chisankho choyamba, afunseni kasinthanitsa T2

Choice	Option A *Chisankho A* (Traditional Maize) (*Chimanga cha makolo)*	Option B *Chisankho B* (Early-maturing maize) *(Chimanga chocha msanga)*
T1	☐ 20 Bags	☐ 15 Bags
T2	☐ 20 Bags	☐ 16 Bags
T3	☐ 20 Bags	☐ 17 Bags
T4	☐ 20 Bags	☐ 18 Bags
T5	☐ 20 Bags	☐ 19 Bags
T6	☐ 20 Bags	☐ 20 Bags

If Option B was not chosen, how many bags would it take for them to switch:________
*Ngati B wasankhidwa, zatengera matumba angati m'chaka choyamba kuti mlimi asinthe maganizo:*______

36. Suppose you have the choice of accepting 20 (50kg) bags of traditional maize **for each season for two years** (Option A) or a larger amount of food in if you **intercrop** pigeon pea and maize within the same field (Option B). For each of the six choice sets presented, check the box for the option you prefer?
Tingoyerekeza mwapatsidwa mwayi wolandira matumba 20 (a 50 kg) a chimanga cha makolo m'chaka chilichonse kwa zaka ziwiri (chisankho A) kapena matumba ochulukirapo a chakudya mu chaka choyamba kapena chachiwiri ngati mungalime chimanga ndi nandolo mwa kasakaniza m'munda womwewo (Chisankho B). Pa chisankho chilichonse mwa zisankho zisanu n'chimodzi, chongani mu bokosi lomwe likusonyeza chisankho cha mlimi.
Note – Emphasize that both crops are planted simultaneously, but pigeon pea matures later into the season once the farmers have harvested maize.
Tsimikirani mfundo yokuti mbeu zonsezo zimadzalidwa pa kamodzi, koma kaufiti amakhwima mochedwerapo alimi atakolora kale chimanga.

Choice	Option A (Maize Monoculture)	Option B (Maize-Pigeon Pea Intercrop)
T1	☐ 20 Maize Bags	☐ 15 Maize Bags + 7 Pigeon Pea Bags
T2	☐ 20 Maize Bags	☐ 16 Maize Bags + 7 Pigeon Pea Bags
T3	☐ 20 Maize Bags	☐ 17 Maize Bags + 7 Pigeon Pea Bags
T4	☐ 20 Maize Bags	☐ 18 Maize Bags + 7 Pigeon Pea Bags
T5	☐ 20 Maize Bags	☐ 19 Maize Bags + 7 Pigeon Pea Bags
T6	☐ 20 Maize Bags	☐ 20 Maize Bags + 7 Pigeon Pea Bags

If Option B was chosen, how many bags in year one, would it take for them to switch:___________
Ngati B wasankhidwa, zatengera matumba angati m'chaka choyamba kuti mlimi asinthe maganizo:______

37. Suppose you have the choice of accepting 20 (50kg) bags of traditional maize **for each season for two years** (Option A) or a larger amount of maize in a **second season** if you cultivate sole soybean the first year (Option B). For each of the six choice sets presented, check the box for the option you prefer?
Tingoyerekeza mwapatsidwa mwayi wolandira matumba 20 (a 50 kg) a chimanga cha makolo m'chaka chilichonse kwa zaka ziwiri kapena matumba ochulukirapo a chimanga mu chaka chachiwiri ngati mungalima soya payekha m'chaka choyamba. Pa chisankho chilichonse mwa zisankho zisanu n'chimodzi, chongani mu bokosi lomwe likusonyeza chisankho cha mlimi.

Choice	Option A *Chisankho A* (Maize 1st Season -> Maize 2nd Season)	Option B *Chisankho B* (Soybean 1st Season -> Maize 2nd season)
T1	☐ 20 Maize -> 20 Maize Bags	☐ 30 Soybean -> 26 Maize Bags
T2	☐ 20 Maize -> 20 Maize Bags	☐ 30 Soybean -> 28 Maize Bags
T3	☐ 20 Maize -> 20 Maize Bags	☐ 30 Soybean -> 30 Maize Bags
T4	☐ 20 Maize -> 20 Maize Bags	☐ 30 Soybean -> 32 Maize Bags
T5	☐ 20 Maize -> 20 Maize Bags	☐ 30 Soybean -> 34 Maize Bags
T6	☐ 20 Maize -> 20 Maize Bags	☐ 30 Soybean -> 36 Maize Bags

If Option B was not chosen, how many bags in year two, would it take for them to switch:________

Ngati B wasankhidwa, zatengera matumba angati m'chaka choyamba kuti mlimi asinthe maganizo:______

38. Suppose you have the choice of accepting 20 (50kg) bags of traditional maize **for a single season** (Option A) or a larger amount of food in **one season** if you **intercrop** cowpea and maize within the same field (Option B). For each of the six choice sets presented, check the box for the option you prefer?

Tingoyerekeza mwapatsidwa mwayi wolandira matumba 20 (a 50 kg) a chimanga cha makolo kwa chaka chimodzi (chisankho A) kapena matumba ochulukirapo a chakudya ngati mungalime chimanga ndi khobwe mwa kasakaniza m'munda womwewo (Chisankho B). Pa chisankho chilichonse mwa zisankho zisanu n'chimodzi, chongani mu bokosi lomwe likusonyeza chisankho cha mlimi.

Choice	Option A (Maize 1st Season -> Maize 2nd Season)	Option B (Intercrop 1st Season
T1	☐ 20 Maize Bags	☐ 15 Maize + 6 Cowpea Bags
T2	☐ 20 Maize Bags	☐ 16 Maize + 6 Cowpea Bags
T3	☐ 20 Maize Bags	☐ 17 Maize + 6 Cowpea Bags
T4	☐ 20 Maize Bags	☐ 18 Maize + 6 Cowpea Bags
T5	☐ 20 Maize Bags	☐ 19 Maize + 6 Cowpea Bags
T6	☐ 20 Maize Bags	☐ 20 Maize + 6 Cowpea Bags

If Option B was not chosen, how many bags in year one, would it take for them to switch:________

Ngati B wasankhidwa, zatengera matumba angati m'chaka choyamba kuti mlimi asinthe maganizo:______

39. Suppose you have the choice of accepting 20 (50kg) bags of traditional maize (Option A) from weeding twice or a larger amount for more labor, not tilling the land and reserving maize residues for mulching the next season (Option B). More labor would entail three weedings as well as cutting **and** applying crop residues prior to sowing maize. For each of the six choice sets presented, check the box for the option you prefer?

Tingoyerekeza mwapatsidwa mwayi wolandira matumba 20 (a 50 kg) a chimanga cha makolo chifukwa chopalira kawiri (chisankho A) kapena matumba ochulukirapo chifukwa cha ntchito yochulukirapo (chisankho B). Ntchito yochulukirapo ikutanthauza kupalira katatu komanso kuthira manyowa mmudza tisanadzale chimanga. Pa chisankho chilichonse mwa zisankho zisanu n'chimodzi, chongani mu bokosi lomwe likusonyeza chisankho cha mlimi.

Choice	Option A *Chisankho A* (2 Weedings)	Option B *Chisankho B* (3 Weedings + No Till + Crop Residue App.)
T1	☐ 20 Bags -> 20 Maize Bags	☐ 20 Bags -> 21 Maize Bags
T2	☐ 20 Bags -> 20 Maize Bags	☐ 20 Bags -> 22 Maize Bags
T3	☐ 20 Bags -> 20 Maize Bags	☐ 20 Bags -> 23 Maize Bags
T4	☐ 20 Bags -> 20 Maize Bags	☐ 20 Bags -> 24 Maize Bags
T5	☐ 20 Bags -> 20 Maize Bags	☐ 20 Bags -> 25 Maize Bags
T6	☐ 20 Bags -> 20 Maize Bags	☐ 20 Bags -> 26 Maize Bags

If Option B was not chosen, how many bags in year two, would it take for them to switch:_______

Ngati B wasankhidwa, zatengera matumba angati m'chaka choyamba kuti mlimi asinthe maganizo:______

40. Suppose you have the choice of accepting 20 (50kg) bags of traditional maize (Option A) or a larger amount by applying herbicide (Option B). Option A comes with enough fertilizer for a 1-acre field to receive 20 bags. Option B comes with a sprayer and enough herbicide to apply across a 1-acre field. For each of the six choice sets presented, check the box for the option you prefer?
Tingoyerekeza mwapatsidwa mwayi wolandira matumba 20 (a 50 kg) a chimanga cha makolo (Chisankho A) kapena matumba ochulukirapo pothira mankhwala opha tchire mmunda (Chisankho B). Chisankho A chikubwera ndi matumba a fetereza wokwanira kuthira munda wa 1 acre kuti mudzapate matumba 20. Chisankho B chikubwera ndi sprayer komanso mankhwala opha tchire okwanira kuthira m'munda wa 1 acre. Pa chisankho chilichonse mwa zisankho zisanu n'chimodzi, chongani mu bokosi lomwe likusonyeza chisankho cha mlimi.

Choice	Option A *Chisankho A* (2 Weedings + 1 Fertilizer)	Option B *Chisankho B* (No Weeding + Herbicide)
T1	☐ 20 Bags	☐ 21 Bags
T2	☐ 20 Bags	☐ 22 Bags
T3	☐ 20 Bags	☐ 23 Bags
T4	☐ 20 Bags	☐ 24 Bags
T5	☐ 20 Bags	☐ 25 Bags
T6	☐ 20 Bags	☐ 26 Bags

If Option B was not chosen, how many bags would it take for them to switch:________
Ngati B wasankhidwa, zatengera matumba angati m'chaka choyamba kuti mlimi asinthe maganizo:______

41. Suppose you have the choice of accepting 20 (50kg) bags of traditional maize (Optio A) or larger amount by applying herbicide (Option B). Option A will cost 31,250MKW for 25kgs of seed. You will not ba able to apply fertilizer. Optoin B will cost 31,250 for seed, 20,000 for a sprayer and 3,650 for herbicide. So Option A will cost 31,250 and Option B will cost 54,900MW. For each of the six choice sets presented, chock the box for the option you prefer.
Tingoyerekeza mwapatsidwa mwayi wolandira matumba 20 (a 50 kg) a chimanga cha makolo (Chisankho A) kapena matumab ochulukirapo a chimanga pothira mankhwala opha tchire mmunda (Chisankho B). Chisankho A chikutengerani MK 31,250 pogula mbeu yokwana 25kg. Simukyenera kuthira fetereza. Chisankho B mugwiritsa Ntchito MK31,250 kugulira mbeu, MK20,000 kugulira sprayer komanso MK3,650 kugulira mankhwala okupha tchire ndipo chisankho B ndalama YOnse pamodzi ikuwana MK54,900. Pa chisankho chilchonse mwa zisankho zisanu n'chimodzi, chongani mu bokosi lomwe likusonyeza chisankho cha mlimi.

Choice	Option A *Chisankho A* (No Herbicide)	Option B *Chisankho B* (Herbicide)
T1	☐ 20 Bags	☐ 22 Bags
T2	☐ 20 Bags	☐ 24 Bags
T3	☐ 20 Bags	☐ 26 Bags
T4	☐ 20 Bags	☐ 28 Bags
T5	☐ 20 Bags	☐ 30 Bags
T6	☐ 20 Bags	☐ 32 Bags

If Option B was not chosen, how many bags in would it take for them to switch:________
Ngati B wasankhidwa, zatengera matumba angati m'chaka choyamba kuti mlimi asinthe maganizo:______

Section F. Debriefing

Question	**Answer (CODE NN)**
Enumerator Assessment of Data Quality/Farmers Ability to Recall Information	
Time to complete questionnaire	

APPENDIX 3. Key for Survey Questionnaire

Code A
1. Red flowers *(maluwa ofiila)*
2. Yellow flowers *(maluwa a chikasu)*
3. Pink flowers *(maluwa ofiilirako)*
4. Small red roots *(timizu tofiila)*
5. It grows underground unlike an annual *(maka uyo yekhayo amakulira pansi pa nthaka osaonekera)*
6. Tiny thin leaves (spike leaf arrangement)
7. White roots
8. Grows on maize plant
9. Smaller/thinner than annual weeds

99. Other (specify) (*Zina [tchulani]*)

Code B
1. No yield vs some yield *(osakolora kalikonse kapena kukolora zochepa kwambiri)*
2. ¼ of what you would receive (*limodzi mwa ma gawo anayi a zimene mumayembekezera [quarter]*)
3. ½ of what you would receive (*theka la zimene mumayembekezera)*
4. ¾ of what you would receive (*magawo atatu mwa anayi a zomwe mumayembekezera)*
5. Short/stunted (*chachifupi/chokwinimbira)*
6. Skinny/thin (*choonda/toonda)*
7. Wilting
8. Poor germination
9. Cob formed early (before maize plant was fully grown) *chimanga chimabereka mwamsanga (cgisanakule)*

99. Other (specify) (*Zina [tchulani]*)

Code C
1. Maize wilts even though there is water *(Chimanga chimafota ngakhale pamakhala pali chinyontho)*
2. Maize wilts even though there is fertilizer *(chimanga chimafota ngakhala pamakhala pathiridwa fetereza)*
3. Maize wilts before 2^{nd} weeding *(chimanga chomafota tisanapalire kachiwiri)*
4. Tassle forms early (before maize plant is fully grown) *chimanga chimamasula mwamsanga (chisanakule)*
5. Cob forms early (before maize plant is fully grown) *chimanga chimabereka mwamsanga (cgisanakule)*
6. Yellowing of leaves
7. Stunted growth/early maturity
8. Thin maize stalk
9. Poor germination

99. Other (specify) (*Zina [tchulani]*)

Code D
1. Removes nutrients from soil *(amachotsa chakudya cha mu nthaka)*
2. Removes water from soil *(amachotsa madzi mu nthaka)*
3. Poisons roots *(mizu yake ndi poizoni/chiphe)*
4. Attaches to roots *(amamera pa mizu inzake)*
5. Removes water from plant *(amamwa madzi mu zomera zathu)*
6. Removes nutrients from plant. *(amayamwa chakudya kuchoka mu zomera zathu)*
7. Harbors pests

99. Other (specify) (*Zina [tchulani]*)

CODE E
1. Heavy infestation of non-Striga weeds (*lochuluka chire losakhala kaufiti)*
2. Acidic soil (*la mchere wa acid)*
3. Sandy soil (*la mchenga)*
4. Little to no soil organic matter (manure) (*popanda chonde chokwanira [manyowa]*)
5. Eroded soil (*nthaka yokokololoka)*
6. Low fertility (*Fetereza wosakwanira)*
7. Water logging/hard pan (*la madzi ochuluka)*
8. Iron/red soil
9. Hard pan (clay soil)

99. Other (specify) (*Zina [tchulani]*)

CODE F
1. Before tasseling *(chisanamasule)*
2. At tasseling *(chitamasula)*
3. Before you see the cob but after tasseling *(chitamasula*
4. Once cob appears *(chitabereka tiana)*
5. Once cobs have reached full maturity *(chimanga chitakhwima)*

99. Other (specify) (*Zina [tchulani])koma chisanabereke ana)*

CODE G
1. Short/stunted plant (*chachifupi/chokwinimbira)* | Short/stunted cob
2. Skinny/thin (*choonda/toonda)* | Skinny/thin cob
3. Poor Germination (*sizinamere bwino)*
4. Maize leaves turn purple (*Masamba a chimanga amasanduka mtundu wa purple)*
5. Maize leaves turn yellow (*Masamba a chimanga amasanduka mtundu wa chikasu)*
6. Maize leaves turn brown before harvest (early leaf senescence) (*Masamba a chimanga amasanduka mtundu wotuwa chisanakoloredwe [masamba amauma msanga]*)
7. Early maturity (bearing cob before fully grown)

99. Other (specify) (*Zina [tchulani]*)

CODE H	**CODE I**	
1. Normal/no difference (*zabwinobwino)* 2. ¼ of what you would receive (*limodzi mwa ma gawo anayi a zimene mumayembekezera [quarter])* 3. ½ of what you would receive (*theka la zimene mumayembekezera)* 4. ¾ of what you would receive (*magawo atatu mwa anayi a zomwe mumayembekezera)* 5. Basically nothing 6. 1/3 of what you would receive 99. Other (specify) (*Zina [tchulani])*	0. None 1. Erosion *Kukokoloka kwa nthaka* 2. Drought *ng'amba* 3. Lack of fertilizer *kusowa kwa fetereza* 4. Lack of compost, manure, mulch, etc., 5. Soil acidity *mchere wa mu dothi* 6. Low soil fertility *kuchepa kwa chonde mu nthaka*	7. Waterlogging 8. Pests, disease *tizilombo, matenda* 9. Lack of seed 10. Annual weed pressure; too many weeds 11. Flooding 12. Termites 13. Lodging 14. Lack of labor 15. Illness 99. Other (specify) (*Zina [tchulani])*

CODE J	**CODE K**	**CODE L**	**CODE M**
0. Nothing 1. Kupalira (scraping) 2. Kuzulira atapanga maluwa (uprooting after flowering) 3. Kuzulira asanapange maluwa (before flowering) 4. Kusenda/Kuojekera (cover weeds with soil) 5. Kubandira (banking) 6. Herbicide (*Mankhwala wopha tchire)* 7. Deep tillage (*kulima mozama/mwakuya)* 8. Point manure application (*Kuika manyowa pa phando lodzalira)* 9. Burning affected area 10. Point fertilizer application 11. Point manure application 12. Point maize bran application 13. Point ash application 14. Remove and bury in a deep pit 99. Other (specify) (*Zina [tchulani])*	1. 0-2 2. 3-5 3. 6-10 4. 10+	1. NGO/Inter. Org. (*Mabungwe wosakhala a boma)* 2. Radio (*Wailesi)* 3. Poster/Hand Out (*Postala/zojambulidwa pa pepala)* 4. Demonstration trial (*Munda wachionetsero)* 5. Extension agent (*Alangizi)* 6. Market (*Ku msika)* 7. Experimentation (*Kuyeselera/kafukufuku*) 8. Neighbor/Farmer (*Wokhala moyandikana naye/mlimi)* 9. Farmer group/coop (*ku gulu/bungwe la alimi)* 10/14. Family, relatives 11. Tradition *Za makolo* 12. Agro-dealer (*Wogulitsa zipangizo za ulimi)* 13. Intuition (*Kungopanga poganiza kuti ndizotheka)* 15. School 99. Other (specify) (*Zina [tchulani])*	1. Striga would come back **less in short term** (same season) (*Kaufiti anameranso pasanadutse nthawi yaitali)* 2. Striga would come back **less in the long term** (next season) (*Kaufiti anameranso koma wochepa [m'chaka chotsatira])* 3. Striga would not come back at all (*Kaufiti sanamerenso)* 4. Soil fertility would increased (*Chonde chimaonjezereka)* 5. Biomass for fuel or fodder would increase (*Mapesi amachuluka)* 6. Maize yield would **increase in the short term** (same season) (*Zokolora zimachuluka m'chaka chimenecho)* 7. Maize yield would **increase in the long term** (next season) (*Zokolola zimachuluka m'chaka chotsatira)* 8. Aggregate food production would increase (*Chakudya chimachuluka)* 9. Pest incidence would decrease (*Tizilombo toononga mbeu timachepa)* 10. Profit (from on-farm production) would increase (*Phindu [purofiti] lochokera ku zokolola zathu limachuluka)* 11. On-farm labor would decrease (*Ntchito yogwira pamundapo imachepa)* 12. Overall weed pressure decreased 13. Delayed Striga emergence 14. Improved water retention/soil moisture holding capacity 15. Reduced erosion; improved soil structure/texture 16. Sustained Striga control; prevented Striga problem from getting worse 99. Other (specify) (*Zina [tchulani])*

CODE N

0. None
1. Kupalira (scraping)
2. Kuzulira atapanga maluwa (uprooting after flowering)
3. Kuzulira asanapange maluwa (before flowering)
4. Kusenda/Kuojekera (cover weeds with soil)
5. Kubandira (banking)
6. Herbicide (*Mankhwala wopha tchire)*
7. Deep tillage (*kulima mozama/mwakuya)*
8. Point manure application (*Kuika manyowa pa phando lodzalira)*
9. Burning
10. Point fertilizer application
11. Point manure/fertilizer mix application
12. Point maize bran application
13. Point ash application
14. Remove and bury in a deep pit
99. Other (specify) (*Zina [tchulani])*

CODE Q

0. The same season (*Chaka chomwecho)*
1. The following season (*Chaka chotsatira)*
2. The following 2 seasons (*Patatha zaka ziwiri)*
3. The following 3-5 seasons (*patatha zaka zitatu kufikira zisanu)*
4. The following 6-10 seasons (*patatha zaka chisanu n'chimodzi kufikira khumi)*
5. The following 10+ seasons (*Patatha zaka zoposera khumi)*
99. Other (specify) (*Zina [tchulani])*

CODE O

0. Nothing (*Palibe)*
1. Burn (*Kuyatsa)*
2. Incorporate into ridge (*Kumukwilira mu mzere)*
3. Put in furrow (*Kumuika mu khwawa)*
4. Remove from field (*Kumutaya kunja kwa munda)*
5. Consumed/Fed to livestock (*Kudya/kudyetsera ku ziweto)*
6. Bury in a deep pit
99. Other (specify) (*Zina [tchulani])*

CODE P

0. None/no change

(positive) Ubwino wake

1. Striga came back **less in short term** (same season) (*Kaufiti anemeranso koma wocheperapo m'chaka chomwecho)*
2. Striga came back **less in the long term** (next/multiple season/s) (*Kaufiti anameranso koma wocheperapo patapita nthawi [chaka/zaka] zotsatira)*
3. Striga did not come back at all that season (same season) (*Kaufiti sanamerenso m'chaka chimenecho)*
4. Soil fertility increased (*chonde chinaonjezereka mu nthaka)*
5. Increased biomass for fuel or fodder (*mapesi wochuluka omwe anagwira ntchito ngati nkhuni kapena chakudya cha ziweto)*
6. Maize yield **increased in the short term** (same season) (*zokolola chimanga zinachuluka m'chaka chomwecho)*
7. Maize yield **increased in the long term** (next season) (*Zokolola zinachuluka m'chaka chotsatira)*
8. Aggregate food production increased *Chakudya (chonse tikachiphatikiza chinachuluka)*
9. Pest incidence reduced (*tizilombo toononga mbeu tinachepa)*
10. Profit (from on-farm production) increased *(Phindu [purofiti] lochokera ku zokolola zathu linachuluka)*
11. On-farm labor decreased (*Ntchito yogwira pamundapo inachepa)*

(negative) kuipa kwake

12. Striga came back **more in short term** (same season) (*Kaufiti anameranso m'chaka chomwecho koma wochulukirapo)*
13. Striga came back **more in the long term** (next season) (*Kaufiti anameranso wochuluka m'chaka chotsatira)*
14. Maize yield **decreased in the short term;** harvested little (same season) (*Zokolora zinachepa m'chaka chimenecho)*
15. Maize yield **decreased in the long term;** harvested little (next season) (*zokolola chimanga zinachepa m'chaka chotsatira)*
16. Aggregate food production decreased (*Chakudya chonse tikachiphatikiza chinachepa)*
17. Pest incidence increased; harbored pests (*Tizilombo toononga mbeu tinachuluka)*
18 Profit (from on-farm production) decreased (*Phindu [purofiti] lochokera ku zokolola zathu linachepa)*
19. On-farm labor increased (*Ntchito yogwira pamundapo inachuluka)*
20. Inputs became unavailable (*zipangizo zogwilira ntchito ya ulimi zinasowa)*
21. Inputs became too expensive (*zipangizo zogwilira ntchito ya ulimi zinakwera mtengo)*
22. Delayed Striga emergence
23. Reduced overall weed pressure
24. Improved water retention/soil moisture holding capacity
25. Reduced erosion/Improved soil structure/texture
26. Sustained Striga emergence; prevented Striga problem from getting worse
27. Damaged soil
99. Other (specify) (*Zina [tchulani])*

CODE R	CODE S
0. None/nobody	0. None (*Palibe)*
1. Neighbor/Farmer (*Wokhala moyandikana naye/mlimi)*	1. 0-5
2. Farmer group/coop (*ku gulu/bungwe la alimi)* specify) (*Zina [tchulani])*	2. 5-10
3. NGO/Inter. Org. (*Mabungwe wosakhala a boma)*	3. 10-15
4. Agro-dealer (*Wogulitsa zipangizo za ulimi)*	4. 15-20
5. Family, relatives	5. +20
99. Other (specify) (*Zina [tchulani])*	

CODE T

1. Kupalira (scraping)
2. Kuzulira atapanga maluwa (uprooting after flowering)
3. Kuzulira asanapange maluwa (before flowering)
4. Kusenda/Kuojekera (cover weeds with soil)
5. Kubandira (banking) *tchire)*
7. Deep tillage (*kulima mozama/mwakuya)*
6. Herbicide (*Mankhwala wopha*
8. Point manure application (*Kuika manyowa pa phando lodzalira)*
9. Burning
10. Point fertilizer application
11. Point manure/fertilizer mix application
12. Point maize bran application
13. Point ash application
14. Remove and bury in a deep pit
99. Other (specify) (*Zina [tchulani]) [tchulani])*

CODE U

1. No time *Analibe mpata (nthawi)*
2. Shortage of household labor (*Kuchepa kwa wogwira ntchito panyumba)*
3. Could not hire outside labor (*Sakanakwanitsa kulemba a ganyu)*
4. Illness/death in family (*Matenda/Maliro wokhudza banja)*
5. Rain (*Mvula)*
6. Market price for outputs (e.g., legume grain) was too low (*Mitengo ya zokolola (mwachitsanzo, mbeu za gulu la nyemba) inali yotsika kwambiri)*
7. Ganyu labor took away from practice (*Aganyu anatsata njira ina osakhala imene anauzidwa)*
8. Could not afford inputs (*Sindikadakwanitsa kupeza zipangizo zotsatilira njirayi)*
9. Input availability (*Kapezekedwe ka zipangizo)*
10. Did not know; Not enough information/training (*samadziwa za mmene ndingatsatire njirayi; sanaphunzitsidwe/sanapatsidwe upangiri)*
99. Other (specify) (*Zina [tchulani])*

CODE V

1. Crop rotation (*Kulima mwa kasinthasintha)*
2. Manure application (*Kuthira Manyowa)*
3. Early yielding variety (*Kubzala mbeu zocha msanga)*
4. Fertilizer application (*Kuthira fetereza)*
5. Legume crop residue mulch (*Kuphimbira ndi masangwi a mbeu zathu za mgulu la nyemba)*
6. Maize crop residue mulch *(Kuphimbira ndi mapesi a chimanga)*
7. Intercropping (*Kulima mwa kasakaniza)*
8. Minimum tillage (*mtayakhasu)*
9. Deep tillage (*Kulima mozama/mokuya)*
10. Pre-emergence herbicide (*kuthira mankhwala okupha tchire [wothira mbeu zisanamere]*
11. Maize residue incorporation
12. Legume residue incorporation
13. Maize + legume residue mix incorporation
14. Tobacco pellet application
15. Maize bran application
16. Ash application
17. Planting leguminous trees (e.g., tephrosia)
99. Other (specify) (*Zina [tchulani])*

CODE W

1. 0-2
2. 3-5
3. 6-10
4. 10+

CODE X

1. NGO/Inter. Org. (*Mabungwe wosakhala a boma)*
2. Radio (*Wailesi)*
3. Poster/Hand Out (*Postala/zojambulidwa pa pepala)*
4. Demonstration trial (*Munda wachionetsero)*
5. Extension agent (*Alangizi)*
6. Market (*Ku msika)*
7. Experimentation (*Kuyeselera/kafukufuku*)
8. Neighbor/Farmer (*Wokhala moyandikana naye/mlimi)*
9. Farmer group/coop (*ku gulu/bungwe la alimi)*
10 or 14. Family, relatives
11. Tradition *Za makolo*
12. Agro-dealer (*Wogulitsa zipangizo za ulimi)*
13. Intuition (*Kungopanga poganiza kuti ndizotheka)*
15. School
99. Other (specify) (*Zina [tchulani])*

CODE Y

1. Striga came back **less in short term** (same season) (*Kaufiti anemeranso koma wocheperapo m'chaka chomwecho)*
2. Striga came back **less in the long term** (next/multiple season/s) (*Kaufiti anameranso koma wocheperapo patapita nthawi (chaka/zaka zotsatira)*
3. Striga did not come back at all that season (same season) (*Kaufiti sanamerenso m'chaka chimenecho)*
4. Soil fertility increased (*chonde chinaonjezereka mu nthaka)*
5. Increased biomass for fuel or fodder (*mapesi wochuluka omwe anagwira ntchito ngati nkhuni kapena chakudya cha ziweto)*
6. Maize yield **increased in the short term** (same season) (*zokolola (chimanga) zinachuluka m'chaka chomwecho)*
7. Maize yield **increased in the long term** (next season) (*Zokolola zinachuluka m'chaka chotsatira)*
8. Aggregate food production increased *Chakudya (chonse tikachiphatikiza) chinachuluka*
9. Pest incidence reduced (*tizilombo toononga mbeu tinachepa)*
10. Profit (from on-farm production) increased *(Phindu [purofiti] lochokera ku zokolola zathu linachuluka)*
11. On-farm labor decreased (*Ntchito yogwira pamundapo inachepa)*
12. Delayed Striga emergence
13. Decreased overall weed pressure
14. Improved water retention/soil moisture holding capacity
15. Reduced erosion; improved soil structure/texture
16. Sustained Striga emergence; prevented Striga problem from getting worse
99. Other (specify) (*Zina [tchulani])*

CODE Z 0. None 1. Crop rotation (*Kulima mwa kasinthasintha)* 2. Manure application (*Kuthira Manyowa)* 3. Early yielding variety (*Kubzala mbeu zocha msanga)* 4. Fertilizer application (*Kuthira fetereza)* 5. Legume crop residue mulch (*Kuphimbira ndi masangwi a mbeu zathu za mgulu la nyem* 6. Maize crop residue mulch *(Kuphimbira ndi mapesi a chimanga)* 7. Intercropping (*Kulima mwa kasakaniza) ba)* 8. Minimum tillage (*mtayakhasu)*	9. Deep tillage (*Kulima mozama/mokuya)* 10. Pre-emergence herbicide (*kuthira mankhwala okupha tchire [wothira mbeu zisanamere])* 11. Maize residue incorporation 12. Legume residue incorporation 13. Maize + legume residue mix incorporation 14. Tobacco pellet application 15. Maize bran application 16. Ash application 17. Planting leguminous trees (e.g., tephrosia) 99. Other (specify) (*Zina [tchulani])*
CODE AA 0. None/no change *<u>(positive) Ubwino wake</u>* 1. Striga came back **less in short term** (same season) (*Kaufiti anemeranso koma wocheperapo m'chaka chomwecho)* 2. Striga came back **less in the long term** (next/multiple season/s) (*Kaufiti anameranso koma wocheperapo patapita nthawi [chaka/zaka] zotsatira)* 3. Striga did not come back at all that season (same season) (*Kaufiti sanamerenso m'chaka chimenecho)* 4. Soil fertility increased (*chonde chinaonjezereka mu nthaka)* 5. Increased biomass for fuel or fodder (*mapesi wochuluka omwe anagwira ntchito ngati nkhuni kapena chakudya cha ziweto)* 6. Maize yield **increased in the short term** (same season) (*zokolola chimanga zinachuluka m'chaka chomwecho)* 7. Maize yield **increased in the long term** (next season) (*Zokolola zinachuluka m'chaka chotsatira)* 8. Aggregate food production increased *Chakudya (chonse tikachiphatikiza chinachuluka)* 9. Pest incidence reduced (*tizilombo toononga mbeu tinachepa)* 10. Profit (from on-farm production) increased *(Phindu [purofiti] lochokera ku zokolola zathu linachuluka)* 11. On-farm labor decreased (*Ntchito yogwira pamundapo inachepa)*	*<u>(negative) kuipa kwake</u>* 12. Striga came back **more in short term** (same season) (*Kaufiti anameranso m'chaka chomwecho koma wochulukirapo)* 13. Striga came back **more in the long term** (next season) (*Kaufiti anameranso wochuluka m'chaka chotsatira)* 14. Maize yield **decreased in the short term;** harvested little (same season) (*Zokolora zinachepa m'chaka chimenecho)* 15. Maize yield **decreased in the long term;** harvested little (next season) (*zokolola chimanga zinachepa m'chaka chotsatira)* 16. Aggregate food production decreased (*Chakudya chonse tikachiphatikiza chinachepa)* 17. Pest incidence increased; harbored pests (*Tizilombo toononga mbeu tinachuluka)* 18 Profit (from on-farm production) decreased (*Phindu [purofiti] lochokera ku zokolola zathu linachepa)* 19. On-farm labor increased (*Ntchito yogwira pamundapo inachuluka)* 20. Inputs became unavailable (*zipangizo zogwilira ntchito ya ulimi zinasowa)* 21. Inputs became too expensive (*zipangizo zogwilira ntchito ya ulimi zinakwera mtengo)* 22. Delayed Striga emergence 23. Reduced overall weed pressure 24. Improved water retention/soil moisture holding capacity 25. Reduced erosion/Improved soil structure/texture 26. Sustained Striga emergence; prevented Striga problem from getting worse 27. Damaged soil 99. Other (specify) (*Zina [tchulani])*
CODE BB 0. The same season *M'chaka chomwecho* 1. The following season (*Chaka chotsatira)* 2. The following 2 seasons (*Patadutsa zaka ziwiri)*	3. The following 3-5 seasons (*Patatha zaka za pakati pa zitatu mpaka zisanu)* 4. The following 6-10 seasons (*Patatha zaka za pakati pa chisanu n'chimodzi mpaka zaka khumi)* 5. The following 10+ seasons (*Patatha zaka zoposera khumi)*

CODE CC 0. None/nobody 1. Neighbor/Farmer (*Wokhala moyandikana naye/mlimi)* 2. Farmer group/coop (*ku gulu/bungwe la alimi)* specify) (*Zina [tchulani])* 3. NGO/Inter. Org. (*Mabungwe wosakhala a boma)* 4. Agro-dealer (*Wogulitsa zipangizo za ulimi)* 5. Family, relatives 99. Other (specify) (*Zina [tchulani])*	**CODE DD** 0. None (*Palibe)* 1. 0-5 2. 5-10 3. 10-15 4. 15-20 5. +20

CODE EE	**CODE FF**	**CODE GG**	**CODE HH**	**CODE II**
1. Common bean (*Nyemba)* 2. Soybean (*Soya)* 3. Cowpea *Khobwe* 4. Groundnut (peanut) (*Mtedza)* 5. Pigeon Pea (*Nandolo)* 6. Cereal (sorghum, millet) (*mawere, mapira)* 7. Cash Crop (Tobacco, Cotton) (*Fodya, Thonje)* 8. Root tuber/starch (Cassava, Pumpkin, Sweet Potato, Irish Potato) (*Chinangwa, mawungu, mbatata, mbatata ya kachewere)* 99. Other (specify) (*Zina [tchulani])*	1. Saved seed (*Mbeu yosungidwa)* 2. Purchased (*Mbeu yochita kugula)* 3. Subsidy *(Mbeu yotsika mtengo)* 4. Private trader (*Mbeu yogula kwa a ma bizinesi)* 5. NGO (free) (*Kuchoka ku mabungwe osakhala a boma [yaulere])* 99. Other (specify) (*Zina [tchulani])*	1. Cow *(Ng'ombe)* 2. Goat (*Mbuzi)* 3. Chicken or other poultry (*Nkhuku kapena zina za gulu la nkhuku)* 4. Pig (*Nkhumba)* 5. Compost mixed with manure (*Manyowa)* 6. NPK (*Fetereza wa chitowe)* 7. Urea (*Fetereza wa Urea)* 8. CAN (*Fetereza wa CAN)* 9. Maize residues 10. Legume residues 11. Maize + legume residue mix 12. Maize bran 99. Other (specify) (*Zina [tchulani])*	1. From own production/livestock (*Kuchokera ku ziweto zathu)* 2. Purchased (*Kugula)* 3. Paid ganyu to collect/apply (*Ndinalemba waganyu kuti akatenge/athire)* 4. Given by other farmer (*Ndinapatsidwa ndi mzanga)* 5. Gathered in village (*Ndinasonkhanitsa a mmudzi)* 6. Subsidy (*Ndinapeza wotsika mtengo)* 7. Received from NGO (*Ndinalandira kuchokera ku mabungwe omwe si aboma)* 8. Agro-dealer (*Wogulitsa zipangizo za ulimi)* 9. Family, relatives 99. Other (specify) (*Zina [tchulani])*	1. When turning ridges early right after harvest (*Popanga mizere moyambilira tikangomaliza kukolora)* 2. When turning ridges just before first planting rains (*Popanga mizere mvula ikayandikira)* 3. When turning ridges after first planting rains (*Popanga mizere mvula yoyamba ikangogwa)* 4. After ridge turning but before planting (incorporate) (*Mizere itapangidwa koma tisanadzale)* 5. After ridge turning but before planting (planting station application) (*Kuthira pa phando [tisanadzale])* 6. At planting station with seed *Kuthira pa phando (nthawi yodzala)* 7. About 10 days after planting with first weeding (*Patadutsa masiku khumi chidzalireni m'nthawi ya kupalira koyamba)* 8. About 30 days after planting with second weeding (*Patadutsa masiku makumi atatu chidzalireni m'nthawi ya kupalira kachiwiri)* 9. Dig basin/zaii pit 99. Other (specify) (*Zina [tchulani])*

CODE JJ	CODE KK	CODE LL	CODE MM
1. Crop rotation (*Kulima mwa kasinthasintha)* 2. Manure application (*Kuthira Manyowa)* 3. Early yielding variety (*Kubzala mbeu zocha msanga)* 4. Fertilizer application (*Kuthira fetereza)* 5. Legume crop residue mulch (*Kuphimbira ndi masangwi a mbeu zathu za mgulu la nyemba)* 6. Maize crop residue mulch *(Kuphimbira ndi mapesi a chimanga)* 7. Intercropping (*Kulima mwa kasakaniza)* 8. Minimum tillage (*mtayakhasu)* 9. Deep tillage (*Kulima mozama/mokuya)* 10. Pre-emergence herbicide (*kuthira mankhwala okupha tchire [wothira mbeu zisanamere])* 11. Maize residue Incorporation 12. Legume residue Incorporation 13. Maize + legume residue mix 14. Maize bran Application 15. Leguminous trees (e.g., tephrosia) 99. Other (specify) (*Zina [tchulani])*	1. Cow *(Ng'ombe)* 2. Goat (*Mbuzi)* 3. Chicken or other poultry (*Nkhuku kapena zina za gulu la nkhuku)* 4. Pig (*Nkhumba)* 5. Compost mixed with manure (*Manyowa)* 6. NPK (*Fetereza wa chitowe)* 7. Urea (*Fetereza wa Urea)* 8. CAN (*Fetereza wa CAN)* 9. Maize Bran 99. Other (specify) (*Zina [tchulani])*	1. Common bean (*Nyemba)* 2. Soybean (*Soya)* 3. Cowpea (*Khobwe)* 4. Groundnut (peanut) (*Mtedza)* 5. Pigeon Pea (*Nandolo)* 6. Cereal (sorghum, millet) (*mawere, mapira)* 7. Cash Crop (Tobacco, Cotton) (*Fodya, Thonje)* 8. Root tuber/starch (Cassava, Pumpkin, Sweet Potato, Irish Potato) (*Chinangwa, mawungu, mbatata, mbatata ya kachewere)* 99. Other (specify) (*Zina [tchulani])*	1. No time *Analibe mpata (nthawi)* 2. Shortage of household labor (*Kuchepa kwa wogwira ntchito panyumba)* 3. Could not hire outside labor (*Sakanakwanitsa kulemba a ganyu)* 4. Illness/death in family (*Matenda/Maliro wokhudza banja)* 5. Rain (*Mvula)* 6. Market price for outputs (e.g., legume grain) was too low (*Mitengo ya zokolola (mwachitsanzo, mbeu za gulu la nyemba) inali yotsika kwambiri)* 7. Ganyu labor took away from practice (*Aganyu anatsata njira ina osakhala imene anauzidwa)* 8. Could not afford inputs (*Sindikadakwanitsa kupeza zipangizo zotsatilira njirayi)* 9. Input availability (*Kapezekedwe ka zipangizo)* 10. Did not know; Not enough information/training (*samadziwa za mmene ndingatsatire njirayi; sanaphunzitsidwe/sanapatsidwe upangiri)* 99. Other (specify) (*Zina [tchulani])*

CODE NN

1. Poor
2. Fair
3. Good
4. Very Good
5. Excellent

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CHAPTER 3: CROP MODELING: AN INTEGRATED APPROACH TO SIMULATING EMERGENCE AND PERSISTENCE OF STRIGA ASIATICA

3.1 Introduction

Smallholder farmers (cultivating <2ha) comprise the majority of the agrarian population in Malawi (Ricker-Gilbert et al., 2014). Among the smallholder population, maize (*Zea mays*) is the most commonly cultivated food crop and its production is often used as an indicator for rural food security and wealth (Dorward & Chirwa, 2011). In recent years, production has faced numerous challenges, one being the emergence and parasitism of witchweed (*Striga spp*.). As a hermiparasitic angiosperm, witchweed attaches to maize underground and extracts minerals, photosynthates and water (Khan et al., 2010). Attachment is visible several days after, creating a pathogenic effect, as underground juveniles disrupt the hormonal balance and reduce photosynthetic processes (Watling & Press, 2001). Once the weed emerges, more pronounced effects can be seen. The leaf tissue of *Striga* has greater osmotic pressure than maize, and being that its leaves have lower stomatal resistance, a higher transpiration rate renders *Striga* a stronger sink for the solutes and water than maize (Musambasi et al., 2002). Growth and development are severely affected by this sink, resulting in yield losses between 30-100% (Parker, 2012).

Striga is one of the most widely studied weeds in the world. Countless short-term (1-3 year) studies conducted at research stations have investigated the drivers of germination, attachment and emergence. Germination, for example, is largely guided by the seed sowing depth, cereal root canopy and conjugated forms of flavonoids leached by this canopy (among many others) (Chaboud & Rougier, 1991; Doggett, 1994; Ndakidemi & Dakora, 2003). Less research, however, has focused on the dynamic behavior between the three aforementioned stages with respect to time and practice (e.g., manual removal, crop rotation). More specifically, less research has investigated the fluctuation between juvenile, dormant seed and viable seed populations across an extended period of time (>5 years). Understanding feedback behavior between these populations is critical for two reasons. One, different processes leading up to seed production need to be quantified to determine what stages of the lifecycle should be intervened with different controls (Van Mourik et al., 2007). Second, quantification of populations at these stages informs farmers how long and to what extent a practice (or practices) should be applied to control *Striga* emergence at a given threshold.

One way to assess interactions between weeds and their agricultural systems is to use process-based models. These models simulate competing and synergetic relationships between weeds and crops for light, water, and macronutrients (Keating et al., 2003). The objective of this study was to develop a process-based model that could simulate the accumulation and dissipation of *Striga asiatica* seeds, juveniles and flowers in a one-hectare field cultivated by a Malawian smallholder. The model addresses three primary questions: (1) how do different seed, underground-juvenile, seedling and flowering populations of *S.* asiatica fluctuate in response to one another (if at all)?; (2) what overriding interactions or feedback behavior (if any) influence the *S*. asiatica seedbank?; (3) how does cowpea- (*Vigna unguiculata*) maize intercropping, mulching and/or ridging influence the emergence and fecundity of *S. asiatica* in smallholder farming systems? Findings from the study inform which practice or a combination of practices are more effective to control *S. asiatica* in a Malawian smallholder context.

3.2 Background

3.2.1 Crop Models, Their Required Inputs & Selection Considerations

A crop model is a quantitative scheme for predicting growth, development and yield of a plant. Thus, crop models simulate events that have already occurred to inform future decisions about farm management. To simulate weed growth, models typically require four inputs: crop selection, weather data (e.g., rainfall), soil base (e.g., water balance, nutrient balance), and management specifications (e.g., sowing density, tillage). Many of these data can be collected via household farm surveys. If data is not available for the necessary parameters, literature may be sourced. In the arena of agricultural simulation, there are generally three types of models. These include empirical, stochastic or deterministic models. An empirical model is based on observed quantitative relationships between parameters without any insight into the functional or causal operation of the system. A stochastic model uses one or more functional relationships that depends on random parameters, and are thus, related to a probability distribution. Deterministic models are non-stochastic in nature, that is, no random variables are recognized. Exact relationships are postulated, and the output is predicted by the input with complete certainty.

Prior to selecting or developing a crop modeling system, researchers must first consider how the model will be applied. A strategic model focuses on a long-term objective whereby inter-year analyses are conducted. A tactical model addresses a within-season decision whereby intra-year analyses are conducted. Then literature suggests modelers should reflect on three questions:

(i) what is the intended use of the model? (e.g., scientific understanding, decision/policy support);

(ii) what approaches must researchers take to modify the model (if needed)?; and finally,

(iii) what are the target scales for the model? (e.g., field, landscape) (Jones et al., 2016).

In this study a dynamic cropping systems model (CSM) is developed by using Vensim. Vensim is an industrial-strength simulation software used to develop models for analyzing dynamic feedback between stocks (e.g., emerging seedlings, dormant seeds). The CSM is composed of several stocks that interact directly or indirectly with one another to demonstrate the fluctuating behavior of a *S. asiatica* seedbank when one or several control practices are applied. In response to the three questions posed by Jones et al. (2016)-

(i) The intention of CSM is not to account for every single component that drives emergence or fecundity, but rather to expand an understanding about the behavior between *S. asiatica* seedbanks and their relative emergence. In addition, the CSM was developed to serve as a decision-support tool for selecting and determining how long one or several practices should be implemented.

(ii) To improve model performance, the CSM will combine findings from previous studies and a greenhouse trial to calibrate each component.

(iii) The CSM is scaled to a one-hectare field, aimed to conduct inter-year analyses for informing long-term strategies to reduce the *S. asiatica* seedbank and subsequent emergence.

3.2.2 Factors to Consider When Modeling Weed Emergence

Several components of the lifecycle of a weed should be considered before developing or modifying a crop model to simulate Striga emergence. These factors include allelopathy, conditions required for germination, attachment, emergence, flowering, seed dispersal, seed predation, seed dormancy and control practice. Each factor is included in the proceeding paragraphs of this section. Many times, not all of these components can be included in a model for several reasons. First, data availability and accuracy are two of the largest limitations to calibrate parameters. Second, available data may have been collected at different scales (e.g., kg/ha), creating challenges to scale them equally and upload into a model. Finally, adding an exhaustive list of parameters can create more room for error in model outputs (Jakeman & Hornberger, 1993).

3.2.2.1 Allelopathy

Striga spp. germination is triggered by allelopathy. That is, seed conditioning, germination, parasitic contact (attachment) and penetration are mediated by chemical communication between host (or false host) and parasite (Maass, 1999). Once seeds are ripened and exposed to warm moist conditions for several days, exogenous chemical signals produced by a cereal or legume root system can stimulate germination (Worsham, 1987). Elevated levels of soil-phosphorous (P) has shown to reduce the production of these signals, or rather simulants, thus limiting attachment by underground juveniles (Hearne, 2009).

Upon germination, a germ tube, which is in close proximity to the host roots, elongates towards the root of the host, haustorium develop to create a bridge between the parasite and its host. The bridge then acts as a one-way pump, depriving the host of its water, mineral nutrients and carbohydrates (Frost et al. 1997). Hydrolytic enzymes carry out the penetration of the xylem and/or phloem. Still, allelopathy is a complicated process which is not completely understood in the research community. Ndakidemi and Dakora (2003) explain though, when conjugated forms of flavonoids and nitrogenous metabolites (e.g., alkaloids, amino acids) solubilize and enter the soil, they suppress weed seed germination in the Scrophulariaceae plant family (i.e., the plant family of parasitic weeds).

3.2.2.2 Conditions needed for germination

The optimum day/night temperatures for germination and attachment are 15 and 20°C, respectively (Baskin & Baskin, 1998). In terms of soil-water content, seeds persist in free drainage environments (e.g., sandy). If exposed to moist conditions for a prolonged amount of time, the seed can enter a state of wet dormancy (Mohamed et al., 1998). The osmotic potential of seeds requires a preconditioning period at -1.2 and -1.5 MPa[4]. Generally, *S. asiatica* seeds must be exposed to moist conditions for 2-3 weeks at warm (26ºC) temperatures prior to germination (Song et al., 2005).

There is no light requirement for the plant, but seeds thrive in less-fertile acidic soils, hence their omnipresence across intensely mined soils (Singh et al., 1997). The gaseous environment of the soil can affect germination as well (e.g., ethylene enhances germination). Other compounds such as gibberellic acid, strigol analogues and hypochlorite can trigger germination (Visser, 1989). Limited literature is available which explains the extent seeds are susceptible to microbial activity; however, seeds of a similar species (*Alectra vogelii*) will fail to germinate

[4]Megapascals (MPa) are units used to measure internal pressure

when colonized by *Fusarium oxysporum and Fusarium solani* (Riches, 1989). Thus, if their maternal environment is housed by these fungi, seed persistence may negatively be affected. Apart from water and light, germination is heavily dependent on the chemical substances produced by the roots of maize that *Striga spp*. parasitizes (Visser et al., 1987). A number of non-host plants can trigger germination (e.g., *Desmodium* spp). Strong evidence shows that high production of these stimulants is found in fields with low soil-P. Cereals secrete leachates in these soils to assimilate phosphorous from mycorrhizal fungi in exchange for carbohydrates (Hudu & Gworgwor, 1998). Unfortunately, the very leachates that initiate this symbiotic relationship also catalyze *Striga spp*. germination. In addition to low soil-P, high soil-potassium (K) increases germination (Abdul et al., 2012).

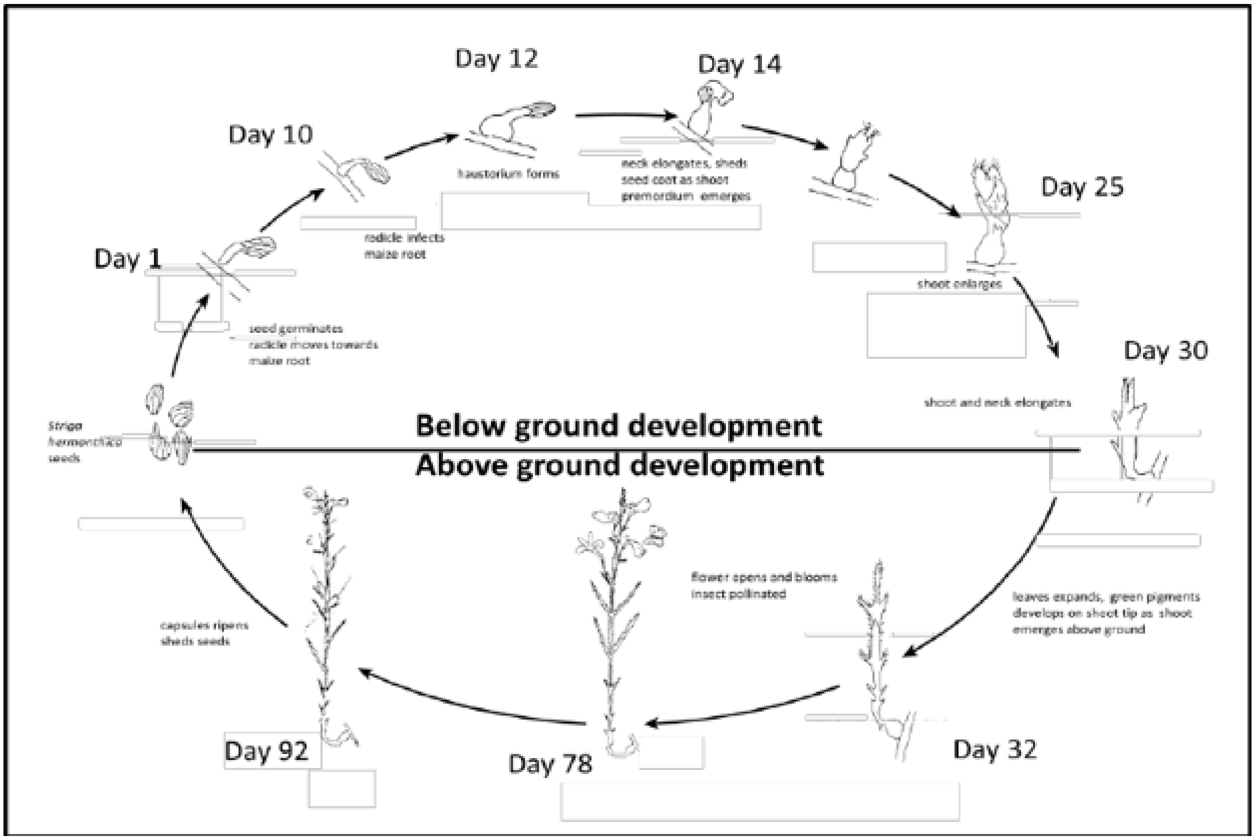
It is difficult to assess exactly when *Striga spp*. will germinate because seed development is contingent upon the quantity and quality of root exudates produced by a host or false host (Li et al., 2013). Research has yet to discover the specific quantities required, but much of the literature suggests a well-established maize plant (4-6 weeks) can secrete enough leachates to trigger germination. Once these leachates are exuded, germination will occur in approximately five days (Ejeta & Butler, 1993). The radicle can only grow 5 mm so a host root must be located 3-4 mm away (Ramaiah et al., 1991). Once a seed germinates, the radicle of parasite must attach to a cereal root within three to five days to survive (Matusova et al., 2005). Otherwise, seed reserves are depleted and root penetration is impossible (Chang & Lyn, 1986). Therefore, root architecture of the host drives attachment in the upper soil area (0-10 mm) (Gurney et al., 1999).

3.2.2.3 Attachment, emergence and flowering

Given the parasitic nature of *Striga spp*., its attachment, emergence and arrival to maturity (i.e., flowering) are dependent on resources accessible to maize, allowing access to nutrients/water and photosynthates for the parasite. The timing and extent of erudites leached will determine germination and subsequent attachment. Parasitism of *S. asiatica* begins approximately 2-3 weeks before the weed emerges from the soil. The leaching of erudites can be delayed when there is a soil-P pool available (e.g., manure) for maize to uptake. Once this pool is depleted, timing of leaching is contingent upon the physiological stage of a cereal plant and its P-demands (Yoneyama et al., 2007). After germination, host root length and density (i.e., canopy) will determine how many underground seedlings can successfully attach and emerge from the soil (Cherif-Ari et al., 1990). A healthy host can support between 14-17 underground seedlings (Smith et al., 1993).

Only 10-30% of underground seedlings that attach to the host will emerge from the soil (Doggett 1965). Seedlings will emerge from the soil between three to six weeks after attachment (Olivier, 1991). Then, after a period of one to two months, a seedling will mature into a flower (see **Figure 4**) (Parker & Riches, 1993). A ripe seed capsule is dropped one week after formation (Webb & Smith, 1996). The number of seeds produced per mature plant vary widely depending on growing conditions, host vigor and host variety (Rodenburg et al., 2006).

Figure 4 - Lifecycle of *Striga asiatica*



3.2.2.4 Seed dispersal

Extreme estimates posit that one *S.* asiatica plant can produce 400,000 to 600,000 seeds (Visser, 1978). More conservative estimates have found that mature flowers produce between 36,308 and 45,729 seeds/plant in Malawi (Abdul et al., 2012). Microscopic seeds are easily spread by wind and surface water flow. Controlled experiments have shown that *S. asiatica* can set seed as a result of either self- or cross-pollination. The reticulated surface of the minute seeds trap pockets of air when they float on water, making the seed buoyant and easily dispersed at least for short distances on rainwater run-off. The trumpet-like structure of the outer seed coat makes the seeds aerodynamically suited to for wind transfer even in the lightest breeze.

Farmers are the primary dispersal agent through harvest and transfer to un-infested stands. Seeds of the parasite have also been found on contaminated maize grain during threshing and transported to markets or neighboring farms during local sales. Although *S. asiatica* is widespread across semi-arid agroecologies in Africa, further spread is possible as contaminated maize shipments are distributed throughout the continent. Thus, the introduction of biotypes with differential host specificity from one area to another has caused many problems in sub-Saharan Africa (CABI, 2014).

<u>3.2.2.5 Predation (at pre- and post-dispersal)</u>

Pre-dispersal predators include, *Smicronyx, S. albovariegatus*, along with a noctuid moth (*Eulocastra argentisparsa)*. These pests were imported from India and released in Ethiopia for 'classical' biological control of *Striga hermonthica. S.* hermonthica often has similar pests to that of *S. asiatica*. Agromyzids (*Ophiomyia strigalis*) have also been found to mine the stems of *Striga spp.* in East Africa but have yet to be evaluated in terms of *S. asiatica* management. Galling weevils (*Smicronyx spp*.) have been found extensively across western Africa predating *Striga spp.* seed capsules (Pronier et al., 1998). The weevils either tunnel into the stems, causing galls to develop and disrupt vegetative growth, or, penetrate the seed capsules, negatively impacting seed production. In West African countries such as Ghana, *Smicronyx spp*. is found in 22.5% to 50% of *Striga spp.* plants (Kroschel et al., 1995).

<u>3.2.2.6 Seed dormancy</u>

Primary dormancy is broken when ripened seeds are exposed to warm moist conditions (at 28-30°C) for 6-10 days followed by the exogenous chemical signals produced by host roots (Elzein & Kroschel, 2003). A prolonged period of imbibition by water, in the absence of a stimulant, does not induce wet dormancy. With regard to secondary dormancy, seeds in a dry state can remain viable for up to 10 years until a host is planted (Bebawi et al., 1984). Dormant seeds generally lie at >15 cm depth given that 0-15 cm is ideal for germination (Baskin & Baskin, 1998; Doggett, 1984).

Striga spp. have a type IV persistent seed bank. That is, the seeds remain viable for more than one year and have a large persistent germination rate year-round (pending that the host is growing nearby). The weed does not differentiate between seasons, but rather waits for a host to be planted. Some might argue that if a host, such as maize, is planted off-season, then this would classify *Striga spp.* as having a type III persistent seed bank.

3.2.2.7 Controls

There are several controls practiced in Malawi which affect *Striga spp.* prevalence and persistence. These involve removing the weed physically, sowing maize at various depths, altering the soil profile (making less favorable conditions for germination), inducing suicidal germination and predating seeds. Hand-pulling is an effective method to control *Striga spp.* if the plant is removed prior to the flowering stage. If weeds cannot be removed prior to maturity, flowers can be buried at deep soil depths, so their seed cannot attach to maize between 1-30 mm of soil. Also, deep planting maize on raised beds can reduce root length in the upper soil layers where *Striga spp.* seeds are predominantly found. In doing so, less underground seedlings can attach, and those that do, may die overtime (Van Delft et al., 2000). Under rain fed conditions, Elzein and Kroschel (2003) note that underground development of *S. hermonthica* was lower when sorghum (*Sorghum bicolor*) was sown in holes 30 cm lower than the surface of the ridge compared to sorghum directly sown in the ridge. In addition to planting at lower depths, transplanting maize has also been found to reduce parasitic attachment (Oswald et al., 2001). The practice allows maize to develop a juvenile root system before being exposed to parasites, which is less prone to the phytotoxic effect (Graves et al., 1989; Ransom et al. 1996).

Intercropping and the rotation of legumes has shown to reduce parasitic weeds in degraded environments. Certain legumes have the ability to chemically inhibit weed growth by exuding substances from their roots. Legumes with these capacities are often referred to as trap-crops. In the presence of legumes, absent of cereals, parasitic seeds will germinate, transpire and deplete their soil seedbank over several growing seasons (Khan et al., 2010). The extent or rate of suicidal germination is contingent upon legume type, sowing density and planting date. Legume species, such as cowpeas, have been found to induce germination by 60% (Carsky et al., 1994). Others, such as silverleaf (*Desmodium* spp.), induce >90% germination (Khan et al., 2010). Much of their success is contingent upon their placement (e.g., in-row) and sowing time (e.g., relay cropping 10 weeks after sowing) (Oswald et al., 2002). Underground seedlings that do survive may be less effective in attaching to the host, as haustorium development is truncated (Oswald et al., 2002). It is difficult to quantify the rate of suicidal germination induced by living roots versus the rate induced by decomposing leaves and roots. Suicidal germination is primarily attributed to living roots that secrete leachates, but a smaller percentage is attributed to decomposing leaf and root tissues (Sanginga et al., 2003). Legume residues left to decompose after harvest (as opposed to being burned or consumed by livestock), therefore, should not be discounted in the control of *Striga spp.*

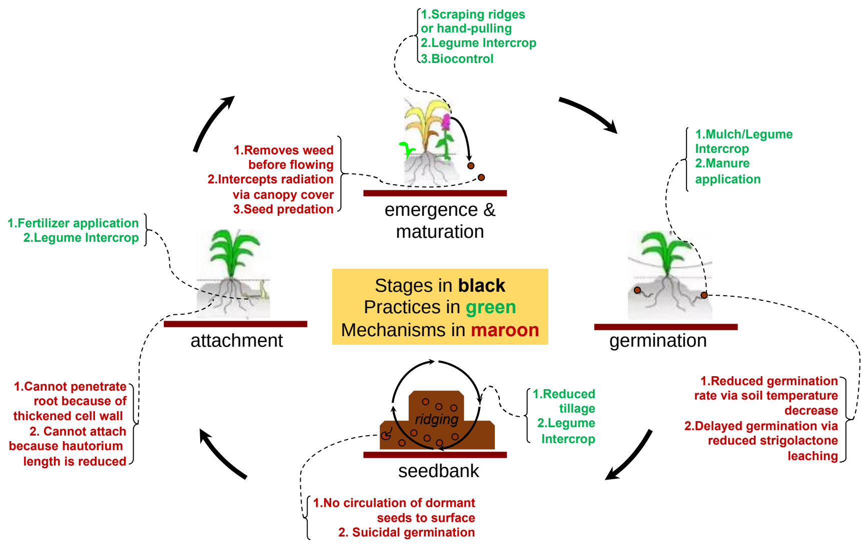
Several authors posit that the incorporation of legumes and their mulches in cereal-based systems not only boosts soil fertility, but alters soil conditions, creating less favorable conditions for weed growth. For instance, pigeon pea can utilize iron-bound phosphorous in alfisols, thereby increasing total P availability and reducing parasitic-potential (Ae et al., 1993). An increase in soil-P via legumes or manure application delays the secretion of strigolactones employed by maize to signal mycorrhizal fungi for assimilating P (Kanampiu et al., 2003). When secretion is delayed, the time-window for *Striga spp.* germination is shortened (e.g., 4-month growing season vs 3-month growing season). With a shorter time-window, less seeds are able to germinate, leaving them in the soil to decay or become predated.

Some argue that organic fertilizer application significantly reduces the density of the soil weed seed-bank as well when legumes are incorporated with cereals (Jiang et al., 2014). Increased soil-nitrogen (N) is associated with higher N-concentration in maize roots, increasing their cell-wall, and therefore, reducing cell-wall degradation by enzymes via haustorium attachment (Cechin & Press, 1993). Legume canopies also make less conducive environments for parasites by reducing soil temperature. For example, intercropping groundnuts in the same row as sorghum has been observed to decrease soil temperature by 2°C at a 10cm depth (Matthews et al., 1991). Such reductions decrease the viability of seeds, thus, decreasing their chance to germinate the following season (Carsky et al., 1994; Carson, 1989). Viability can also be decreased by increasing the pH of the soil. One practice commonly implemented by smallholders is the application of ash on maize planting stations (Netzly, 1988).

The application of biocontrol agents has also been shown to reduce emergence and overall seedbank of Striga. Local insects that damage tobacco (*Spodoptera litura, Heliothes armigera,* *Myzus persicae*) can infect Orobanche plants, perhaps as a result of tobacco compounds in the parasite. These insects seem to be a more appropriate control for the weed since they are natural across the sub-Saharan African landscape (SP-IPM, 2003). Little literature cites natural predators of *Striga spp.* seed once the seed has been dropped on the soil. In terms of post dispersal, the introduction of Agromyzid flies (*Phytomyza orobanchia*) have been found to destroy species in the Orobanche genus though. The rate of attack seems to depend on the relative timing of parasite emergence and insect arrival, but in Morocco, Orobanche seed production was reportedly reduced by 95% (Musselman, 1980). Smith et al. (1993) determined the use of some species (*Sm. Umbrinus*) as a biocontrol agent would need to destroy 95% of the seeds each year to reduce Striga density by 50%. Since the seedbank increases markedly from very low densities in just a few seasons, weevils may not be able to effectively control Striga alone.

As mentioned, there are numerous practices that control *Striga spp*. Researchers argue these practices must be used to address the weed at specific points or stages of its lifecycle (see **Figure 5**) (Hearne, 2009). For example, legumes can be used to decrease the soil seedbank by inducing suicidal germination. Fertilizer application can be used to reduce attachment. Weeding can be employed to remove emerging seedlings before they flower. An aggregated approach, therefore, is argued as the most effective manner in controlling the weed (Westerman et al., 2007).

Figure 5 - Practices that address Striga emergence based on the stage of the weed lifecycle



3.2.3 Model justification

Much of the *Striga spp*. literature discusses either the effect the weed has on yield or how effective a control practice is by using cereal yield as an indicator. Less literature, however, focuses on emergence of *Striga spp*. or its subsequent seedbank. Even fewer, study or quantify attachment. There are several reasons why emergence or seedbanks are less studied. First, *Striga spp*. seeds are microscopic and difficult to monitor and/or quantify (Van Mourik et al., 2008). Like seeds, emerging seedlings are difficult to identify and many transpire quickly after emerging from the soil. Second, cereal yields are less affected by *Striga spp*. if ample resources (e.g., fertilizer) are available for production (Doggett, 1975). Unfortunately, the majority of Malawians cultivate low-input systems, augmenting the effect parasitism has on their maize yield (Parker, 1991; Ransom et al., 1990). Thus, the assessment of *Striga spp*. emergence is becoming ever more critical to determine maize yield production in smallholder fields.

There is a considerable amount of deterministic or stochastic *Striga spp*. models found in the literature (Abdul et al., 2012; Chikoye et al., 2011; Ekeleme et al., 2014; Tarfa et al., 2006). The following models often use statistics and/or econometrics as a tool to predict emergence, attachment and flowering. Application of these models offers opportunities to identify certain interactions (e.g., soil acidity: *Striga spp*. emergence) that do not occur out of coincidence. Identification of these processes or interactions improves the understanding about determinants of *Striga spp*. emergence and succession. However, in nature, "different processes interact across different scales in a non-linear way, and such interactions are poorly understood and are not well represented" (Chiang et al., 2004, p. 298). In addition, field experimental data is needed to calibrate numerous parameters needed to model underlying processes. Many times, these data are not available, inaccurate and/or expensive to collect. Some researchers have developed process-based simulators in an effort to address these challenges (Kunisch et al., 1991; Van Mourik et al., 2008). Through a systems approach, researchers simulate the fluctuation of different stocks (e.g., soil moisture) relative to outside parameters (e.g., root growth, evapotranspiration rates). These parameters do not behave in a linear fashion, but rather, change according to the fluctuating stock they feed into or pull from (Kopainsky et al., 2012). It is important to account for the fluctuation or plasticity of parameters. While quantitative analyses such as econometrics can illustrate the *elasticity* or sensitivity certain variables have upon *Striga spp*. emergence, system dynamics allows the observation of both the elasticity and *plasticity* of parameters. In addition to this flexibility, parameters in systems models can be applied with values or equations (provided by the literature) when there is incomplete or missing data. While this is not advisable, researchers can develop and run systems models without being confined to data availability. As a final note, one of the most the most significant contributions of the method is its ability to model causal relationships, and therefore, test hypotheses about causation.

3.3 Methods

The manner in which the CSM was parameterized is explained in the following section. After outlining the development of the model, study area and protocol of a greenhouse experiment are defined. Finally, the methods used to analyze model outputs and greenhouse results are explained.

3.3.1 Model review

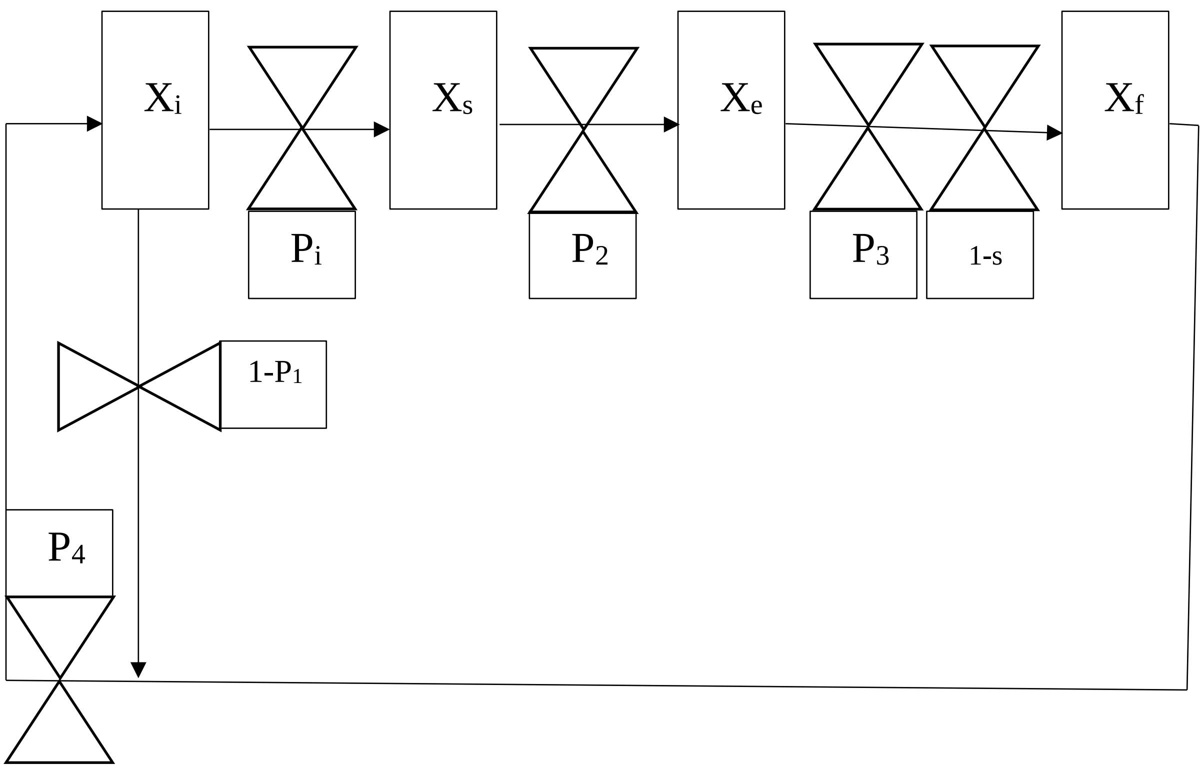
Different stages of the *Striga spp*. lifecycle were used to inform how to construct the CSM. Supporting literature was then sourced to confirm the structure and apply values or equations to its parameters (e.g., seedbank, attachment, germination and flowering parameters). Several reviews and short-term studies provided starting values and equations for parameters. To explain the manner in which the CSM was developed, the structures of several models are presented in this subsection. Then, the parameterization of the CSM is described based on the strength and limitations of each model.

3.3.1.2 Model 1

3.3.1.2.1 Structure and Objective

In the first model (**Figure 6**), Smith et al. (1993) developed a deterministic biocontrol simulator (DBS), with transition probabilities defining the proportion of *S. hermonthica* plants surviving from one life stage to the next. The DBS employs an annual time-step, evaluating seed populations in a one square meter area where millet (*Pennisetum glaucum*) is sown. The model evaluates the potential of gall-forming weevils (*Smicronyx umbrinus* Hustache) as a biocontrol agent of *S. hermonthica*. The structure of the DBS was developed from the earlier work of Kunisch et al. (1991) where *Striga spp*. develops at five defined stages, beginning from an existing seed bank and ending with the dispersal of new seeds from flowers. In between these two stages, germination (i.e., the preconditioning and stimulation by root exudates), attachment, underground growth, emergence and maturity occur. This model appears to be one of the earlier *Striga spp*. emergence simulators developed and its structure has since been used to inform several others since.

Figure 6 - Structure and flow between state variables of *Striga spp*.



Note: Structure of the model showing flow between the state variables [*Striga* seed bank (m^{-2}), X_j; simulated *Striga* seeds (m^{-2}), X_e; *Striga* seeds produced (m^{-2}), X_f] according to the annual transition rates (probability of stimulation, p_1; probability of emergence, p_2; average seed production per emerged plant, p_3; proportion of seeds destroyed by *Smicronyx, s*; seed viability, p_4)
Source: Figure modified from Kunisch et al. (1991)

3.3.1.2.2 Strengths and limitations

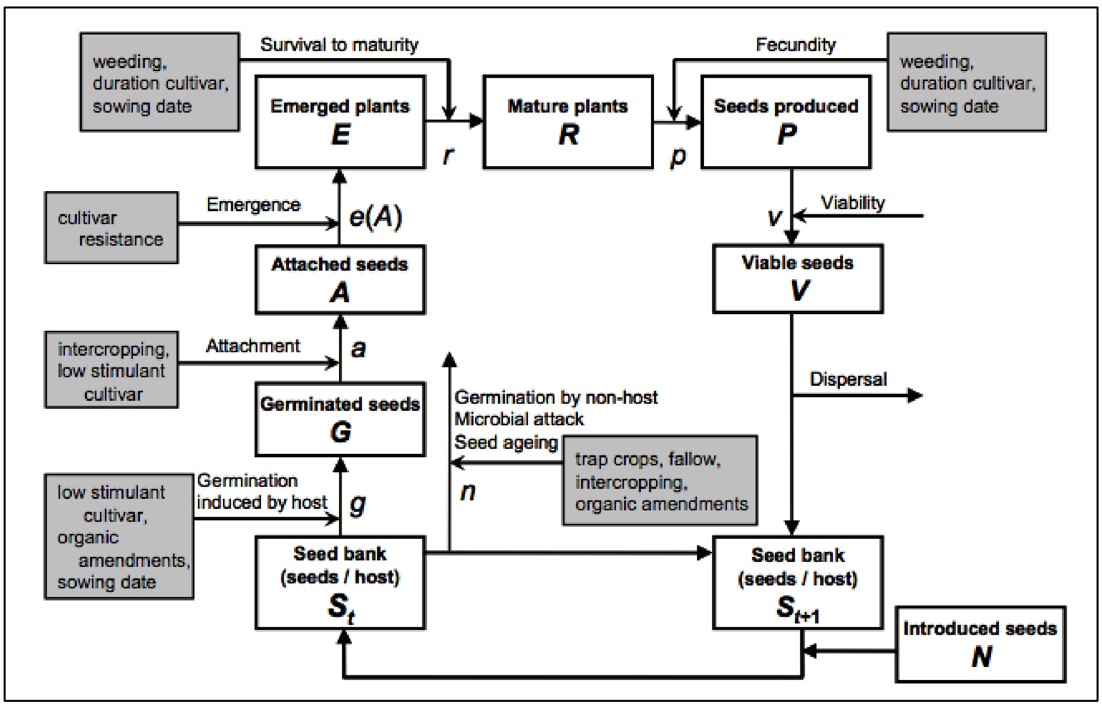
There were several strengths and limitations of the DBS, particularly if it is used as a tool for evaluating control strategies to reduce the *S.* hermonthica seedbank. One of the primary strengths lies in its ability to show the persistent seedbank of *S.* hermonthica, even from only several flowers emerge in a given field. By accurately reflecting this high fecundity, the model is able to postulate whether weevils are an in/effective biocontrol or not. There were several limitations to the model. First, much of the parameters were applied from fragmented data collected from farmer fields or pot experiments (Van Mourik et al., 2008). Fragmented data limits how much results can be extrapolated to other settings. Second, the model was not sensitive to changes in key parameters such as the control agent population. Predator populations should fluctuate according to seed availability and vis-à-vis. Given this non-dynamic nature, model results do little to inform how much (or how little) a control should be administered seasonally.

<u>3.3.1.3 Model 2</u>

3.3.1.3.1 Structure and objective

In the second model (**Figure 7**), was developed by Van Mourik et al. (2008). The stochastic model assessed the probability of successful establishment of *S. hermonthica* in millet- (*Pennisetum glaucum*) based systems. In this model, seeds dispersed by flowers are added to the soil seedbank at the end of each annual time step. Seven stages are outlined in the structure, including viable seeds, germinated seeds, attached seedlings, emerged plants, mature reproductive plants, seeds on reproductive plants, seed shed by flowers, and viable seed added to the seedbank. The model evaluates different controls of *S. hermonthica* based on seed populations across a one-hectare field. These practices include planting long and short duration millet varieties, weeding of *S. hermonthica* flowers at different times, intercropping cowpea and sesame (*Sesamum indicum*) or planting them as fallow crops. Each practice was evaluated separately.

Figure 7 - Life cycle diagram of *Striga hermonthica*



Source: Van Mourik et al. (2008)

3.3.1.3.2 Strengths and limitations

The stochastic model is powerful in the sense that it assesses the probability of attachment in un-infested fields across different scenarios. This assessment yields opportunities to “explore the extent to which cropping systems are vulnerable to invasion” (Van Mourik et al., 2008, p.,84). In addition to highlighting this vulnerability, the model informs readers that intercrops or rotator crops must be employed for at least 3 years to reduce the seedbank to a significant

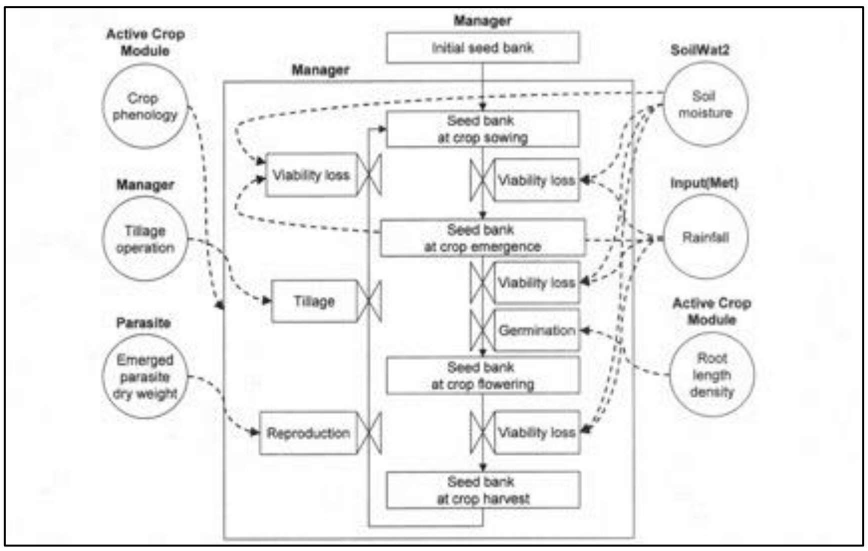
threshold (90%). Practically speaking, many experiments do not show this reduction in three years, regardless of setting (e.g., farm, experiment) (Abunyewa & Padi, 2003; Franke et al., 2006; Murdoch & Kunjo, 2003; Oswald & Ransom, 2001; Schulz *et al*., 2003). A 90% reduction in a seedbank or emergence is seldom reported in three years, and the studies that do report such reductions are typically conducted under strict controlled conditions (Khan et al., 2010).
The projection limits how much model results can be extrapolated to field outcomes. In addition, model developers admit that more life cycle processes should be added to their structure (e.g., suicidal germination), but "further research would be needed to assess the stochastic nature of the different phases in Striga development" (p. 85). Finally, model simulations indicate that planting a cowpea intercrop with millet simultaneously should suppress *S. hermonthica* emergence. In reality though, smallholders sow cowpea two to four weeks later and do not have as high of a sowing density used in the model.

3.3.1.4 Model 3

3.3.1.4.1 Structure and objective

In the third model (**Figure 8**), Grenz et al. (2005) developed a model from APSIM software (Agricultural Production systems Simulation) to simulate the parasitism of broad bean (*Vicia faba* L.) by broomrape (*Orobanche crenata* Forsk.). Broomrape is in the same genus (Orabanche) as *Striga spp*. The objective of the model was to quantify the effect crop rotation, tillage, hand-pulling and combined strategies on a dynamic seedbank. As seen in the parameters of the model, seed production is measured by parasite dry weight. Seeds fluctuate at three different levels in the soil. Seed viability follows a negative exponential function given that seed decay is driven by soil moisture. Effect of external factors such as temperature are not included. The model is calibrated with data that reflects daily changes in soil moisture (0-15 and 15-30 cm), precipitation, broad bean root length density and dry weight of emerged parasites. The model is event-based whereby events occur over crop development stages, catalyzing changes in the broomrape seedbank.

Figure 8 - Flow diagram of parasitic weed crenate broomrape (*Orobanche crenala Forsk*.) in APSIM



Note: Dashed arrows represent input of information form APSIM modules (module names printed in bold). Simulated crop phenology and rules defined in the APSIM-Manager module determine the timing of process. The initial seedbank is specified by user. "Seed bank at crop emergence" is based on the parasitism of broad bean (Vicia faba L.). For further information on APSIM framework, see Keating et al., (2003). Source: Grenz et al. (2005)

3.3.1.4.2 Strengths and limitations

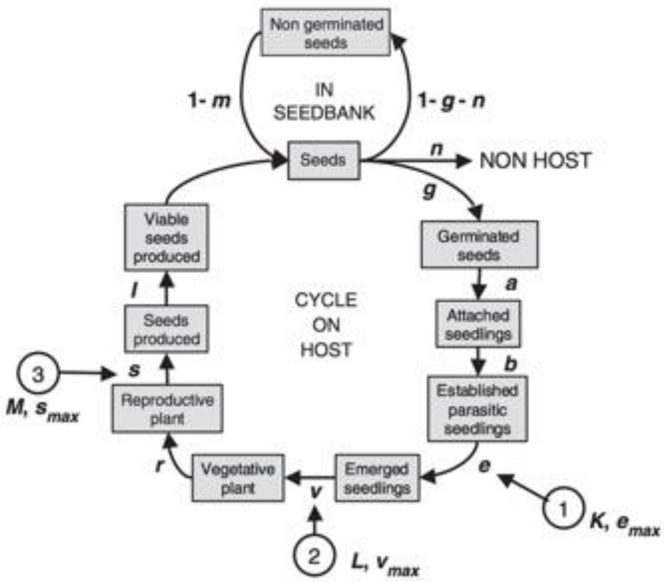
Calibration of parameters at daily time-steps allows more accurate interactions to occur between the host, parasite, environment and imposed management practices. In doing so, the model is able to make more precise assessments and conclude that the parasite population can only be contained by combining several management approaches. As detailed as the model is, there are several limitations. First, seed decay is only driven by soil moisture, regardless of soil temperature, seed predation, microbial activity and soil chemical properties (e.g., pH), which are considered as important determinants of seed decay (Grenz et al., 2005). Another limitation is that seeds are assumed to be distributed homogenously across horizontal layers of soil. In smallholder fields, parasite seed distributions are usually patchy (González-Adujár et al., 2001). This assumption can cause an overestimation of parasitism. Finally, the model only specifies one event/stock where seeds germinate and attach to millet. In fact, this event should be separated into three different events: germination, seedling formation without attachment, and attachment to the host (ter Bor & van Ast, 1991).

3.3.1.5 Model 4

3.3.1.5.1 Structure and objective

In the fourth model (**Figure 9**), Westerman et al. (2007) developed a density-dependent feedback model (DDFM) to simulate sorghum parasitism by *S.* hermonthica. The researchers developed the model to assess how attachment was affected by host varieties that emitted fewer exudates from their root systems. The objective of the model was to identify key points in the *S.* hermonthica life cycle where intervention strategies could be applied. The model sourced literature to apply values/equations for parameters and was run using existing and earlier published data. The model is divided into 10 steps, each assuming different transition probabilities (except for seed production). The processes and probabilities associated with the life cycle included "…(1) conditioning and germination of S. hermonthica seeds in response to crop host roots (g), (2) spontaneous germination…germination in response to non-host cues (n), (3) attachment (a), (4) establishment (b), (5) subsurface growth until seedling emergence (e), (6) the proportion that develops into above-ground vegetative plants (v), (7) the proportion that becomes reproductive (r), (8) seed production (s), (9) viability of newly produced seeds (l), and (10) survival of non-germinated seeds into the next season (1m; with m mortality of seeds in the seedbank).” (p., 221).

Figure 9 - Density-dependent feedback model (DDFM): Striga hermonthica emergence in sorghum-based system



Source: Westerman et al. (2007)

3.3.1.5.2 Strengths and limitations

Unlike the previous three models, the DDFM emphasizes the importance of feedback behavior. Also, the model highlights the importance of attachment given that it is a ‘bottleneck’ parameter, which strongly influences the populations of the other nine steps regardless of outside control practices. Finally, the model includes a ‘shape parameter’, indicating the max number of seedlings that can attach at specific time points during the sorghum lifecycle. Although the model emphasizes how important feedback behavior is in the lifecycle, only two parameters (i.e., “non-germinated seeds” and “seeds”) demonstrate feedback. Otherwise, the rest of the parameters operate in a consecutive linear fashion (i.e., one after the other). Another limitation of the model is that it operates in annual timesteps, constricting the effect of any inter-seasonal events (e.g., rainfall, fertilizer application). Lastly, the model only includes one parameter that influences non-host germination. As mentioned in subsection "*Controls*", germination may be trigged by several factors, including host exudates, false-host exudates (e.g., legumes) and false-host residues. Each of these factors induces germination at different rates (e.g., 95% vs 10%).

3.3.2 Model development

The objectives, structure, strengths and limitations of each model were used to inform the development of a single CSM (see **Figure 10**) to simulate *S. asiatica* emergence in maize-based systems across Malawi at monthly intervals. Explanations regarding these considerations are outlined in the subsection below.

Figure 10 - Cropping Systems Model (CSM): Emergence of *Striga asiatica* in maize-based system

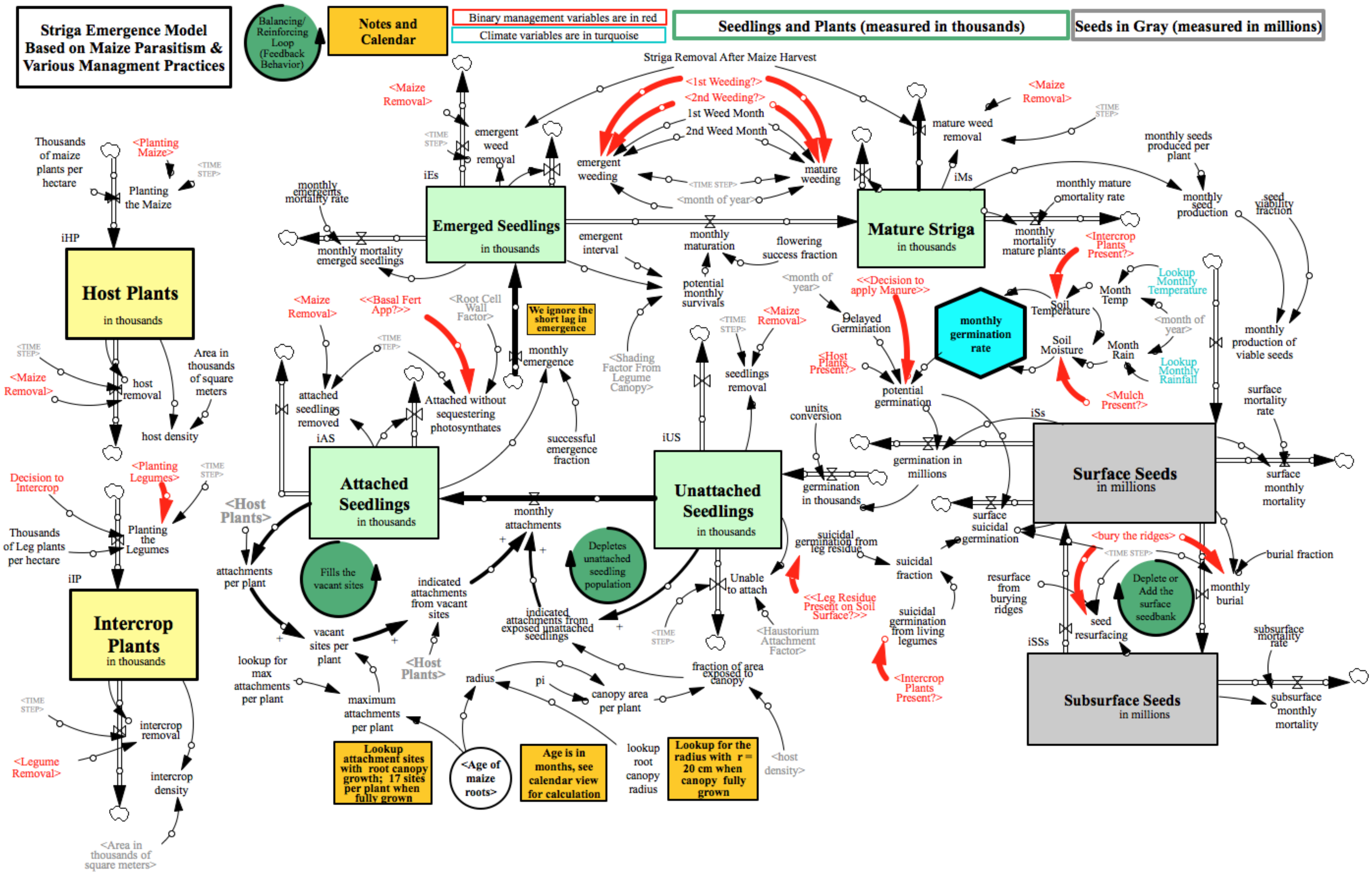
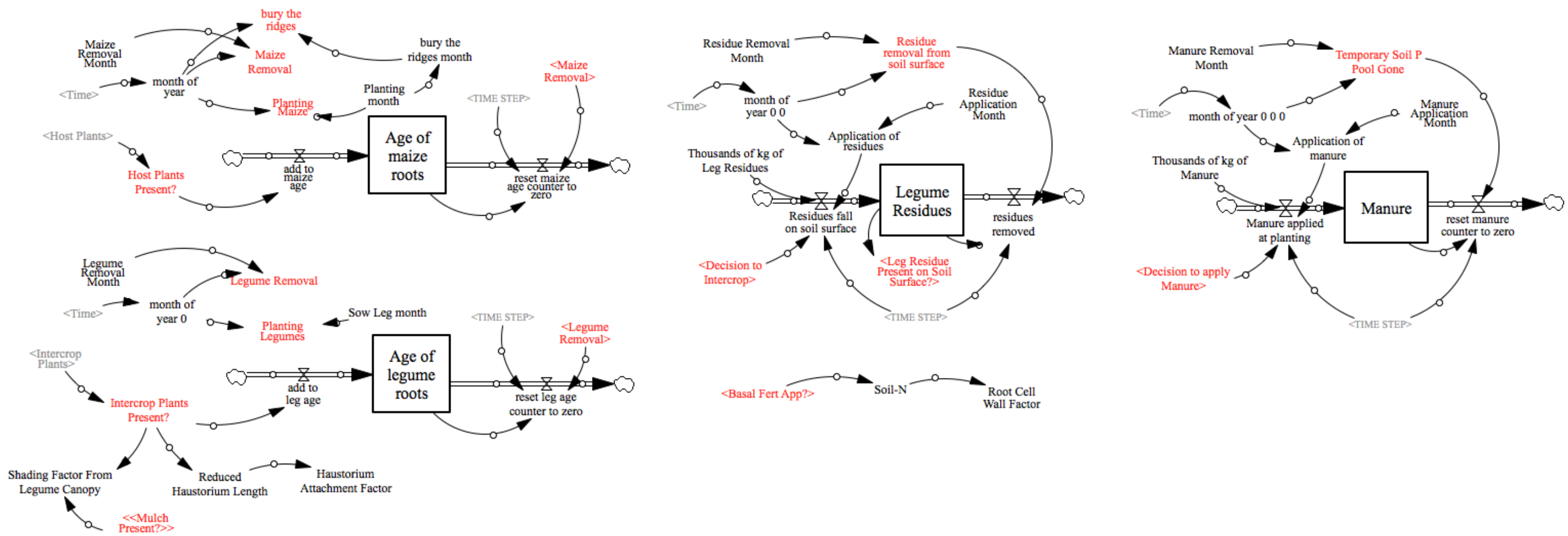


Figure 10 (cont'd)



Note: Secondary view of parameters embedded within initial structure

3.3.2.1 Parameter considerations

The general structure of model 1 was used as a jumping point to initially parameterize the CSM. After which, other parameters were added. In model 1, however, predation of *Striga spp*. seed was included, which were not included in any of the other models discussed. Second, the application of an equation for the flowering parameter with a high seed-rain value was used in the CSM to accurately reflect high fecundity. Third, the emergence factor in the CSM was validated sourcing a long-term *S. asiatica* control experiment in Malawi. The factor was validated in this manner to avoid relying fragmented data which model 1 had done. Fourth, the CSM connects multiple parameters (e.g., attachment population relative to germination rate) to reflect the dynamic nature of a parasitic seedbank. This type of parameterization was carried out so seedbank populations were sensitive to the intensity of one or more control practices. Model 1 did not account for these control practices.

Two parameters from model 2, specifically “attached seedlings” and “viable seed added the seedbank”, were included in the CSM structure. In addition, the cowpea-maize intercrop parameter was integrated into the CSM structure. Van Mourik et al. (2008) mentioned that calibration of certain management parameters (e.g., intercrop sowing date) in model 2 did not align with farmer practices, rendering an overestimation of *S. asiatica* control in their results. To avoid inaccurate outputs, the CSM calibrated its emergent rate factors with results from a greenhouse experiment using farmer-managed soils. This experiment will be explained later in the study. In addition, the greenhouse experiment followed a protocol that attempted to mimic farmer practices (e.g., fertilizing maize two weeks after sowing as opposed to at sowing) in an effort to more accurately reflect emergence in the field.

Viable seed depth (0-15 cm) and dormant seed depth (15-30 cm) were two key components integrated from model 3 into the CSM structure. In addition, a tillage parameter was connected to these two components to guide seedbank fluctuation. This soil disturbance parameter was added since dormant seeds can be shifted from lower depths (15-30 cm) to higher ones (0-15 cm) (Van Delft et al., 2000). Root density and root depth could not be added to the CSM, but the number of parasites that can attach per maize plant were included. Grenz et al. (2008) advised future modelers to consider the use of multiple parameters to model the efficacy of controls, above and below ground. Hence, the control parameters (e.g., weeding, intercropping) were adjustable in the CSM so weed emergence could be evaluated in the event a farmer used one or several control practices. Model 3 developers also admitted that key external factors such as temperature and moisture were not included in the calibration of seed decay and germination. The CSM included these factors.

Two critical strengths of model 4 lay in its ability to simulate feedback and specifying a threshold of attachment by *S.* hermonthica onto sorghum. These two specifications in model 4 informed the parameterization of a maize root canopy with max attachment converter in the CSM as well as a reinforcing loop between germinating seed stock and the attachment outflow. Both specifications allowed the CSM to illustrate how the flooding of several thousand germinating seeds (as compared to hundreds of thousands) can still drive max emergence and flowering rates. The developers of the DDFM mentioned that the model did not necessarily demonstrate the relationships between increased soil fertility and consequent crop growth affected parasitism (Westerman et al., 2007). This statement encouraged the inclusion of these three parameters and their respective converters to reflect this relationship. First, manure application was attached to germination to delay germination based on soil-P. Second, legume intercropping was connected to the attachment rate to decrease successful attachments made between the parasite and the host due to reduced appendage growth. Lastly, fertilizer application was connected to the attachment stock to illustrate how fertilizer application and thicker root tissues allowed attachment, but not the siphoning of photosynthates.

As a final note, none of the four models simulated the parasitization of maize by *S*. *asiatica*. The CSM modeled this specific host and parasite species given their cultivation and emergence, respectively, across Malawi. The parasitization of millet and sorghum by *S.* hermonthica is more characteristic of Western and Eastern Africa (Kim et al., 2002). Among the 42 *Striga* species, "*asiatica*" is the most widespread across Africa (Nail et al., 2014).

3.3.2.2 Application of values/equations to parameters

The table below outlines the application of various parameters in the model. The values and/or equations applied to each parameter are explained in the **Appendix 1**. Each explanation is supported by literature and/or previous studies that investigated the germination, attachment, emergence and flowering of *S. asiatica* in the presence of maize across southern Africa. If no values or equations could be found in studies with the aforementioned context, other sources were used with species akin to *S.* asiatica (e.g., *S. hermonthica*) under semi-arid conditions (i.e., Benin).

3.3.3 Greenhouse experiment

A greenhouse experiment was conducted from December 2017 to March 2018 at the Chitedze Research Station in Malawi in order to evaluate the effects of tillage and cowpea-intercropping had on *S. asiatica* emergence in maize based systems. Soils used for the experiment were collected from farmer-managed plots from July 20-22, 2017. Farmers were affiliated with the Conservation Agriculture project funded by Total Land Care (TLC) and CIMMYT-Harare in partnership with the Ministry of Agriculture in Malawi. The project funded by TLC advocates for minimal disturbance of the soil, retaining crop residues on the soil surface during- and off-season and/or rotating legumes. After forming a cooperative (10-12 farmers), cooperatives in communities are given several inputs (fertilizer, maize seed, cowpea seed) by TLC to assist with beginning one or all farming practices.

3.3.3.1 Site Description

Soil sampling took place in the Zidyana and Mwansambo extension planning areas (EPA) which are part of the Salima Agricultural Development Division (ADD), central Malawi. The EPAs are located in the southern region of the Nkhotakota district along the lakeshore plain. Altitude ranges between 200-500 meters above sea level and receive a mean annual rainfall between 600-800 mm. Rainfall commences in November and generally concludes in April. The EPA is generally comprised of alkaline Lithosols having a pH of 6.1. The texture of soils generally ranges between loamy-sand (upper region) to sandy-loam (lower region) given that they are situated near the lake (Kanyama-Phiri et al., 2000). Farmers primarily cultivate maize, cotton (*Gossypium*) and cassava (*Manihot escuelenta*), but rice (*Oryza sativa*) along river valleys.

3.3.3.2 Sampling

Two phases of sampling occurred during the study. The first sampling phase consisted of selecting farmers to collect soils from for the greenhouse experiment. The second sampling phase took place after soils were transferred into pots. During this phase, *S. asiatica* emergent rates were observed in a greenhouse. Each sampling phase is outlined below.

3.3.3.2.1 Farmer field soils

Soils were collected from farmer plots that administered one or all three practices over different periods of time. The practices ranged from-

1.) soil disturbance (ridging [via hand hoe] or zero tillage carried out during November 2016 to prepare fields for the 2016/17 growing season);
2.) soil cover (applied with maize residues or removed post-harvesting); and
3.) crop diversity (cultivated with continuous-maize or intercropped with cowpea).

According to these practices, plots in farmer fields were first segregated into three strata-

1.) minimum tillage + mulching with sole maize (treatment 1 [T1])
2.) minimum tillage + mulching with maize-cowpea intercrop (treatment 2 [T2])
3.) conventional tillage with sole maize (treatment 3 [T3])

Then, plots were further segregated into three sub-strata according to length of practice-

1.) <4 years
2.) 4-7 years
3.) >7 years

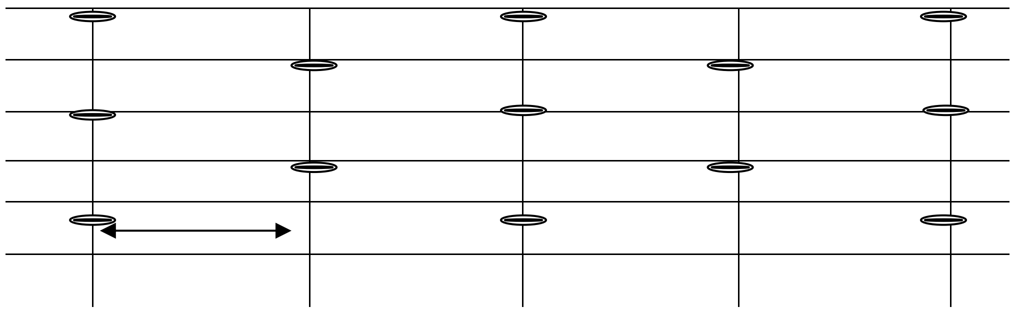
In total, 15 farmers were selected which cultivated all three treatments. Five farmers were selected who had been cultivating the plots for <4 years, five who had been cultivating the plots for 4-7 years and five who had been cultivating the plots for >7 years. Each field was approximately 0.25 ha of which was sub-divided into 3 equal plots (0.08 ac each) for each practice. In T1, farmers administered minimal soil disturbance at time of sowing, crop residues were retained for mulch and maize was planted on a flat plain with rows spaced at 75 cm apart and 25 cm between stations with one seed per station. In T2, the same tillage and residue management were administered with cowpea planted alongside maize, but in between the stations. This equates to 25 kg of maize seed per hectare, equating to 53,000 plants. For cowpea, 35-40 kg seed were sown per ha, equating to 27,000 plants. Treatment 1 and 2 rendered 45-60% groundcover. In T3, no crop residues were retained, ridges were approximately 22-30 cm wide and 75 cm apart. Maize spacing was the same as the two previous treatments (refer to **Table 12** for further clarification about practices associated with treatments). The maize variety used in these plots were hybrid, DKC8033. The cowpea variety used was IT1833. Four bags of fertilizer were applied; two for basal dressing (23-21-0+4S) and two bags of urea (46%) for top-dressing, giving the recommended rate of 69 kg/ha.

Table 12 - Details of Plot Management

	Minimum tillage	Ridging	Residue applied	Cowpea intercrop
Treatment 1	x		x	
Treatment 2	x		x	x
Treatment 3		x		

All samples were collected according to grids defined in sketch below (**Figure 11**). Samples were taken from alternate grids on rows. Second grid sampling points were made half way inside from the first and third grid points. Each sampling point was separated by 20 meters vertically and 10 meters horizontally.

Figure 11 - Sampling procedure conduct in farmer plot



Using a hand hoe, five samples were collected at two sampling depths (0-10 cm and 10-20 cm) in each plot. For T1 and T2, one sample was taken from the 0-10 cm depth, and then in the same hole, another sample was taken at the 10-20 cm depth. For T3, one sample was taken from the ridge (for the 0-10 cm depth) and one sample was taken from the furrow (for the 10-20 cm depth). Therefore, for T1 and T2, 30 samples were taken from the 0-10 cm depth and 30 samples were taken from the 10-20 cm depth. For T3, 30 samples were taken from the ridge and 30 samples were taken from the furrow. A total of 60 samples were taken per field, 180 samples per farmer and 900 soil samples for the entire experiment (see **Table 13**). Each sample consisted of 2 kg soil samples in 5 kg blue polysacks.

Table 13 - Number of soils samples per treatment, depth and field location (ridge vs furrow)

Treatment	Depth	Ridge	Furrow	Total
Treatment A	0-10cm	75	75	300
	10-20cm	75	75	
Treatment B	0-10cm	75	75	300
	10-20cm	75	75	
Treatment C	0-10cm	75	75	300
	10-20cm	75	75	
TOTAL		450	450	900

3.3.3.2.2 Sampling – Greenhouse data collection and protocol

Two types of data were collected from the greenhouse experiment. First, *S. asiatica* emergent rates, and second, soils. Six weeks after sowing (September 9, 2017), emerged seedlings were counted daily. Emergence was observed twelve weeks after sowing (January 12, 2018). Aggregate samples from each farmer according to soil depth and treatment were sampled for soil analysis. In total, 90 samples were collected (15 Farmers x 2 depths x 3 treatments), 6 from each farmer.

3.3.3.3 Greenhouse design

Observation of *S. asiatica* emergent rates were conducted in a greenhouse at Chitedze Research Station. Chitedze is located on latitude 13^0 59' S, and longitude 33^0 38' E, Lilongwe, Malawi. The site is 1146 meters above sea level, has a mean annual temperature of 20^oC and mean annual rainfall of 892 mm. Mean maximum and minimum temperatures are 24^oC and 16^oC respectively (MoAFS, 2007).

3.3.3.3.1 Transfer from field to greenhouse

One composite sample was taken for each depth at each plot to analyze the pH, soil texture, NPK and organic matter. The five samples taken at each plot for each depth were mixed, totaling to approximately 10 kg (5 sampling points x 2 kg) composite sample available for the soil analysis and the greenhouse experiment. Given that 5 kg of soil were needed for filling the 6L pots to analyze emergence in the greenhouse, the remaining approximate 5 kg were available for analysis. Approximately 1 kg was needed for each composite for soil analysis, leaving approximately 4 kg to supplement any 6-liter pot that had a deficit depth after watering. The researchers had to account for deficits, given that some soils were loamier than others. Hence, when watering, the soil depth would decrease, requiring more soil. One 6-liter pot was filled with five samples taken for each plot at one depth. Each pot was sown with a susceptible host (8338-1) (see **Figure 12**). In all, there were 360 samples (i.e., 60 samples per treatment) used for soil analysis; 180 samples for the top layer (0-10 cm) and 180 samples for the bottom layer (10-20 cm) (see **Table 14**).

Figure 12 - Greenhouse experiment at Chitedze Agricultural Research Center

Table 14 - Details of greenhouse sample

Treatment	Depth	Ridge	Furrow	Total
Treatment A	0-10cm	30	30	120
	10-20cm	30	30	
Treatment B	0-10cm	30	30	120
	10-20cm	30	30	
Treatment C	0-10cm	30	30	120
	10-20cm	30	30	
TOTAL		180	180	360

3.3.3.3.2 Labeling & pot organization

Each pot was labeled according to treatment, depth and farmer. As mentioned previously, treatments were labeled as T1, T2 and T3. Depths were labels as A (0-10 cm) or B (10-20 cm). Farmers were coded with the values 1 through 15. For example, Treatment A, taken at 0-10 cm, from farmer 1 would be labeled as T1A1. For the bottom layer (10-20 cm) of the same farmer, the label would read T1B1. Farmer codes were loaded in GenStat (Discovery 18th Edition) 24 times (360 pots / 15 farmers = 24) in chronological order. Then the program randomized the order in one column. In the parallel column, 1 through 360 were inputted. With this order, the pots were placed in the greenhouse in chronological order (see **Table 15)**. In the greenhouse, four blocks were created, equating to 90 pots per block. Each block was comprised of pots with different sampling locations, soil depths and treatments.

Table 15 - Location in greenhouse based on sampling location

[1]**Random # (Pot Placement)**	**Block**	**Treatment**	**Soil Depth**	**Sample Location (Farmer #)**	[2]**Corresponding Code**
1	1	Continuous CA + Sole maize *(T1)*	0 -10 cm *(A)*	2	*T1A2*
57	1	Sole maize conventional tillage (*T3)*	10 -20 cm *(B)*	14	*T3B14*
91	2	CA + Maize/legume intercrop 2 *(T2)*	0 -10 cm *(A)*	2	*T2A2*
116	2	CA + Maize/legume intercrop *(T2)*	10 -20 cm *(B)*	14	*T2B14*
188	3	Sole maize conventional tillage (*T3)*	0 -10 cm *(A)*	10	*T3A10*
226	3	Continuous CA + Sole maize *(T1)*	10 -20 cm *(B)*	3	*T1B3*
310	4	CA + Maize/legume intercrop *(T2)*	0 -10 cm *(A)*	8	*T2A8*
352	4	Sole maize conventional tillage (*T3*)	10 -20 cm *(B)*	7	*T1B7*

[1]Written on tag in pot
[2]Written on pot
*Note: Farmers 1 through 5 corresponded to 0-4 years of practice; farmers 6 through 10 corresponded to 4-7 years of practice; farmers 11 through 15 corresponded to >7 years of practice

3.3.3.3.3 Management protocol

On July 15th (2017) all pots were transferred to the greenhouse. For a two-week period, pots were watered each morning using a watering can with a fine rose top to keep the soil moist and avoid hard pan forming on the surface. This action was carried out to mimic the two-week conditioning period where *S. asiatica* received rainfall in farmer fields from light rains in November. After two weeks of conditions, all pots were sown with maize on July 29th, 2017. After which, watering was continued daily for 3 months to mimic the rainy season. Watering was based on physical observation of whether the pot was dry or not to avoid overwatering of the seeds. Pots were not perforated to avoid the leaching of nutrients and reduced moisture stress. In previous experiments, perforated pots dried quickly and required researchers to water plants frequently (3 times per day). In addition, dry pots increased plant stress (Mwale, 2009).

Pots were applied two weeks after sowing (August 17th, 2017) with a basal application of the same fertilizer (23-21-0+4S) used in farmer fields. Pots were applied with the equivalent amount of 33 kg NPK/ha. Application was only made on pots where emergence occurred so as to mimic fertilizer application practices employed by farmers. Fertilizer is applied in this manner to avoid application to seeds that will not emerge. No side dress of Urea was made given that few farmers in the sample had done so in the past nor was it considered as a common practice countrywide given the state of poverty.

3.3.4 Analysis

3.3.4.1 Greenhouse

3.3.4.1.1 Soil

At the Chitedze Agricultural Research Center, samples were analyzed for pH, % organic matter, % nitrogen (NO_3-N), phosphorous (ug/g), potassium (Cmol/Kg), % sand, % silt and texture class. Analyses were conducted by six soil technicians in the Malawian Ministry of Agriculture Soil Analysis Lab. The lab was located at the Chitedze Agricultural Research Center. Soil was passed through a 2 mm screen after being air-dried. Soil-P and K were determined using an ammonium fluoride (NH_4F) and an ethylenediaminetetraacetic acid (EDTA) based extradant that is associated with extractants used in the semi-arid tropics (Wendt, 1995). Soil pH was determined in 1:2.5 soil/water ratio (Snapp et al., 1998). Texture was assessed by dispersal and hydrometric readings (i.e., a measure of density) (Anderson & Ingram, 1989).

As discussed in previous sections, *Striga spp*. emergence is associated with different levels of nitrogen, phosphorous, potassium and soil texture. The connection between organic matter (OM) and Striga emergence is more abstract than nitrogen, phosphorous, potassium and soil texture. While abstract, OM was collected for several reasons. OM is composed of living and decomposing plant and animal remains. Different percentages of OM are associated with different practices and lengths of implementation. For example, consecutive annual applications of mulch can increase OM. In addition to sand, silt and clay, soils are composed of OM particles. Clay and OM have net negative charges. That is, they are composed of more negatively charged ions (i.e., anions) than positively charged ions (i.e., cations). The net charge of soils determines their anion exchange capacity (AEC). AEC influences the ability of soil particles to absorb negatively charged minerals, such as inorganic forms of phosphorous (i.e., orthophosphate [H_2PO_4-]). AEC is affected by amount of clay particles it is comprised of as well as the addition of OM. More clay particles and OM allows for more inorganic-P to be captured and later assimilation by plants such as maize. As the quantity of clay particles increases, the P-sorption capacity increases (Cordell et al., 2009). Clay particles have relatively larger surface area than sand particles which affords for more phosphate sorption. The addition of OM provides organic phosphate which can be converted to inorganic forms of phosphate later. Also, organic anions from OM can displace sorbed phosphate that are tightly bound to positively charged particles, liberating them for plant uptake (Buresh & Tian, 1997). Furthermore, humus in OM coats aluminum and iron oxides, which reduce P sorption by positively charged soil particles (Cordell et al., 2009). As more phosphorous become available, secrete less strigolactones. Reduced secretion of strigolactones decreases and/or delays Striga germination rates.

3.3.4.1.2 Emergent rates

Parametric tests were planned to be used to analyze emergent rates across practice and/or length of implementation. More specifically an analysis of variance (ANOVA) was going be used to determine if there are any statistical differences between practices and/or length of implementation. If there were, then t-tests would be used to analyze if there are any positively or negatively significant relationships between *S. asiatica* emergence and practice. These tests were not used, reasons for why they were not used are explained in the results section.

3.3.4.2 Model runs

3.3.4.2.1 Sensitivity analysis

A sensitivity analysis was used to evaluate how subtle changes in parameters of the CSM affected the seedbank population as well as attachment, emergence and flowering rates of *S. asiatica*. In crop modeling, sensitivity analyses are used to investigate the resistance and resilience of simulated outcomes against certain events (Patten, 2013). Previous studies have evaluated how different climate parameters affected germination (Elzein & Kroschel, 2003). In this study, lifecycle stage parameters, such as monthly germination rate and monthly successful attachment rate were adjusted 25-50% from their specified averages in the CSM to determine their effects upon subsequent populations, such as emergent seedlings and mature adults.

3.3.4.2.2 Scenario analysis

Scenario analyses are typically conducted in dynamic crop models to investigate the relationship between model outcomes and parameters guided by manager modules (Patten, 2013). For example, the integration of legumes in cereal systems are initiated in manager modules to determine the volume of soil-N associated with intercropping (Waddington, 2002). A scenario analysis, therefore, was conducted to determine which stage or stages of the *S. asiatica* lifecycle were notably affected by a single management parameter (e.g., weeding, intercropping). In addition, the extent to which each stage or stages was affected by a management parameter was assessed. Thereafter, different management practices were initiated together to determine which combination reduced one or multiple stages in the least number of months. Such analyses are generally conducted in a consecutive manner, adding one practice after another, to assess the number and type of practices required to bring a lifecycle stage to an acceptable threshold (University of Honhenheim, 2015). These analyses entail running the model with status quo practices (e.g., hand pulling) first and then adding newer practices such as fertilizer application and/or intercropping.

3.3.4.2.3 Validation

When testing the accuracy of process-based models, it is important to compare model output with field observations. “The comparison is often based on correlation between the calculated and measured values, and regression of measured on calculated values” (Kobayashi & Salam, 2000, p. 345). In this manner, field observations (i.e., *S. asiatica* counts) are plotted against simulated outcomes, a correlation coefficient is calculated and regression lines are fitted. Unfortunately, there were not enough emergent seedling observations to compare model behavior across different soils, practices and lengths of implementation. Another avenue used to validate model behavior is by comparing runs against the results of other peer-reviewed articles. For instance, the use of legume intercrops in combination with other SFM practices (e.g., fertilizer application) should take no less than 3 years to significantly reduce the soil seedbank (Abunyewa & Padi, 2003; Franke et al., 2006; Murdoch & Kunjo, 2003; Oswald & Ransom, 2001; Schulz *et al*., 2003). This behavior is exemplified in Model 3 by Van Mourik et al. (2008). Model runs can also be validated if the behavior of specific stocks respond to specific controls. For example, Model 4 exemplified drastic differences in attachment between traditional sorghum and *S.* hermonthica-resistant sorghum varieties (Westerman et al., 2007). If a control, such as weeding is loaded in the CSM, drastic drops in mature *S. asiatica* populations should be reflected in the results.

3.4 Results & Discussion

3.4.1 Soil

Soil analyses revealed subtle differences in soil-acidity, organic matter (OM), nitrogen (N), phosphorous (P), potassium (K), percent clay, percent silt and overall texture between *S. asiatica* control practices, sampling depth and length of practice. These differences are presented in **Table 16**.

Table 16 - Soil analyses of practices by length of implementation and soil depth

		Continuous Maize + Minimum Tillage + Mulch				**Maize-Cowpea Intercrop + Minimum Tillage + Mulch**				**Continuous Maize + Tillage**				**All Practices**
		0-4 Years	*4-7 Years*	*>7 Years*	*All Years*	*0-4 Years*	*4-7 Years*	*>7 Years*	*All Years*	*0-4 Years*	*4-7 Years*	*>7 Years*	*All Years*	*Avg.*
Text Class[1]	*0-10cm*	2.40	2.60	2.60	2.53	4.10	3.00	2.80	2.97	2.90	3.00	2.50	2.80	2.71
	10-20cm	3.70	2.50	2.70	2.73	2.90	2.80	2.60	2.77	2.40	2.60	2.40	2.47	
	Both Depths	2.70	2.55	2.65	2.63	3.00	2.90	2.70	2.87	2.65	2.80	2.45	2.63	
OM[2]	*0-10cm*	2.35	1.98	2.19	2.18	2.68	2.48	2.32	2.49	1.97	2.09	2.22	2.09	2.24
	10-20cm	1.88	1.78	2.46	2.04	2.27	2.10	2.87	2.41	2.00	1.88	2.85	2.24	
	Both Depths	2.12	1.88	2.32	2.11	2.48	2.29	2.59	2.45	1.98	1.98	2.54	2.17	

Table 16 (cont'd)

[3]**Clay**	*0-10cm*	15.04	12.46	17.94	15.15	17.84	12.40	18.34	16.19	19.04	11.60	16.74	15.79	16.58
	10-20cm	20.24	13.77	20.34	18.11	19.84	13.20	19.54	17.53	15.84	14.00	20.34	16.73	
	Both Depths	17.64	13.12	19.14	16.63	18.84	12.80	18.94	16.86	17.44	12.80	18.54	16.26	
[4]**Sand**	*0-10cm*	78.56	80.74	77.66	78.98	79.36	84.80	76.86	80.34	77.36	85.60	78.06	80.34	79.25
	10-20cm	76.16	80.8	74.86	77.28	76.16	84.80	76.46	79.14	80.56	82.80	74.86	79.4	
	Both Depths	76.86	80.77	76.26	78.13	77.76	84.80	76.66	79.74	78.96	84.20	76.46	79.87	
pH	*0-10cm*	6.12	6.20	5.76	6.02	6.08	6.30	5.94	6.12	5.99	6.21	5.95	6.05	6.04
	10-20cm	6.06	6.06	5.86	5.99	5.96	6.23	5.95	6.05	6.06	6.05	5.93	6.01	
	Both Depths	6.09	6.13	5.81	6.03	6.02	6.27	5.95	6.07	6.03	6.13	5.94	6.01	
[5]**N**	*0-10cm*	0.12	0.10	0.11	0.11	0.13	0.12	0.12	0.12	0.10	0.10	0.11	0.10	0.11
	10-20cm	0.09	0.09	0.12	0.10	0.11	0.11	0.14	0.12	0.10	0.09	0.14	0.11	
	Both Depths	0.11	0.09	0.12	0.11	0.12	0.11	0.13	0.12	0.10	0.1	0.13	0.11	
[6]**P**	*0-10cm*	73.06	32.70	25.33	43.70	62.37	56.30	26.40	48.36	59.88	26.22	33.83	39.98	39.69
	10-20cm	47.24	28.16	25.47	33.62	66.77	32.50	25.81	41.69	50.71	15.91	25.81	30.82	
	Both Depths	60.15	30.43	25.50	38.66	64.57	44.40	26.11	45.02	55.30	21.06	29.83	35.50	
[7]**K**	*0-10cm*	0.09	0.06	0.12	0.09	0.10	0.08	0.14	0.11	0.09	0.08	0.18	0.12	0.10
	10-20cm	0.07	0.05	0.13	0.08	0.07	0.06	0.14	0.09	0.08	0.07	0.13	0.09	
	Both Depths	0.08	0.06	0.13	0.09	0.09	0.07	0.14	0.10	0.09	0.07	0.16	0.11	

[1]Text Class represents an ordinal value of soil texture where 1 = sand, 2 = sandy loam, 3 = loam, 4 = silty loam, 5 = clayey loam, 6 = silty clay and 7 = heavy clay
[2]OM represents total percent organic matter in soil
[3]Clay represents total percent clay in soil
[4]Sand represents total percent sand in soil
[5]N represents total percent nitrogen in soil
[6]P represents soil-phosphorous measured in units of micrograms by gram (ug/g)
[7]K represents soil-potassium measured in units of centimoles by kilograms Cmol/Kg

The physical characteristics of each soil across practices, sampling depth and length of practice varied little. All samples were characterized as primarily sandy loams (40) or loamy sands (42), aligning with regional classifications of soil within the central region of Malawi (Snapp et al., 1998). Soil texture varied little across practices, especially with regard to clay content (μ=16.58%). The sample mean (79.25%) of sand was similar to regional averages (78.21%). The same can be said for OM, where the sample average (2.24) differed slightly from the regional average (2.10%) (Kamanga, 2011). Intercropping assumed the highest percentage as compared to mulching (2.11%) and tillage (2.17%). The higher average among intercropping practices may be due to the application of both maize and legume residues.

Chemical composition varied little as well. All practices were found to have slightly acidic (μN=6.04) soils which aligns with the regional average. Intercropping soils were marginally more alkaline than soils cultivated without legumes. Overtime, maize cultivation and fertilizer application practices may have decreased the pH, if only slightly, across years. Percent nitrogen and potassium were virtually the same (μN=0.11%, μK=0.10%) across all farming practices, sampling depths and lengths of practice. The regional average of soil-N (0.06%) explains that nitrogen, while higher as a sample average, is considered as one of the most limiting factors to production among smallholders (Snapp et al., 2014).

More noticeable differences were found between soil-P and treatments. For example, intercropping illustrated a 16-22% difference in available phosphorous compared to its counterparts. Higher levels may be attributed to the liberation of phosphorous in the legume rhizosphere and increased microbial biomass (Tang et al., 2014). Attributing higher phosphorous availability between treatments should be cautioned however, as the sample average (39.69 ug/g) was larger than the regional average (24.2 ug/g) (Snapp et al., 1998). In addition, some treatment plots were not located in a single field, but separate fields. Dissimilar soil-P levels, therefore, may be attributed to field variability. The physical and macronutrient soil properties provide optimal conditions for *S. asiatica* germination and attachment being that soil is slightly acidic and has low CEC (as evidenced by low OC/OM). Under such conditions, it is difficult for maize to assimilate what little micronutrients are available, obligating the crop to release high concentrations of strigolactones (Gebreslasie et al., 2018).

3.4.2 Emergence

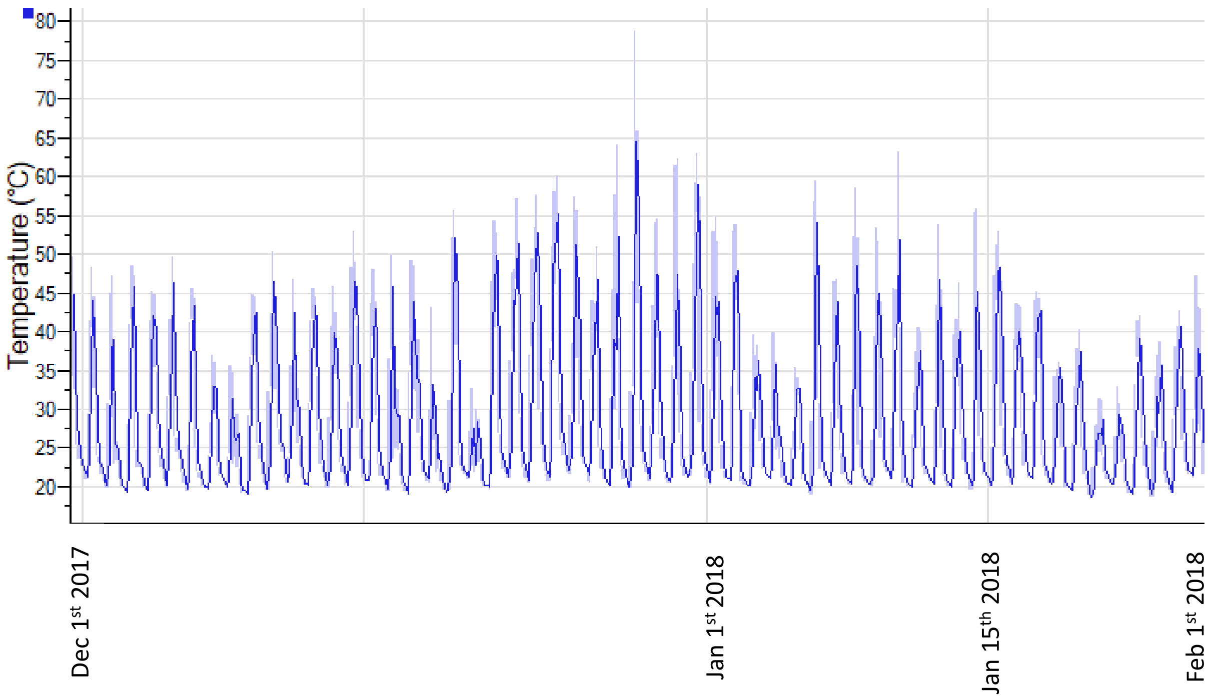
Very few Striga successfully emerged from pots in the greenhouse (see **Table 17**). No statistical inferences could be made from the small number of observations across practices, depth of sampling or length of practice. The highest frequency was found among practices that excluded mulching and intercropping. In addition, more emergence was observed at shallower soil depths. These observations concur with previous studies suggesting that legumes, minimum tillage and mulching are associated with lower emergence rates when compared to continuous maize cultivation and tillage practices (Thierfelder et al., 2015).

Table 17 – *S. asiatica* emergence by practice, length of implementation and soil depth

		Continuous Maize + Minimum Tillage + Mulch				**Maize-Cowpea Intercrop + Minimum Tillage + Mulch**				**Continuous Maize + Tillage**				**All Practices**
		0-4 Years	*4-7 Years*	*>7 Years*	*All Years*	*0-4 Years*	*4-7 Years*	*>7 Years*	*All Years*	*0-4 Years*	*4-7 Years*	*>7 Years*	*All Years*	*TOTAL*
Striga Counts	*0-10cm*	3	0	0	3	3	0	0	3	2	2	0	4	10
	10-20cm	2	1	1	3	0	0	0	0	2	2	1	4	7
	Both Depths	4	1	1	6	3	0	0	3	3	4	1	8	17

Failed emergence may have been attributed to a number of factors. Germination and attachment may have occurred, but hosts may have not been healthy enough to support one or more parasites. The health of maize plants was most likely compromised by repeated exposure to maximum temperatures (>35C°) in the greenhouse (see **Figure 13**). The ideal, or rather, base temperature of maize is approximately 26°C (Sánchez et al., 2014). Exceeding base temperatures, shortened the thermal time it took maize to reach full maturity.

Figure 13 - Greenhouse average daily temperature during experiment



Plants progress through different phenological stages (e.g., vegetative, reproductive) based on degree-days or heat units, as opposed to calendar-days or hour units (Ritchie & NeSmith, 1991). Their lifecycle or progression of through phenological stages are closely related to their thermal environment. The photoperiod is also used to modify thermal time. When plants are exposed to higher base temperatures under adequate soil-moisture and nutrient conditions, they progress through various vegetative stages at the expense of biomass production. With little biomass, organs (e.g., roots) are not adequately developed to support critical phenological stages (e.g., grain filling), and in the case of this experiment, expire prematurely (Tebaldi & Lobell, 2018).

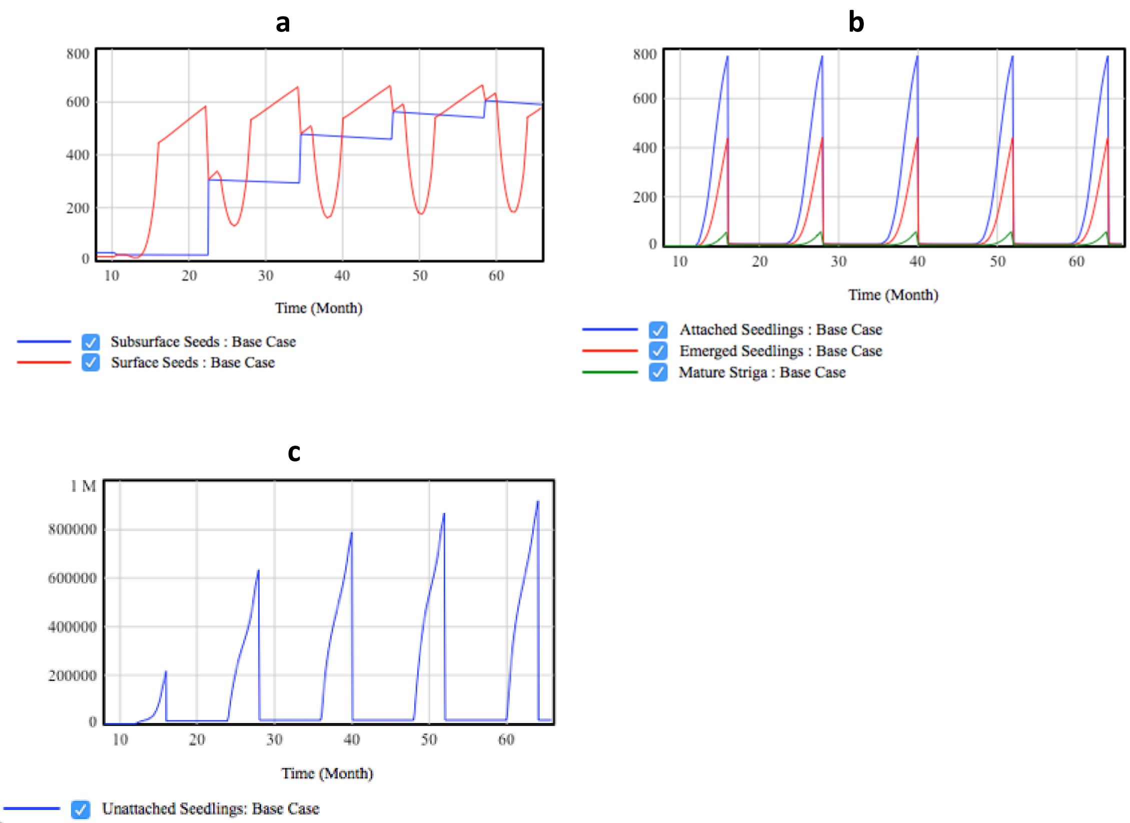
In the greenhouse experiment, maize had reached the VT-R1 stage in week 7 (44-49 days), which is 2-3 weeks earlier than normal. Hastened growth may have jeopardized the emergence of *S. asiatica* in several ways. First, dwarfed root systems may have not reached certain areas of the soil where seeds were present. Observation revealed many of plants did not have a fully developed root system that reached the wider and lower soil depths of their 6-liter pots. Second, moisture is critical at the R1 stage. Even with daily water application, heat stress and transpiration during this critical period may have caused the plants to die. Increased transpiration from leaves may have left little water to secrete leachates to trigger germination and/or supply a vigorous root system to support parasites. Third, pots were not perforated to prevent seed loss. Without drainage, fertilizer losses (with ample phosphorous) were probably minimal, leaving a pool for maize to assimilate phosphorous from. With this available pool, maize may have secreted little strigolactones to signal fungi to assist with the assimilation of phosphorus. Minimal secretion of strigolactones may have hindered *S. asiatica* germination.

3.4.3 Model runs

3.4.3.1 Sensitivity analysis

The behavior of the model will first be explained absent of any control prior to assessing its sensitivity to variations in individual parameters. In **Figure 14(a)**, there is an initial decrease in surface seeds (0-10 cm) in month 11/23/35/47 given that 50% of the surface level seed population is circulated via ridging in November to the subsurface seed stock. After which, a second reduction occurs in the surface seed population whereby seeds germinate from month 12/24/36/48/60 to 16/28/40/52/64. Then, there is a sharp spike because seeds are being dropped by mature flowers. In the offseason (month 17/29/41/53 to 23/35/47/59), there is a slow increase because seeds are still settling from transpiring flowers. Across 60 months, the surface level seed population quickly reaches a peak, leveling out at 700 million seeds. The subsurface seed (0-10 cm) population increases in a stepwise manner, spiking in months 11/23/35/47 from the transfer of seeds from 0-10 cm depth via ridging. Between months 12/24/36/48/60 and 23/35/47/59 there is marginal decline in subsurface seeds due to decay and predation.

Figure 14 - Base case runs: seedbank (a), germination (b), attachment-emergence-flowering (c)



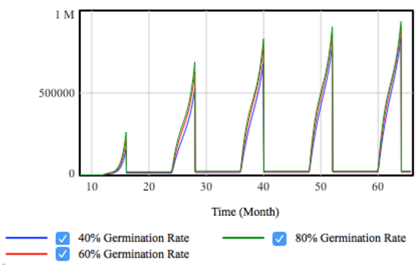
**Note: The Y-axis of graph A is scaled in millions. Graph B and C are scaled in thousands*

In **Figure 14 (b** and **c)**, between months 12/24/36/48/60 and 16/28/40/52/64, seeds germinate, attach to the host, emerge from the soil and flower. In **Figure 14(b)**, the model demonstrates an increasing S-curve, whereby the germinating seed population reaches a maximum population of 950,000. In **Figure 14(c)**, the large number of germinating seeds occupies any and all available attachments; hence max attachment (775,000), emergence (425,000) and mature flowering (50,000) populations are reached in the first cropping season and persist into the proceeding seasons. Base case runs demonstrate how quickly a 1 ha field can become inundated with *S. asiatica* seed, seedlings and flowers. With no controls, max saturation in almost all stocks is reached in 65 months. The behavior of the model (e.g., exponential growth) reflects what practitioners may observe in the subsurface seed and unattached seedling stocks across a 1 ha Malawian smallholder field if no controls are implemented (Ejeta, 2007). One result which validates the model is that max flowering reaches approximately 70,000 flowers. Being that there are 54,000 hosts (which can potentially support 918,000 parasites), one may expect more than 1-2 flower per maize plant (70,000 flowers/ 54,000 maize plants = 1.30 flowers per maize plant). This was observed in a field cultivated by one of the participants of the study.

3.4.1.3.1 Germination rate

In the base case run, the monthly germination rate ranged between 60% to 80% based on monthly rainfall and temperature. For the sensitivity analysis, the germination rate was altered between 40% to 80%. As the germination rate increased by 25%, the CSM only reflected noticeable changes in surface/subsurface seed stocks. This finding validates the behavior the CSM based on earlier studies which found varying germination rates affected the seedbank, but not necessarily attachment (Vallance, 1950). The CSM did not reflect any moderations in attachment, emergence or flowering if the germination rate was altered. The CSM did demonstrate, however, more noticeable differences between unattached seedlings with varying germination rates (see **Figure 15**). Each 25% increment in germination (e.g., 40% to 60%) reflected approximately a 17% increase in germination (e.g., 500,000 to 600,000).

Figure 15 - Monthly unattached seedlings in association with varying germination rates

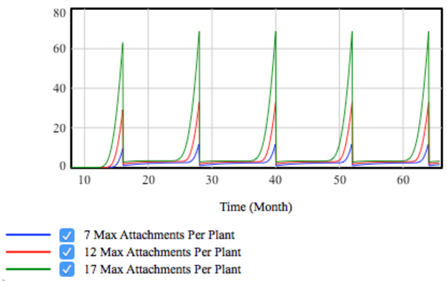


**Note: The Y-axis of graph is scaled in thousands*

3.4.1.3.2 Attachment rate

In the base case run, the monthly attachment rate ranged between 13 and 17 parasites per maize plant based on the basal application of N-based fertilizer. For the sensitivity analysis, the attachment rate was altered between 7 and 17 parasites per maize plant. As the attachment rate was altered, noticeable changes were seen across all stocks, particularly the flowering (see **Figure 16**). The flowering population associated with 17 attachments reached 70,000 by the second season and sustained this population into the following seasons. The flowering populations associated with 7 and 12 attachment rates were sustained at 9,000 and 29,000, respectively. Based on these rates, there was approximately an 86% difference between the lowest and highest attachment rates, indicating a strong reduction in seeds dropped by flowers, unattached seedlings, and consequently, emerged seedlings. It appears then, monthly attachment rate is one of the (if not the most) sensitive parameters of the CSM. Previous studies validate this behavior, arguing that *Striga spp*. resistant varieties drastically reduce the parasite seedbank via reduced attachment within three seasons (Westerman et al., 2007).

Figure 16 - Monthly flowers in association with varying attachment rates



**Note: The Y-axis of graph is scaled in thousands*

3.4.1.3.3 Emergence and flowering rate

In the base case run, the successful emergence fraction (i.e., monthly emergence rate) did not change from its base value (70%) because no other parameters were attached to this fraction. For the sensitivity analysis, the germination rate was altered between 34% and 70%. A 25% decrease in the emergence fraction equated to a 33% decrease in the surface and subsurface seed populations (see **Figure 17**). Similar behavior of these stocks was seen when the flowering rate decreased by 25% (e.g., 25%, 38%, 50% flowering rate). No changes were reflected in attached seedlings or mature *Striga* in the proceeding seasons when emergence varied. When flowering rates were varied between 25% and 50%, attachment remained at the same population as its base case (see **Figure 18**). Attachment did not fluctuate due to the inundation of unattached seedlings occupying potential attachment sites. Even with little emergence or flowering, the fecundity of *S. asiatica* (34,000 seeds per flower) provided over one million seeds with just 30 flowers. The behavior in the CSM concurs with previous studies that contend reductions in seedling emergence or flowering rates are ineffective in controlling *S. asiatica* due to its overwhelming fecundity (Khan et al., 2002).

Figure 17 - Monthly surface seeds in association with varying successful emergence fractions

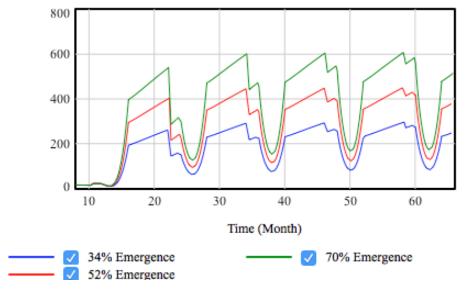
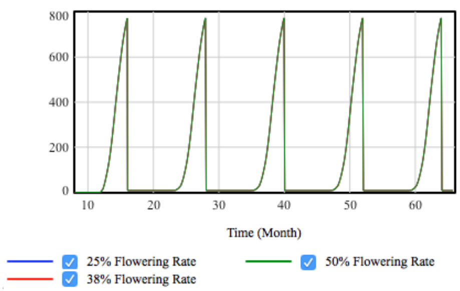


Figure 18 - Monthly attachments in association with varying flowering success fractions



**Note: The Y-axis of graph A is scaled in millions. Graph B is scaled in thousands*

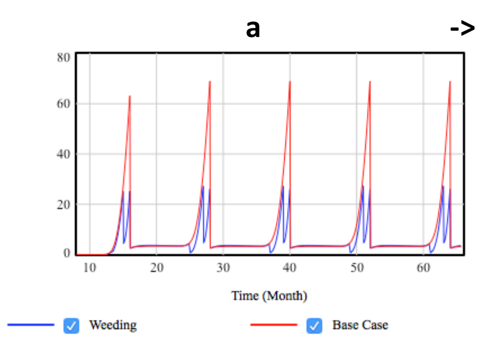
3.4.4.2 Scenario analysis

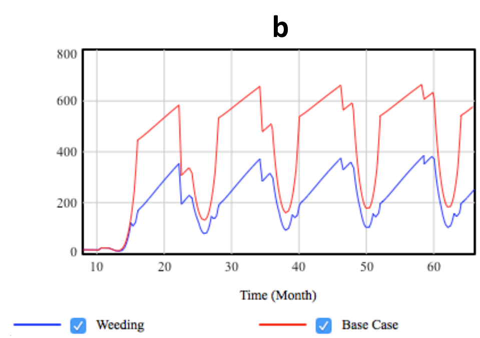
Practices were individually run in the CSM to highlight any notable behavior at certain lifecycle stages across time. Identifying this behavior informed which practices to combine and how their aggregation addressed emergence (if at all) in a specific timespan. Weeding and manure application are some of the most widely implemented control practices implemented by smallholders in the region (Orr et al., 2002). Legume intercropping or mulching (e.g., conservation agriculture) are relatively newer and costlier (e.g., additional seed cost) when compared to the aforementioned practices (Giller et al., 2009). The combination of new and traditional practices ran in the CSM were done so based on their practicality to smallholder settings (e.g., labor constraints, financial scarcity, compliments already-implemented practices).

3.4.4.2.1 Weeding

Weeding in January and March illustrated a sharp decline in the mature *Striga*, yet the population remained at approximately 25,000 in the CSM (see **Figure 19[a]**). The sharp decline does little to re-emerging seedling and mature flower populations. To elaborate, the slope of mature *Striga* in a weeding scenario was similar to the slope of the base case, illustrating that timely weeding was ineffective to controlling *S. asiatica* emergence. This may be attributed to *S. asiatica* emerging in areas where smallholders began weeding before they finish weeding an entire 1 ha field. Sharp declines in the Mature *Striga* stock led to minor dips in the surface seed population three months after weeding months (see **Figure 19[b]**). There were noticeable differences in surface seedbank populations between the base case and weeding runs (350 million vs 590 million), but with a high seedbank feeding into the unattached seedling stock, the attached seedling population is unaffected by weeding. Disconcertingly, this is the stage maize yield is negatively affected the most by parasitism (Frost et al., 1997). The finding agrees with the argument that timely weeding throughout the season is ineffective in reducing *Striga spp*. emergence (Joel, 2000).

Figure 19 - Reductions in monthly Mature Striga (a) and surface seed (b) in response to weeding



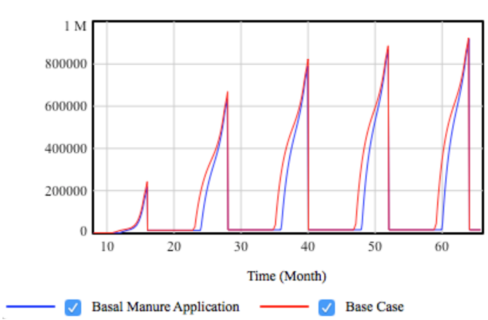


**Note: The Y-axis of graph A is scaled in thousands. Graph B is scaled in millions*

3.4.4.2.2 Manure application

The CSM demonstrated that manure application delayed the onset of germination. As evidenced by multiple studies, basal applications of well-decomposed manure (which at that point is considered compost) can delay germination when applied at planting (Yoneyama et al., 2007; Sherif, 1986). Soil-P availability is contingent upon several conditions (e.g., pH, soil moisture), but the CSM demonstrated a delay in germination by one month, reducing the unattached seedling population marginally (850,000 vs 800,000) (see **Figure 20**). Soil-P pools that remain longer around the root canopy (e.g., January) can decrease window of germination (e.g., 4 months vs 3 months), equating to more evident reductions in the unattached seedling population. Larger applications can achieve this objective, but damage maize seedlings if the manure is not fully decomposed (i.e., nutrient burning) or applied under dry conditions (Materechera, 2010). This finding suggests the repeated application of manure could significantly reduce emergence, which seems to be little studied. Smallholders may not have access to an extensive amount of well-decomposed manure, or the labor to repeatedly apply the input at an effective rate (Schulz et al., 2003).

Figure 20 - Monthly unattached seedlings in response to basal manure application

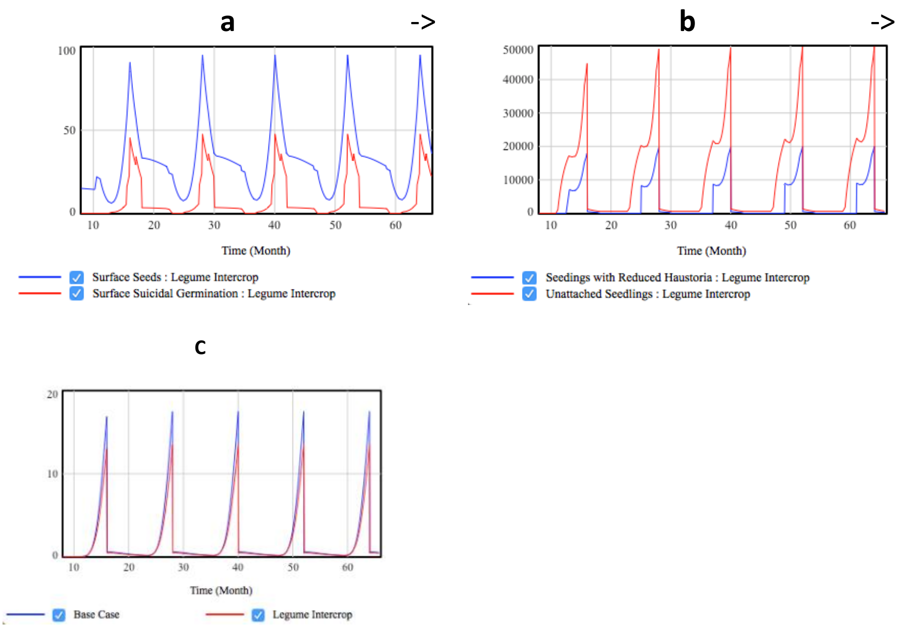


3.4.4.2.3 Intercropping

The CSM indicated legume intercrops were associated with reductions in the *S. asiatica* seedbank, unattached seedlings and mature flowers as a result of suicidal germination, reduced haustorium growth and shading, respectively (Sanginga et al., 2003; Oswald et al., 2002). In **Figure 21(a)**, the surface seed stock did not accumulate into February (month 14/26/38/50/62), but rather, abruptly decreased as additional germination was triggered by legume leachates, countering an increase in the population from flowering. In the offseason (month 17/29/41/53 to 23/35/47/59), there was a less steep decline in surface seeds, but a decline none the less, due to continued suicidal germination from decomposing legume residues.

In **Figure 21(b)**, an influx of unattached seedlings with truncated haustoria did not lead to a reduction in attachment or emergence. Certain legumes (e.g., *Desmodium spp*.) have shown to significantly reduce *Striga spp*. seedbank and its related emergence in several seasons (Khan et al., 2002). The reduction was not only attributed to suicidal germination, reduced haustoria growth, but also soil-N contributions. The CSM demonstrated with cowpea could not decrease emergence given that little soil-N was contributed. In comparison, cowpea is a poor N-fixer relative to *Desmodium* spp. (Piha & Munns, 1987). Had there been more N contributions, perhaps the CSM would have indicated reduced attachment and consequent emergence in this scenario. Shading from the legume canopy did reduce mature flowering population slightly (**Figure 21[c]**). Reductions via legume canopy is noted in the literature (Kureh et al., 2006). In a separate scenario, mulching demonstrated the same effect legumes had on the mature *Striga* stock. The CSM demonstrated that legumes do not necessarily reduce attachment, but reduce *S. asiatica* emergence by keeping the seed bank and flowering population below a certain threshold. The finding implies maize-cowpea intercropping alone will not successfully reduce *S. asiatica* emergence in the long-term.

Figure 21 - Monthly seedbank (a), unattached seedlings (b) and mature Striga (c) reductions in response to cowpea intercropping



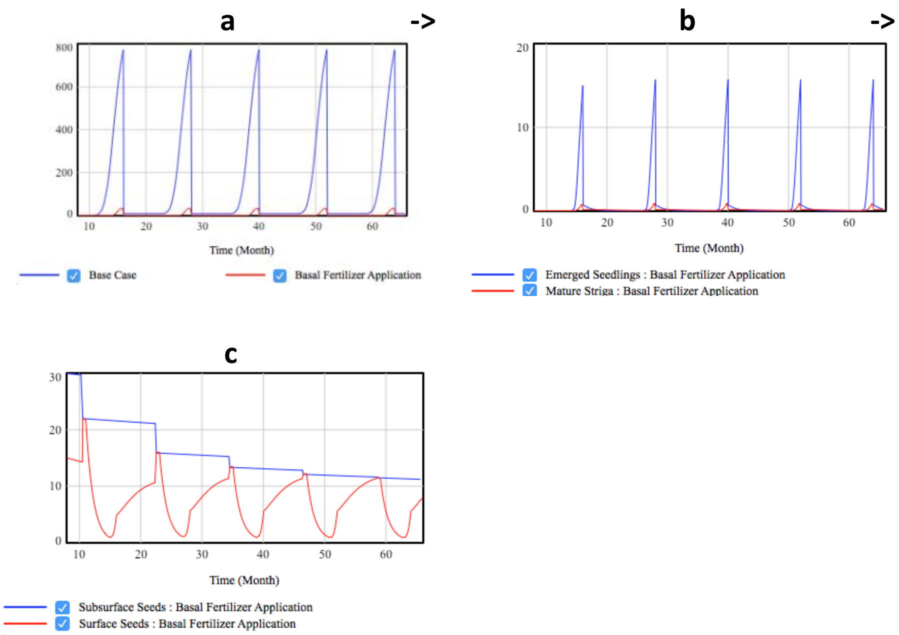
**Note: The Y-axis of graph A is scaled in millions. Graph B and C are scaled in thousands*

3.4.4.2.3 Fertilizer Application

The CSM illustrated a stark reduction in attachments (see **Figure 22[a]**) in response to a basal fertilizer application at planting, equating to reductions in emerged/mature *Striga* (**Figure 22[b]**) and the seedbank (**Figure 22[c]**). The reduction in successful attachment corroborated findings whereby N-based fertilizer applications were associated with >40% reductions in *S. asiatica* emergence (Dugje et al., 2006). Like legume-intercropping, the CSM demonstrated fertilizer applications reduced flowering and seed stock population to a point, but not enough to eradicate the weed in a 5-year timespan. Seedbank behavior did not demonstrate a decreasing trend in the off-season as evidenced by the previous intercropping scenario. Fertilizer application reduced emergent seedling and mature *S. asiatica* rates by approximately

96% (50,000 vs 425,000) and 97% (2,000 vs 70,000), respectively, relative to the base case. These notable changes were attributed to the voluminous starting seedbank. Had it been smaller, the changes would not have been noteworthy. Previous studies argue the effect of a control practice, such as N-applications, is more evident in fields with higher infestations (Carson, 1989).

Figure 22 - Monthly attachment (a), seedling/flowering (b) and seedbank (c) reductions in response to N-based basal fertilizer application at planting

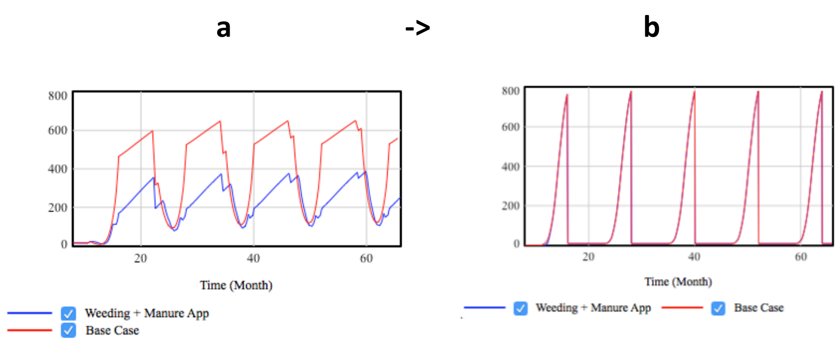


**Note: The Y-axis of graph A and B are scaled in thousands. Graph C is scaled in millions*

3.4.4.2.6 Aggregated practices

The application of manure at planting in coordination with weeding lowered the surface seed bank to a threshold (375 million) (see **Figure 23[a]**). The decrease had no effect on attachment (see **Figure 23[b]**). The delay in germination (**Figure 23[a]**), deduction of emerged seedlings and removal of flowers twice did little to decrease emergence. The finding suggests two weedings and one basal application of manure at planting will not address attachment and subsequent seedling emergence. The finding disagrees with previous findings suggesting this strategy will control *Striga spp*. within 3-4 seasons (Oswald, 2005). The behavior of the CSM illustrated weeding and manure application are either not addressing enough stages in weed lifecycle or not substantially decreasing stocks to reduce emergence. This control strategy is typically implemented by smallholders who cannot afford additional inputs, and without them, the weed will likely persist. The model was not parameterized to simulate the *S. asiatica* lifecycle, not maize yield, but if it was, we would expect 30-100% losses across 3-5 growing seasons (Oswald, 2005).

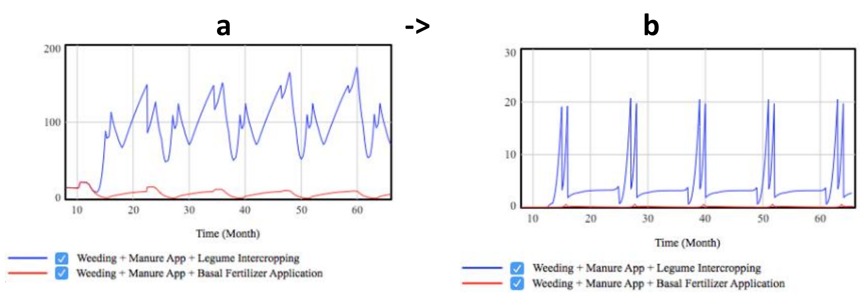
Figure 23 - Monthly surface seed (a) and attachment (b) reductions in response to weeding + manure application



**Note: The Y-axis of graph A is scaled in millions. Graph B is scaled in thousands*

The addition of intercropping or fertilizer to traditional smallholder practices in the CSM illustrated different outcomes. In **Figure 24(a)**, the addition of intercropping to traditional practices kept subsurface seeds under a 175 million threshold. The addition of fertilizer application kept subsurface seeds under a 20 million threshold. While there were stark differences between the two control strategies, 20 million seeds feeding into the unattached seedling stock of the CSM allowed approximately 40,000 attachments. In **Figure 24(b)**, fertilizer application, appeared to be a more effective addition to manure application and weeding as opposed to intercropping. Still, several thousand flowers survived in response to manure application, weeding and fertilizer application. This finding indicates fertilizer appears more effective in managing emergence, but the survival of flowers allowed seeds to be dropped, germinate and attach to maize. By allowing monthly attachment to reach a small threshold each season, even just several thousand across one hectare, *S. asiatica* still remains a significant threat to maize yield (Kim et al., 2002).

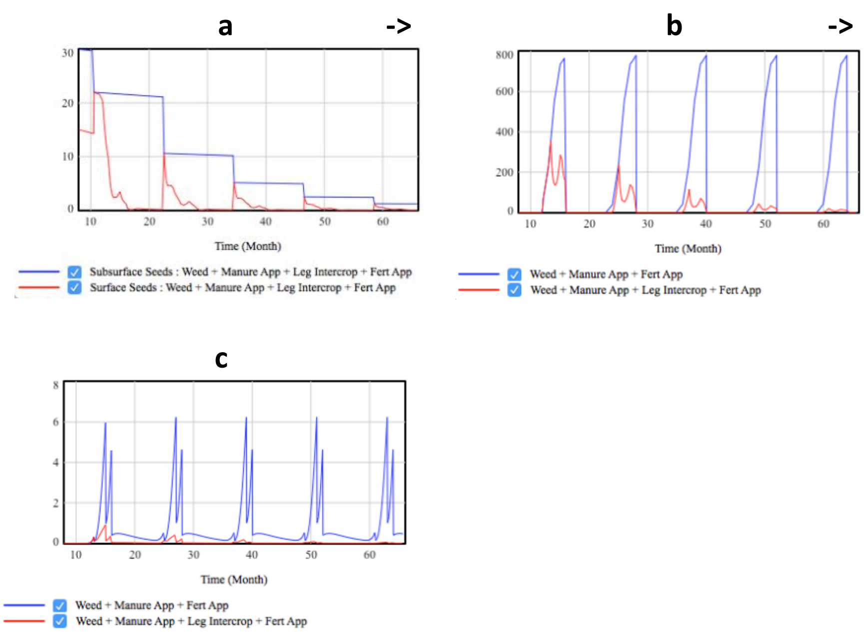
Figure 24 - Monthly surface seed (a) and mature Striga (b) reductions in response to weeding + manure application + legume intercropping VS weeding + manure application + fertilizer application



**Note: The Y-axis of graph A is scaled in millions. Graph B is scaled in thousands*

The combination of intercropping, fertilizer application, manure application and weeding in the CSM denoted an eradication of weed across five seasons (see **Figure 25**). Unlike previous scenarios with different combinations of practices, the aforementioned strategy does not permit any stage of the lifecycle to return to a threshold in one season. Instead, surface seeds and subsurface seeds (**Figure 25[a]**), attachment (**Figure 25[b]**) and mature *Striga* (**Figure 25[c]**) illustrated a consistent downward trend across consecutive seasons in the CSM. The dynamic behavior of the CSM highlights how all major stocks must decrease in a coordinated effort to decrease emergence. Permitting one stock (e.g., mature Striga) to return to the same equilibrium each season, allowed weed emergence to persist. This finding agrees with literature which argues the weed must be managed at all stages of the lifecycle to address its persistent seedbank and emergence (Westerman et al., 2007; Joel et al., 2000). The finding also argues under the specified average seedbank and controls, conservatively, *S. asiatica* will not be eradicated unless all practices are employed in a consistent manner across five seasons. That is not to say the weed will devastate yields if it is not completely eradicated, but will continue to be a significant pest until it is lowered to particular threshold.

Figure 25 - Monthly surface seed (a), attachment (b) and flowering (c) reductions in response to weeding + manure application + legume intercropping VS weeding + manure application + fertilizer application



**Note: The Y-axis of graph A is scaled in millions. Graph B and C are scaled in thousands*

3.5 Conclusions

The following study developed a cropping systems model to simulate the dynamic behavior within the *S. asiatica* lifecycle under various smallholder management strategies. The CSM differed from previous models in that it was adapted to smallholder settings (e.g., *Striga* seed density, marginalized soils) and practices (e.g., ridging). In addition, the model evaluated the efficacy of practices smallholders were already using or strategies which could be adapted to traditional practices and farming systems. Many models have evaluated practices that may be effective in addressing *Striga spp*. emergence (e.g., transplanting of maize seedling, no till), but such practices are unlikely to be implemented in Malawi given their labor demands and/or incompatibility with smallholder farming systems (Giller et al., 2009; Orr et al., 2002). Apart from these practice considerations, the CSM also included a parameter that was either absent or limited in previous models- attachment. As evidenced in this CSM, attachment was quintessential to evaluating emergence in response to one practice or many. Without attachment, a parasitic weed cannot survive.

The CSM highlighted several critical findings for *Striga spp*. researchers and practitioners. Without the use of hybrid seed (e.g., Striga-resistant maize), an aggregated effort must be made to address emergence (Grenz et al., 2005). The CSM highlighted the dynamic nature of *S. asiatica*. In allowing one stage to return to a certain threshold, such as attachment, emergence and flowering will persist. Even though attachment was the most sensitive parameter in the CSM, as evidenced by model behavior, all stages must be addressed to eradicate the weed. In addition to these findings, the CSM suggests smallholders will likely need to modify traditional practices to address *S. asiatica* emergence (i.e., manure application and weeding). Highly infested fields are likely to be colonized without the addition of fertilizer and intercropping or *Striga* resistant seed. While the combination fertilizer application and traditional practices appeared to be more effective than intercropping, induced suicidal germination and shading provided by legumes completed the suppression of emergence. There are human and financial tradeoffs for implementing all practices (if possible) (Oswald, 2005). These tradeoffs must be considered when developing and disseminating new strategies to address *S. asiatica* emergence across Malawi.

There were several limitations to the study and its subsequent findings. Given what little emergence occurred in the greenhouse trial, the model could not be validated from emergent and flowering rates observed across different practices and periods of implementation. Model behavior was largely validated by emergent and flowering studies found in the literature. In addition, there was no stock to account for N-accumulation contributed by N-fixation and N-residues via legume intercropping. These contributions can affect cell wall thickness and associated attachment (Cechin & Press, 1993). Furthermore, the CSM does not account for the 'sink' behavior phenomenon. That is, when a higher density of *Striga spp*. seeds are in the soil (i.e., a sink), a lower percentage can successfully attach because there are less resources (e.g., healthy maize roots) available to support their growth. When this occurs, emergence and flower development are decelerated as compared to a field with less sinks (Hearne, 2009). The last limitation of the model is that several parameters (e.g., mulching) were informed by West African studies investigating *S.* hermonthica emergence. While both weeds are similar, their fecundity and emergent rates are different. These four limitations warrant the need to study maize parasitism in southern Africa further. A replication of the trials conducted in the study will assist in calibrating CSM and validating outputs.

Replicated greenhouse experiments must take into consideration the methodological errors observed in this study. No S*. asiatica* had flowered and very few seedlings had emerged in the experiment. Germination and attachment were not monitored during the experiment until the plants were disposed in the compost pit once after four months. Maize transitioned through its vegetative phases rapidly in the greenhouse, affecting one, if not more, of the growth stages of *S. asiatica*. Hastened growth was most likely attributed to maize being exposed to extended hours of heat above the outside temperature during the day and evening (Fanadzo et al., 2010). Hastened growth, first, was responsible for retarding root growths, shortening the window of strigolactone secretion which triggers *S. asiatica* germination. Second, smaller root canopies reduces the likelihood a root will access an area where *S. asiatica* are, reducing their chances to germinate and attach later. Another factor to consider is that fertilizer (primarily N) was applied. The application is associated with thicker root tissues and prevented the germ tube of the parasites to access the phloem. Adult leaves from V5-VT exemplified a dark green pigment, illustrating they were not N-deficient and most likely had a thick enough root system to reduce the rate of successful attachment. Rather limited soil-P may have been the primary culprit. The macronutrient is responsible for reduced root volume, and consequently, less germination (Yao et al., 2007). A combination of low germination rates and few successful attachments will ultimately lead to fewer observations of emergence and flowering.

Findings from the study, specifically model behavior, have several implications for practitioners and researchers in *S. asiatica* emergence in Malawian smallholder systems. Given the extent attachment has on the system, delaying its onset with repeated micro-dosing of manure at planting stations could assist the financially-constrained farmer. In addition, modifying planting station depth (e.g., poking holes in ridges and sowing >30 cm) provides an economic avenue to controlling the weed (in addition to other practices) (Elzein & Kroschel, 2003). Being that fertilizer addressed the attachment stage in the CSM, other avenues, such as coating seeds with herbicide may be a more economic avenue if fertilizer is more expensive than herbicide

(Kanampiu et al., 2003). These practices must be evaluated further under smallholder conditions, which can be difficult to control from outside factors.

Attachment is difficult to monitor in experiments given its sporadic nature. Perhaps one reason why a disproportionate amount of practices that address emergence and flowering have been disseminated to smallholders is due to the fact that emergent counts and seed rates are relatively more feasible to quantify than attachment. By not modeling the dynamic behavior of this stage or parasitic weeds in general, research will be limited in informing effective policy to address this ever-growing agricultural issue. Given the devastating effects *Striga spp*. has had in Malawi and sub-Saharan Africa, it is imperative to develop parasitic weed modules for crop models to better evaluate smallholder practices (Ejeta, 2007). Models that do not capture underlying biological mechanisms presented in the CSM, risk informing extension with potentially misleading information regarding the efficacy of control practices.

APPENDICES

APPENDICES

APPENDIX 1. Justification off Values/Equations Applied to Parameters of Cropping System Model

Parameter	Value or Equation	Explanation	Source
Initial Values			
Surface Seeds (iSs)	[redacted]	[redacted]	Baskin & Baskin, 1998; Hartman & Tanimonure, 1991; Ngwira et al., 2013; Visser & Wentzel, 1980
Subsurface Seeds (iSSs)	[redacted]	[redacted]	*See source/s of* Surface Seeds (iSs)
Unattached Seedlings (iUs)	[redacted]	[redacted]	N/A
Attached Seedlings (iAs)	[redacted]	[redacted]	N/A
Emerged Seedlings (iEs)	[redacted]	[redacted]	N/A
Mature Striga (iMs)	[redacted]	[redacted]	N/A
Host Plants (iHP)	[redacted]	[redacted]	N/A
Intercrop Plants (iIP)	[redacted]	[redacted]	N/A
Stocks			
Surface Seeds	[redacted]	[redacted]	Babiker et al. (1987); Behawi et al. (1984); Musambasi et al. (2002)
Subsurface Seeds	[redacted]	[redacted]	Behawi et al. (1984); Benvenuti (2007)
Unattached Seedlings	[redacted]	[redacted]	Jamil et al. (2012); Kunisch et al.

	[redacted]	[redacted]	(1991); Makoi & Ndakidemi (2012)
Attached Seedlings	[redacted]	[redacted]	Makoi & Ndakidemi (2012)
Emerged Seedling	[redacted]	[redacted]	Cechin & Press (1993)
Mature Striga	[redacted]	[redacted]	Kabambe et al. (2008)
Host Plants in Field	[redacted]	[redacted]	Kabambe et al. (2008)

			[redacted]	
Intercrop Plants in Field		[redacted]	[redacted]	Kermah et al. (2017); Ngwira et al. (2013)
Flows				
Connected to Surface and/or Subsurface Seeds Stocks	Monthly Production of Viable Seeds	[redacted]	[redacted]	*See source/s of* “Monthly seed production” & “Seed viability fraction”
	Germination in Millions	[redacted]	[redacted]	*See source/s of* “potential germination” & “suicidal fraction”
	Seed Resurfacing	[redacted]	[redacted]	*See source/s of* “Seeds resurfaced from burying ridges” & “Subsurface Seeds”
	Surface Monthly Mortality	[redacted]	[redacted]	*See source/s of* “surface mortality rate” and Surface Seeds”
	Monthly Burial	[redacted]	[redacted]	*See source/s of* “burial fraction” & “Surface Seeds”
	Subsurface Monthly Mortality	[redacted]	[redacted]	*See source/s of* “subsurface mortality rate” & “Subsurface Seeds”

	Surface Suicidal Germination	[redacted]	[redacted]	*See source/s of* "potential germination" & "suicidal fraction"
Connected to Unattached and/or Attached Seedlings Stocks	Germination in thousands	[redacted]	[redacted]	*See source/s of* "germination in millions" & "units conversion"
	Seedlings removal	[redacted]	[redacted]	*See source/s of* "Maize Removal"
	Monthly attachment s	[redacted]	[redacted]	Cechin & Press (1993); Mumera & Below (1993) *See source/s of* "indicated attachments from vacant sites & "indicated attachments from exposed unattached seedlings"
	Unable to attach	[redacted]	[redacted]	Ejeta 2001; Serghini et al. 2001; Tsanuo et al. 2003 *See source/s of* "Haustorium Attachment Factor"
	Attached without sequesterin g photo-synthates	[redacted]	[redacted]	Jamil et al., 2012; Chechin & Price, 1993

			[redacted]	
Connected to Emerged Seedlings and/or Mature Striga Stocks	Monthly emergence	[redacted]		See source/s of "monthly attachments" & "successful emergence factor"
	Monthly mortality of emerged seedlings	[redacted]		*See source/s of "*Emerged Seedlings" & "monthly emergents mortality rate"
	Emergent weed removal	[redacted]	[redacted]	*See source/s of "*Striga removal fraction" & "Emerged Seedlings"
	Emergent Weeding		[redacted]	*See source/s of* "1st Weed Month" and "2nd Weed Month"
	Monthly maturation		[redacted]	*See source/s of "*potential monthly survival" & "flowering success fraction"
	Mature weed removal	[redacted]	[redacted]	*See source/s of "*Striga removal fraction" & "Mature Striga"
	Mature Weeding		[redacted]	*See source/s of* "1st Weed Month" and "2nd Weed Month"

	Monthly mortality of mature plants	[redacted]	[redacted]	*See source/s of* "Mature Striga" & "Striga maturation interval"
Connected to Host Plants Stock	Planting the maize	[redacted]	[redacted]	*See source/s of* "Thousands of plants per hectare" & "Planting"
	Host removal	[redacted]	[redacted]	*See source/s of* "Host Plants" & "Maize Removal"
Connected to Intercrop Plants Stock	Planting the Legumes	[redacted]	[redacted]	Ngwira et al. (2013); Silberg et al. (2017)
	Intercrop Removal	[redacted]	[redacted]	Ngwira et al. (2013)
Converters/Factors Attached to Flows				
Connected to Surface monthly mortality outflow	Surface mortality rate	[redacted]	[redacted]	Ciotola et al. (1995); Lendzemo et al. (2006)n
Connected to Monthly production of viable seeds inflow	Monthly seed production	[redacted]	[redacted]	*See source/s of* "Monthly seeds produced per plant"
	Seed viability fraction	[redacted]	[redacted]	Smith et al. (1993)
Connected to Germination in millions & suicidal germination outflows	Suicidal fraction	[redacted]	[redacted]	*See source/s of* "suicidal germination from legumes" & "suicidal germination from leg residues"

	Potential germination	[redacted]	[redacted]	Aflakpui et al. (1998); Bationo & Mokwunye (1991); Jamil et al. (1998); Netzly et al. (1988); Osman et al. (1991)
Connected to seed resurfacing & monthly burial outflow/inflows	Bury the ridges	[redacted]	[redacted]	Kabambe et al. (2008)
	Resurface fraction with burying ridges	[redacted]	[redacted]	Benvenuti (2007)
	Burial fraction	[redacted]	[redacted]	Benvenuti (2007)
Connected to Subsurface monthly mortality outflow	Subsurface mortality rate	[redacted]	[redacted]	Behawi et al. (1984)
Connected to Germination in thousands inflow	Units conversion	[redacted]	[redacted]	N/A
	<Host plants Present?>	[redacted]	[redacted]	N/A
Connected Unable to Attach outlfow	Unattached Seedlings	[redacted]		*See source/s of* "Unattached Seedlings"
	<Haustorium Attachment Factor>	[redacted]	[redacted]	Ejeta 2001; Oswald et al., 2002; Sanginga et al., 2003; Serghini et

				al. 2001; Tsanuo et al. 2003
	<TIME STEP>	[redacted]	[redacted]	N/A
Connected to Emergent/Mature Weed Removal outflows	<Maize Removal>	[redacted]	[redacted]	N/A
	Striga Removal After Maize Harvest	[redacted]		N/A
	<TIME STEP>	[redacted]	[redacted]	N/A
	Emerged Seedlings/ Mature Striga	[redacted]		*See source/s of* "Emerged Seedlings" and "Mature Striga"
Connected to Emergent Weeding/Mature Weeding outflows	<1^{st} Weeding?>	[redacted]	[redacted]	N/A
	<2^{nd} Weeding?>	[redacted]	[redacted]	N/A
	1^{st} Weed Month	[redacted]	[redacted]	Orr et al. (2002)
	2^{nd} Weed Month	[redacted]		Orr et al. (2002)
	Emerged Seedlings/ Mature Striga	[redacted]		*See source/s of* "Emerged Seedlings" and "Mature Striga"
	<TIME STEP>	[redacted]	[redacted]	N/A
	<Month of Year>	[redacted]	[redacted]	N/A
Connected to Monthly attachments outflow/inflow	Indicated attachments from exposed unattached seedlings	[redacted]		Jamil et al. (2012)
	Indicated attachments from vacant states	[redacted]	[redacted]	Jamil et al. (2012); Makoi et al. (2012)

Connected to Attached Without Sequestering Photosynthates outflow	<Basal Fert App?>	[redacted]	[redacted]	N/A
	<Root Cell Wall Factor	[redacted]	[redacted]	Cechin & Press (1993)
	<TIME STEP>	[redacted]	[redacted]	N/A
Connected to Attached seedlings removed & Host removal outflows	<Maize Removal>	[redacted]	[redacted]	N/A
Connected to Monthly Emergents outflow	Successful Emergence Fraction	[redacted]	[redacted]	Jamil et al. (2007); Smith et al. (1993)
Connected Planting the Maize inflow	Thousands of plants per hectare	[redacted]	[redacted]	Nyagumbo et al. (2016)
	<Planting>	[redacted]	[redacted]	Denning et al. (2009)
Connected Planting the Maize inflow	Thousands of Leg plants per hectare	[redacted]	[redacted]	Ngwira et al. (2013)
	<Planting Leg>	[redacted]	[redacted]	Mhlanga et al. (2016)
Connected to Monthly Mortality Emerged Seedlings outflow	Monthly emergents mortality rate	[redacted]	[redacted]	Jamil et al. (2012); Kabambe et al. (2008)

Connected to Emergent Weed Removal & Mature Weed Removal outflows	Striga removal fraction	[redacted]	[redacted]	Orr & Richie (2004)
	<Maize removal>	[redacted]	[redacted]	N/A
Connected to Monthly Maturation inflow/outflow	Potential monthly survivals	[redacted]	[redacted]	*See source/s of* "Emergent Seedlings", "Shading Factor From Legume Canopy" & "Emergent interval"
	Flowering success fraction	[redacted]	[redacted]	Musselman (1980)
Connected to Monthly Mortality Mature Plants outflow	Monthly Mortality Mature Plants	[redacted]	[redacted]	Hearne (2009)
Converters/Factors attached to other converters/factors				
Connected to Suicidal fraction	Suicidal germination from living legumes	[redacted]	[redacted]	Khan et al. (2002); Musambasi et al. (2002); Rezig et al. (2016)
	Suicidal germination from legume residues	[redacted]	[redacted]	Yonli et al. (2010)
Connected to Suicidal Germination	<Intercrop Plants Present?>	[redacted]	[redacted]	See Intercrop Plants in Notes & Calendar Table

From Living Legumes				
Connected to Suicidal Germination From Legume Residues	<Leg Residue Present on Soil Surface?>	[redacted]	[redacted]	See Legume Residues in Notes & Calendar Table
Connected to Indicated Attachments from Exposed Unattached Seedlings	Fraction of area exposed to canopy	[redacted]	[redacted]	*See source/s of* "Canopy Area"
Connected to Fraction of Area Exposed to Canopy	<Host Density>	[redacted]	[redacted]	N/A
	Canopy area per plant	[redacted]	[redacted]	N/A
Connected to Canopy Area per Plant	Pi	[redacted]	[redacted]	N/A
	Radius	[redacted]	[redacted]	*See source/s of* Lookup root canopy radius
Connected to Radius	<Age of maize roots>	[redacted]	[redacted]	N/A
	Lookup root canopy radius	[redacted]	[redacted]	Van Delft et al. (2000)
Connected to Indicated Attachments from Vacant Sites	<Host Plants>	[redacted]	[redacted]	Kabambe et al. (2008)
	Vacant Sites per plant	[redacted]	[redacted]	*See source/s of* "maximum attachments per plant" & "attachments per plant"
Connected to Vacant Sites per Plant	Maximum attachments per plant	[redacted]	[redacted]	*See source/s of* "max attachments per plant" & "Age of maize roots)
	Attachments per plant	[redacted]	[redacted]	Kunisch et al. (1991); Smith et al. (1993)

Connected to Maximum Attachments per Plant	<Age of Maize roots	[redacted]	[redacted]	N/A
	Lookup for max attachments per plant	[redacted]	[redacted]	*See source/s of* max attachments per plant
Connected to Attachments per Plant	<Host plants>	[redacted]	[redacted]	Kabambe et al. (2008)
Connected to Host Density	Area in thousands of square meters	[redacted]	[redacted]	N/A
Connected to Potential Monthly Survivals	Emergent interval	[redacted]	[redacted]	Nweze et al. (2015)
	Emerged Seedling	[redacted]	[redacted]	Cechin & Press (1993)
	<Shading Factor Form Legume Canopy>	[redacted]	[redacted]	Carsky et al. (1994)
Connected to Monthly Seed Production	Monthly seeds produced per plant	[redacted]	[redacted]	*See source/s of* "Striga lifetime seed production" & "Striga maturation interval"
Connected to Monthly Seeds Produced per Plant	Striga lifetime seed production	[redacted]	[redacted]	Abdul et al. (2012)
Connected to Potential Germination	<Decision to Apply Manure>	[redacted]	[redacted]	Kabambe et al. (2008)
	Monthly Germination Rate	[redacted]	[redacted]	Aflakpui et al. (1998); Carsky et al. (1994); Hsiao et al. (1987);

				[redacted]	Paterson et al. (1982)
	Delayed Germination	[redacted]		[redacted]	Yoneyama et al. (2007)
Connected to delayed Germination	Month of Year	[redacted]		[redacted]	*See source/s of* “Delayed Germination”
[3]Connected to Monthly Germination Rate	Soil Temperature	[redacted]		[redacted]	Aflakpui et al. (1998); Baskin & Baskin (1998) *See source/s of* “Intercrop in Field” & “Monthly temperature”
	Soil moisture	[redacted]		[redacted]	Osman et al. (1991)

		[redacted]	[redacted]	*See source/s of* "Mulching", "Monthly Rainfall" & "Monthly Temperature"
Connected to Soil Moisture	Month rain	[redacted]	[redacted]	N/A
	<Mulch Present?>	[redacted]	[redacted]	*See source/s of* "bury the ridges" & "Mulching"
	Month temp	[redacted]	[redacted]	N/A
Connected to Soil Temperature	<Leg Plant Present>	[redacted]	[redacted]	See source/s of "Intercrop Plants"
	Monthly temperatur e	[redacted]	[redacted]	60 Years Climate data sourced from Malawian Meteorological Services
Connected to Month Temp	Monthly temperatur e	[redacted]	[redacted]	60 Years Climate data sourced from Malawian Meteorological Services
Connected to Month Rain	Month rain	[redacted]	[redacted]	60 Years Climate data sourced from Malawian Meteorological Services

			[redacted]	
Exogenous Parameters				
Host Density		[redacted]	[redacted]	*See source/s of* “Host Plants” & “Area in thousands of square meters”

Notes and Calendar View

Parameter		**Value or Equation**	**Explanation**	**Source**
Stocks				
Age of Maize Roots		[redacted]	[redacted]	N/A
Age of Legume Roots		[redacted]	[redacted]	N/A
Legume Residues		[redacted]	[redacted]	N/A
Manure		[redacted]	[redacted]	N/A
Flows				
Connected to Age of Maize Roots	Add to Maize Age	[redacted]	[redacted]	N/A
	Reset Maize Age Counter to Zero	[redacted]	[redacted]	*See source/s of* “Age of Maize” & “Maize Removal”
Connected to Age of Legume Roots	Add to Leg Age	[redacted]	[redacted]	N/A
	Reset Leg Age Counter to Zero	[redacted]	[redacted]	*See source/s of* “Application of residues”

			[redacted]	
Connected to Legume Residues	Residues Fall on Soil Surface	[redacted]	[redacted]	*See source/s of “Application of residues”*
	Residues Removed	[redacted]	[redacted]	*See source/s of “Residue Removal form Soil Surface”*
Connected to Manure	Manure Applied at Planting	[redacted]	[redacted]	*See source/s of “Application of Manure”*
	Reset Manure Counter to Zero	[redacted]	[redacted]	*See source/s of “Temporary Soil P Pool Gone”*
Converters/Factors attached to flows				
Connected to Add to Maize Age inflow	<Host Plant Present?>	[redacted]	[redacted]	*See source/s of “Host Plants”*
Connected to Reset Maize Age Counter to Zero outflow	<TIME STEP>	[redacted]	[redacted]	N/A
	<Maize Removal>	[redacted]	[redacted]	*See source/s of “Maize Removal Month”*
	Age of maize roots	[redacted]		*See source/s of “”*
Connected to Add to Leg Age	Intercrop Plants Present?	[redacted]	[redacted]	N/A
Connected to Reset Leg Age Counter to Zero	<Legume Removal>	[redacted]	[redacted]	N/A
	Age of Legume Roots	[redacted]		*See source/s of “Age of Legume Roots”*
	<TIME STEP>	[redacted]	[redacted]	N/A
Connected to Residues Fall on Soil Surface	Application of residues	[redacted]	[redacted]	N/A
	Thousands of kg of Leg Residues	[redacted]	[redacted]	N/A

			[redacted]	
	<Decision to Intercrop>	[redacted]	[redacted]	N/A
	<TIME STEP>	[redacted]	[redacted]	N/A
Connected to Residues Removed	Residue Removal from Soil Surface	[redacted]	[redacted]	N/A
	Legume Residues	[redacted]		*See source/s of* "Legume Residues"
	<TIME STEP>	[redacted]	[redacted]	N/A
Connected to Manure Applied at Planting	Application of Manure	[redacted]	[redacted]	N/A
	Thousands of kg of Manure	[redacted]	[redacted]	N/A
	<Decision to Apply Manure>	[redacted]	[redacted]	N/A
	<TIME STEP>	[redacted]	[redacted]	N/A
Connected to Reset Manure Counter to Zero	Temporary Soil P Pool Gone	[redacted]	[redacted]	N/A
	Manure	[redacted]		*See source/s of* "Manure"
	<TIME STEP>	[redacted]	[redacted]	N/A
Converters/Factors attached to other converters/factors				
Connected to <Host Plants Present?>	<Host Plants>	[redacted]	[redacted]	*See source/s of* "Planting the Maize" & "Host removal"
Connected to Sow Maize Month	Month of Year	[redacted]	[redacted]	N/A
	Planting Month	[redacted]	[redacted]	Thierfelder et al. (2013)
Connected to Month of Year	<Time>	[redacted]	[redacted]	N/A
Connected to Maize Removal	Maize removal month	[redacted]	[redacted]	Thierfelder et al. (2013)
	Month of Year	[redacted]	[redacted]	N/A

Connected to Bury the Ridges	Bury the ridges Month	[redacted]	[redacted]	Thierfelder et al. (2013)
	Month of Year	[redacted]	[redacted]	N/A
Connected to Legume Removal Month	Legume Removal	[redacted]	[redacted]	*See source/s of* “Legume Removal Month”
Connected to Month of Year 0	Planting Legumes	[redacted]		*See source/s of* “Sow Leg Month”
	Legume Removal	[redacted]	[redacted]	*See source/s of* “Legume Removal Month”
Connected to <Time>	Month of Year	[redacted]	[redacted]	N/A
	Month of Year 0	[redacted]	[redacted]	N/A
	Month of Year 0 0	[redacted]	[redacted]	N/A
	Month of Year 0 0 0	[redacted]	[redacted]	N/A
Connected to Month of Year 0	Planting Legumes	[redacted]	[redacted]	*See source/s of* “Sow Leg Month”
Connected to Month of Year 0 0	Application of Residues	[redacted]	[redacted]	*See source/s of* “Residue Application Month”
Connected to Month of Year 0 0 0	Application of Manure	[redacted]	[redacted]	*See source/s of* “Manure Application Month”
Connected to <Intercrop Plants>	Intercrop Plants Present?	[redacted]	[redacted]	*See source/s of* Intercrop Plants
Connected to Intercrop Plants Present?	Shading Factor from Legume Canopy	[redacted]	[redacted]	Carsky et al. (1994)
	Reduced Haustorium Length	[redacted]	[redacted]	*See source/s of* “Haustorium Attachment Factor”

Connected to Reduced Haustorium Length	Haustorium Attachment Factor	[redacted]	[redacted]	Ejeta 2001; Serghini et al. 2001; Tsanuo et al. 2003
Connected to Legume Residues	<Leg Residue Present on Soil Surface?>	[redacted]	[redacted]	N/A
Connected to <Basal Fert App?>	Soil-N	[redacted]	[redacted]	N/A
Connected to Soil-N	Root Cell Wall Factor	[redacted]	[redacted]	Cechin & Press (1993); Mumera & Below (1993)
Exogenous Parameters				
Sow Maize Month		[redacted]	[redacted]	*See source/s of* "Month of year" & "Planting month"
Sow Leg Month		[redacted]	[redacted]	Jeranyama et al. (2000)
Residue Application Month		[redacted]	[redacted]	Jeranyama et al. (2000)
Manure Application Month		[redacted]	[redacted]	Whitbread et al. (2000)
Maize Removal Month		[redacted]	[redacted]	Thorton et al. (1995)
Legume Removal Month		[redacted]	[redacted]	Jeranyama et al. (2000)
Residue Removal Month		[redacted]	[redacted]	N/A
Manure Removal Month		[redacted]	[redacted]	Whitbread et al. (2000)

<Basal Fert App>	[redacted]	[redacted]	N/A
<Decision to Intercrop>	[redacted]	[redacted]	N/A
<Decision to Apply Manure>	[redacted]	[redacted]	N/A
<Time>	[redacted]	[redacted]	N/A

Notes

[1] *See Appendix 2 for further explanation*

[2] *See Appendix 3 for further explanation*

[3] *The equation applied for Monthly Germination was based on findings found across slightly acidic soils. The analysis section will explain soils found in study site were slightly acidic; hence, pH was excluded from the equation. In addition, management practices (e.g., N-Fert Application) included in the model would do little to change the soil pH in the specified time (5-6 years).*

[4] *The equation applied for Soil Moisture was based on findings found across loamy sand soils. The analysis section will explain soils found in study site were loamy sand; hence, texture was excluded from the equation. In addition, management practices (e.g., mulching) included in the model would do little to change the soil texture in the specified time (5-6 years).*

APPENDIX 2. Seedbank Calculation

[redacted]

[redacted]

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APPENDIX 3. Root Canopy Calculation

[redacted]

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CHAPTER 4: SYSTEM DYNAMICS - COMBINING CHOICE EXPERIMENTS AND CROP SIMULATION TO MODEL PARASITIC WEED EMERGENCE

4.1 Introduction

Reductions in maize (*Zea mays*) yields attributed to parasitic weeds (*Striga spp*.) has become a concerning problem for smallholder farmers (cultivating <2 ha) in southern Africa. Parasitism in Malawi is influenced by numerous factors such as soil acidity, fertility and moisture (Boukar et al., 1996). Numerous *Striga* control practices (SCPs) have been combined to address both the weed and soil fertility. These packages of practices are often referred to as soil fertility management (SFM) strategies, where mulching and maize-legume intercropping, for example, are implemented simultaneously (Westerman et al., 2007). Soil conditions can change based on the adoption and dis-adoption of these strategies by smallholders. The adoption of SCPs is influenced by an interlinked natural, financial and social environment that surrounds the smallholders who implement them (Debra, 1994). This environment causes SCP-adoption rates and *Striga* emergence to delay and fluctuate between one another. Adoption and emergence are therefore, dynamic, guided by a coupled social-ecological environment.

Evidence suggests the implementation of multiple SFM practices over several consecutive seasons can reduce *Striga spp*. emergence significantly (>95%) (Mignouna et al., 2011). Regardless of these positive outcomes, adoption still is low in some countries of the region (Giller et al., 2009; Grabowski et al., 2018). Subsequently, emergence persists without continued adoption. Low adoption rates may be attributed to a number of reasons, such as low efficacy under field conditions. That is, emergence associated with a practice (or combination of practices) may be more of a result of the environment where they were studied (e.g., controlled biophysical conditions) (Orr et al., 2002). Consequently, equivalent results are not seen in smallholder fields because the practices are little adapted to the diverse agroecological landscape of Malawi (Giller et al., 2011). Furthermore, smallholders frequently do not possess the same labor and financial resources researchers used to carry out these studies, resulting in low adoption rates.

The adoption of agricultural practices and emergence associated with their implementation are frequently studied separately. For example, SFM adoption is studied using quantitative methods (e.g., econometrics) to unveil significant associations between the practice and characteristics of various adopter types (Hanson et al., 2005). In a similar fashion, quantitative methods such as crop models predict growth, development and yield of plants (Jones et al., 2016). Fewer studies, however, combine both econometrics and crop modeling to study agricultural outcomes (Amelia, 2014). Disconcertingly, adoption studies may fail to assess why smallholders would dis-adopt or readopt an SFM strategy if their theoretical framework cannot evaluate the performance of the strategy across seasons. Similarly, panel studies investigating emergence in smallholder fields may fall short in understanding why the performance may be poor if the study does not account for inter-seasonal or inter-annual dis-adoption/re-adoption. An integrated approach, therefore, is warranted to study the adoption and performance of a SCP. One research method that can model the interactions between parasitic weed emergence and SCP adoption is system dynamics (SD). SD modeling (SDM) can demonstrate feedback responses between populations (i.e., a stock of weeds) and endogenous variables (e.g., adoption rates of an SFM practice) (Kopainsky et al., 2012).

The objective of this study was to develop an SDM to simulate emergence of *Striga asiatica* over time in an environment that includes social and natural parameters. The intention of the model was to address the following research questions. How do biophysical and socioeconomic factors related to parasitic emergence connect, interact and generate feedbacks? How does the adoption of different control strategies affect *S. asiatica* parasitism over time? How do various technological attributes affect implementation of SCPs and consequent parasitic emergence over time? How do agroecological changes (e.g., soil fertility, drought) affect the implementation of SCPs and consequent parasitic emergence over time? How do different financial conditions or institutional policies affect the implementation of SCPs and consequent parasitic emergence over time? Findings from the study highlight dynamic behavior that guide emergence. These revelations inform what factors influence adoption and subsequent *S. asiatica* emergence overtime.

4.2 Background

Modeling *S. asiatica* emergence and its influencing natural and social parameters first requires a firm understanding of the term 'adoption'. In this context, adoption refers to the application, abandonment and re-implementation of agricultural technologies (e.g., SCPs). Second, the parameterization of the model demands a thorough review of how these technologies affect emergence. More specifically, studies were reviewed that investigated the extent of time it took for *Striga asiatica* emergence to decrease (or increase) from a implementing a SCP (or multiple SCPs) under smallholder conditions.

4.2.1 Defining adoption

Adoption is often referred to as a conscious decision to implement a new practice or apply a new technology on a continuous basis (Besley & Case, 1993). Adoption is a process of decision-making and behavioral change where potential and acting adopters can reject a change and return to a previous practice or technology. In terms of agriculture, 'technology' is typically a discrete input (e.g., seed) or method (e.g., agroforestry) (Castaño et al., 2002).

There are three notable types (or measures) of adoption mentioned in the literature, including discrete or dichotomous choice, intensity of practice and continuous decision (Jabbar et al., 2003). A discrete adoption example would entail whether a farmer cultivated a new seed or not. The intensity of adoption would involve to what extent the new seed was cultivated in a given time period by an amount or share of farm area (e.g., 10,000kg seed/ha versus 15,000kg seed/ha) (Fufa & Hassan, 2006). Finally, the continuous decision might involve farmers choosing to adopt, dis-adopt, readopt or never adopt the seed. Feder et al. (1985) suggests when determining which measure to use, researchers should consider whether they are assessing individual versus aggregate adoption (e.g., percent adopted in a given region), if adoption requires the implementation of a single practice or suite of practices (e.g. fertilizer and/or hybrid seed) and whether the technology is divisible or non-divisible (e.g., sowing seed [1 practice] versus conservation agriculture [3 practices]).

The decision to adopt a given technology is contingent upon the availability of social, physical and financial resources needed to implement the technology (Mugwe et al., 2009). Resources such as food, land, labor and finances are often constrained among smallholder households. Household decisions to allocate these limited resources, therefore, will be influenced by their resiliency against risk and evaluation of the costs and benefits of the technology (Ajayi et al., 2003). Smallholders are often considered risk-adverse, but when the incentives of the technology reduce risk, empirical evidence has shown that they will increase expenditure and time to such technologies as a strategy to cope with climatic shocks such as prolonged drought (Shiferaw & Bantilan, 2004). Social scientists must also consider the context of when and where the technology will be adopted; thus, adoption is often time and space-specific action (Feder, 1993).

4.2.2 Emergence associated with SCP/s

The adoption of different SCPs affords distinctive reductions in *S. asiatica* (spatially and temporally) as well as secondary benefits (e.g., increases in maize yield). Each SCPs requires different levels of investment, presenting tradeoffs to smallholders. The decision to adopt or dis-adopt such SCPs, therefore, is contingent upon the arrival of benefits in the specified timeframe to repay investments. Each SCP also requires some sort of investment and prior knowledge (see **Table 18**). In addition, secondary benefits from the practice (e.g., maize yield) are dependent on knowledge and investment as well as the type of inputs used for implementation. For example, crop rotation requires legume seed (as an input), which can reduce *S. asiatica* via suicidal germination and contribute nitrogen (N) to the soil, but also increase maize yield prior to eradication of the weed (Oswald & Ransom, 2001; Robinson & Dowler, 1966). The delivery of these benefits during the interim can increase the potential for adoption. One primary reason smallholders employ SCPs is not necessarily to reduce *S. asiatica* but to sustain or increase maize (Khan et al., 2008). Consequently, it is unlikely for a SCP to be continued if maize yield is lowered during or after its adoption, even if the reduction was attributed to other factors (e.g., drought) (Orr et al., 2009).

Table 18 - Characterization of *Striga* control methods for sub-Saharan African smallholders

Control method	**Investment**	**Estimated level of investment**	**Time until effective on *Striga* densities**	**Time until effective on yield of *Striga* host-crop**	**Training required**	**Weaknesses**	**Potential for adoption**
Crop-rotation	Field space, trap crops	Low	3-4 seasons	1 rotation cycle	Medium	Time until effective	High
Intercropping	Trap crops	Low	2-3 seasons	2-3 seasons	Medium	*Striga* host-crop continuously in the field	High
Soil fertility – organic	Labor	Low to medium	3-4 seasons	3-4 seasons	Low	Time until effective; alternative uses of manure	High
Soil fertility – inorganic	Fertilizer	Medium to high	2-3 seasons	Immediate	Medium	Period of time until effective; investment	Medium
Hand-weeding	Labor	Medium	4 seasons	4 seasons	Low	Labor intensive	Low
Transplanting	Labor	Medium to high	Immediate	Immediate	High	Labor intensive and high level of farm management skills required	Low
Catch-cropping	Seed, labor, field space	High	2-3 seasons	2-3 seasons	High	Seed provision and management of catch-crop	Low

Note: The table is based mainly on the experiences and results of the CIMMYT-KARI-Striga -working-group in western Kenya. It is meant to give an overview of the different methods and is based on the current level of science and understanding of the cropping system.
Source: Modified from Oswald (2005)

4.2.3 Interlinked adoption and emergence

The results received from an SCP after one or multiple seasons will determine whether a smallholder continues or discontinues the practice. Hence, feedback occurs between adoption/dis-adoption/re-adoption and performance of the SCP. In some instances, a smallholder will discontinue implementing a practice because an objective was either not met, not attained in a timely manner (e.g., two seasons) and/or not received at an expected level (e.g., 100% increase from previous yield) (Baum et al., 1999). In another respect, a smallholder may feel a SCP lowered emergence to a bearable threshold (e.g., <10% yield loss) and will discontinue the practice the following season (Baum et al., 1999). Even if the practice yielded secondary benefits (e.g., supplementary food source) apart from reduced emergence, discontinuance may be a result of investment (e.g., seed cost, labor) outweighing profit. A smallholder can reimplement the practice later if *S. asiatica* emergence becomes a problem, but will continue status quo practices until this event occurs. Researchers refer to this fluid process as 'technical soundness' (Fujisaka, 1989).

4.3 Methods

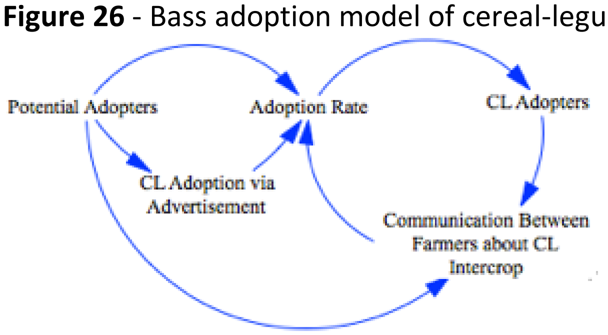
The theoretical framework stems from two theories which inform a consecutive mixed method approach. Those theories and their respective methods are explained in the following sub-sections.

4.3.1 Theoretical framework

Adoption research investigates the factors that are associated with the decision of an individual to implement an innovation (e.g., maize-legume intercropping). The decision can be influenced by any number of factors, including characteristics of the decision-maker (e.g., gender, wealth), characteristics of the environment where the decision is being made (e.g., drought conditions), and performance of that innovation (e.g., increase yield) (Feder & Umali, 1993). Two popular theories which inform quantitative and qualitative methods to study these three factors include utility maximization theory and diffusion of innovations (Hoffman, 2011; Adesina & Baidu-Forson, 1995).

The first theory posits that if the net benefits of a new innovation (e.g., maize yield, *Striga spp*. emergence reduction) outweigh those of a current innovation, then the decision maker will adopt (or reject) the new innovation based on the maximum expected utility of the social and financial attributes of the innovation. The adoption process is often gradual, spanning across several seasons before the innovation is fully implemented (Hockett & Richardson, 2016; Ma & Shi, 2015). The other theory, diffusion of innovations, studies how information about an innovation (positive or negative) is disseminated throughout a specified population (Kopainsky et al., 2012). Under this framework, the speed at which an innovation diffuses through society is contingent upon the existing values, past experience and needs of potential adopters. In addition, the timeframe of adoption is influenced by interest and knowledge of potential adopters (McRoberts, 2008). Knowledge and interest are accumulated from advertisement (via outside party), communication between potential adopters and those who have (or have not) adopted the innovation, and observation of benefits (or drawbacks) by potential adopters in their community (e.g., demonstration trials) (see **Figure 26**).

Figure 26 - Bass adoption model of cereal-legume intercropping



Note: CL should be interpreted as legume-cereal

The model above was derived from an earlier understanding about marketing and purchasing of household appliances. In the model, diffusion (in many respects) is illustrated as a social learning process between those who initiate the practice themselves or those who imitate others (Bass, 1969). These two parties of adopters and potential adopters are referred to as innovators and imitators, respectively. The model assumes diffusion is a function of interactions between innovators and imitators. In this study, an innovator is considered a farmer who decides to implement a SCP based on external factors such as a visit from agricultural extension agent or hearing about the SCP over the radio. An imitator is considered a farmer who decides to implement a SCP based on internal factors such as the number of farmers who have already implemented the SCP and communication between them.

4.3.2 Methodological framework

A mixed method approach was employed by the study to inquire about the adoption and diffusion process. Mixed method approaches often integrate two polarized methods simultaneously or in a sequential manner (Maxcy, 2003). Some of the most common methods include sequential explanatory design or concurrent triangulation design (Ivankova et al., 2006). In a pragmatic manner, the method inquires by using induction (or discovery of patterns), deduction (testing of theories and hypotheses), and abduction to uncover and use the best set of explanations for understanding results (Johnson & Onwuegbuzie, 2004). A sequential explanatory design can orient or inform instrumentation to explore results where one method may be limited (Moghaddam et al., 2003). As Morse (2005) explains, sequential mixed-method designs can be useful when unexpected results arise and require further clarification.

In this study, adoption and diffusion are considered part of a large social-ecological system, composed of human and natural components. These components were investigated using different modes of inquiry. Each component and its respective method employed for collection are outlined in **Table 19**.

Table 19 - Methodological framework

Social Component		**Natural Component**	
Component	*Method*	*Component*	*Method*
-Length of time until seeing result/s of a SCP -Length of time until adopting/dis-adopting a -Source/s informing information about SCP	Questionnaire/literature review	-Striga emergence in response to specific SCPs -Maize yield in response to emergence and climate	Crop modeling/literature review
-Yield tradeoff willing to sacrifice for lower *Striga* emergence -Yield penalty which would cause dis-adoption of SCP practice	Discrete choice experiments	-Monthly Rainfall	Climate database operated by Malawian Meteorological Services
-Institutions that encourage or discourage SCP adoption	Mediated modeling/focus group	-Percent population that received positive/negative outcome from SCP	Questionnaire

4.3.2.3 Focus groups

Three focus group discussions were held in May-June 2017 across three EPAs to determine the practices (i.e., alternatives) farmers were aware of that control *Striga spp*. and the attributes they were most concerned with when implementing them. Data from focus group discussions helped to contextualize and interpret findings by bringing distinction to farmers' voices and personal experiences (Hockett & Richardson, 2016).

During the discussions, a series of open-ended questions were asked in a specific sequence so that attributes of locally implemented *Striga spp*. control practices emerged (refer to **Appendix 1** from Chapter 2 of this dissertation for further detail). First, participants were asked about their familiarity with *Striga spp*. (lifecycle, identification, effect on yield, seed transport), then about the history and extent of its effects in their field (e.g., when *Striga* first appeared in their fields, what yield losses occurred). Then they were asked about specific characteristics of SCPs they considered before implementing them in their field (e.g., labor hours). The assessment of *Striga spp*. knowledge and attributes of concern informed the questionnaire and DCE instruments, respectively. After these two topics were discussed, the researcher probed about the sources and institutions farmers gathered *Striga spp*. knowledge from (e.g., experimentation, agricultural extension). These data would inform the questionnaire, but also the preliminary structure of an SDM which was presented at a mediated modeling workshop later.

Focus group discussions were recorded and transcribed from Chichewa to English. The enumerator who conducted the interviews assisted the researcher with translating each data from each focus group. Then, transcriptions were uploaded into the qualitative data analysis software MAXQDA to analyze the data. Data was coded into nodes and sub-nodes. Nodes included farmer knowledge about the *Striga spp*. lifecycle (e.g., germination, attachment), the type of practices mentioned (e.g., preventative, treatment), their understanding of the control mechanisms employed by each practice (e.g., suicidal germination catalyzed by legumes), the attributes they considered before implementing a practice (e.g., labor) and their preferences for each practice. Additional sub-nodes were added to determine the sources and institutions that facilitated or prevented implementation of SCPs.

4.3.2.4 Questionnaire

A survey was administered from August to September 2017. The questionnaire collected data regarding *Striga spp*. knowledge, current and past agricultural practices, and the effects the weed had on their farms. Please refer to the instrument in **Appendix 2** and **3** of chapter 2 in this dissertation for further clarification about questions and responses. The questionnaire was tested in the field prior to data collection. All enumerators that participated in the study had also fielded questionnaires to the same farmers in March 2016. Once the questionnaire was completed, farmers participated in a DCE. The questionnaire and DCE took approximately 40 to 70 minutes. Farmers were compensated with 5 blocks of laundry soap for completing the questionnaire and one bottle of soda for completing the discrete choice experiment. Survey-respondents primarily consisted of those charged with making farm decisions for their household.

One of the primary themes of the questions was implementation. In this study, implementation is referred to as a conscious decision to employ a new or previously employed practice (i.e., SCP) (Besley & Case, 1993). Implementation is a process of decision-making and behavioral change where potential and acting implementers can reject a change and return to a previous practice or non-practice (Castaño et al., 2002). There are three notable types (or measures) of implementation (also referred to as adoption) mentioned in the literature, including discrete or dichotomous choice, intensity of practice and continuous decision (Jabbar et al., 2003). This study focused on the continuous decision where a household would choose to implement, dis-implement, reimplement or abandon a maize-legume intercropping SCP. Feder et al. (1985) suggests when determining which measure to use, researchers should consider whether they are assessing individual versus aggregate adoption (e.g., percent adopted in a given region), if adoption requires the implementation of single practice or suite of practices (e.g. fertilizer and/or hybrid seed) and whether the practice is divisible or non-divisible (e.g., sowing seed [1 practice] versus conservation agriculture [3 practices]).

To collect data about the implementation process, questions specifically asked about the sources households heard a treatment or preventative SCP from. Then, if they implemented the SCP (based on that source), what outcomes occurred and who did they share the results with. With this data, approximations could be made about the diffusion process (i.e., how information about a practice traveled through a system). In addition, estimations could be made about the probability of hearing about SCP versus the probability of implementing the SCP after. To avoid collecting an insufficient amount of data about implementation, questions asked about two different types of SCPs rather than just one (e.g., maize-legume intercropping). These SCPs included treatment and preventative practices. Treatment practices are employed when *Striga spp.* is observed in the field and removed by a famer. In some instances, after the weed is removed, a treatment practice may also entail applying an input where it emerged. Oppositely, preventative practices are employed before *Striga spp.* is observed in the field in an effort to create less favorable conditions for germination.

4.3.2.5 Discrete choice experiments

Discrete choice experiments (DCEs) are a quantitative method used to elucidate how farmers value attributes or benefits delivered by an innovation. Many times, the implementation of a practice will depend on the tradeoff farmers are willing to make between implementing a new innovation against other alternatives (e.g., receiving an initial decrease in maize yield for long-term reductions in *S. asiatica* emergence). DCEs can unveil these tradeoffs and farmer-priorities (Fujisaka, 1997). To conduct the experiment, real-life scenarios are presented to farmers where each innovation will have a different set of attributes with varying levels. The varying levels present costs and benefits to the farmer to choose from. By choosing an innovation, researchers can determine what tradeoffs (e.g., maize kg) farmers are willing (or not willing) to make to implement a SCP versus continuing the status quo (Ortega et al., 2016; Waldman et al., 2016). A mixed logistic regression analysis was then used to determine which SCP attributes significantly influenced decisions and the tradeoffs farmers were willing to make to implement them.

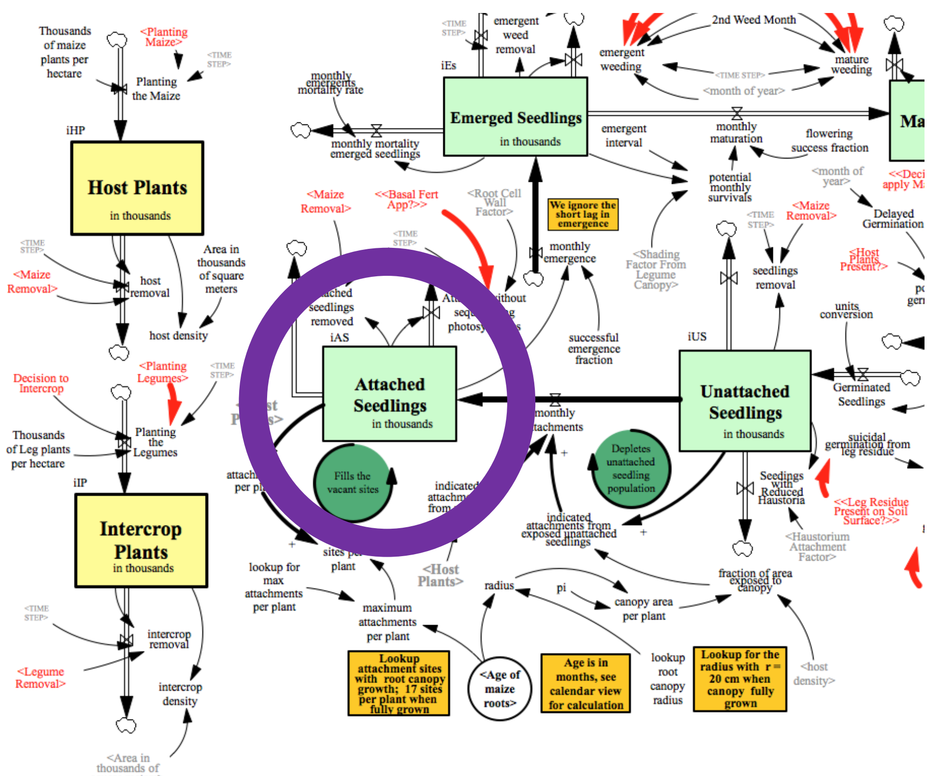
DCEs were conducted by presenting six hypothetical scenarios (often referred to as choice tasks) to 10 respondents at a time. In each scenario, respondents could choose one of two alternatives (i.e., SCPs) or choose to opt out. Each alternative was presented in the form of five attributes with varying levels. The attributes included soil fertility benefit, *S. asiatica* emergence, labor requirement, legume yield and maize yield. Except for maize yield, each attribute consisted of three levels, low, medium and high. Maize levels entailed percentages of maize yield gains or losses; 50% loss, 25% loss, no loss or gain and 20% gain. Each group of respondents had an enumerator explain the purpose of the DCE and clarify any questions respondents had afterwards. Respondents were then given a card with a blue, green and orange circle corresponding to alternative 1, alternative 2 and opt out, respectively. Each choice task respondents would indicate which choice participants made by pointing to the circle behind their back so as not to influence others' decisions. Refer to **Appendix 1** for further clarification of how choice tasks were presented to respondents.

4.3.2.6 Crop modeling

In addition to implementation decisions, another popular quantitative method used for analyzing agricultural technologies is crop modeling. These models predict growth, development and yield of plants. Crop models are useful for researchers, farmers and policy makers aiming to identify options for improving management techniques or limiting negative externalities (e.g., nutrient runoff). The benefits of dynamic crop models lie in their ability to inform users *when* to perform various management practices rather than *how* to execute them (Jones et al., 2016). These outcomes are achievable so as long as the necessary data is available. Data availability and accuracy are some of the two largest limitations that affect one's confidence in model performance. Simulated outcomes can be verified by comparing results to previous studies or field observations.

In a separate study, the researcher developed a cropping system model (CSM) to simulate the dynamic behavior of *S. asiatica* within its lifecycle under various smallholder management strategies. Different stages of the *S. asiatica* lifecycle were used to inform how to construct the CSM. In addition, the structures of several previously developed parasitic weed models were reviewed to inform the parameterization of the CSM (Grenz et al., 2005; Smith et al., 1993; Van Mourik et al., 2008; Westerman et al., 2007). Supporting literature was then sourced to confirm the structure and apply values or equations to its parameters (e.g., seedbank, attachment, germination and flowering parameters) (Denning et al., 2009; Jamil et al., 2007; Kabambe et al., 2008; Mhlanga et al., 2016; Ngwira et al., 2013; Nyagumbo et al., 2016). Model behavior was validated by this literature as well. The model was developed specifically to simulate *S. asiatica* emergence behavior, but accounted for the number of attached *S. asiatica* seedlings per maize plant across a 1 ha field (see **Figure 27**). The population of attachments varied across individual and multiple SCPs run in the CSM. Maize yield approximations were made based on three conditional statements: high/low attachment, yes/no fertilizer application, and adequate/inadequate rainfall. Attachment rates were calculated by whether a field was intercropped and/or fertilizer was applied. These rates were based on the outputs of the CSM. Application was based on whether a fertilizer subsidy was initiated or not. Adequate rainfall for a growing season was based on whether a region received 1200mm of rain (or not) during the growing season. If two out of three conditions were favorable (e.g., low attachment and adequate rainfall), then a field received favorable maize yield and continued implementation.

Figure 27 - Reduced view of CSM (attached seedlings stock circled in purple)



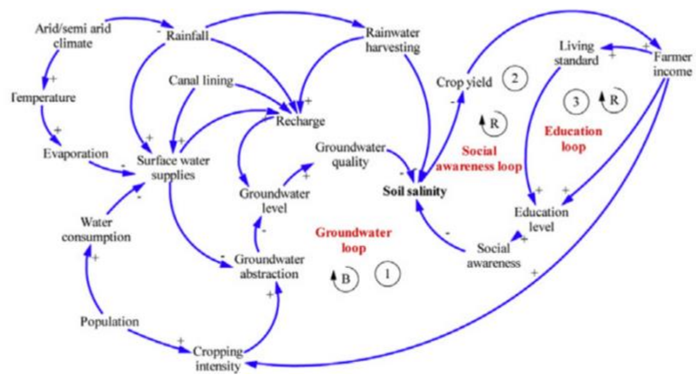
4.3.2.6 Mediated modeling

A mediated modeling workshop was held on September 14, 2017 with the objective to collectively parameterize a system dynamics model (SDM). The SDM included socioeconomic and natural parameters that could influence *S. asiatica.* emergence as well as SCP implementation across smallholder systems in Central Malawi. Group model-building has been used in a number of contexts, such as water and wildlife management (Beall & Zeoli, 2008; Pahl-Wostl & Hare, 2004; Schmitt Olabisi et al., 2016). During modeling exercises, opinions, information and perspectives are exchanged, catalyzing social learning between participants (Van den Belt, 2004). From these discussions, stakeholders with different professions can reach a consensus on difficult and contentious issues (Schmitt Olabisi, 2010).

SDMs simulate the fluctuation of different stocks (e.g., *S. asiatica* emergence) relative to outside influencing factors (e.g., adoption of SCPs). These influential factors do not operate in a linear one-way fashion, but rather, change according to the stock they feed into or pull from (Kopainsky et al., 2012). System dynamics is a valuable instrument for modeling various environmental, political and financial events that affect resource (e.g., labor) availability, and accordingly, alter implementation (Shi & Gill, 2005). Such models are unique in that explanatory variables can be altered, to assist social scientists and policy makers investigating whether certain strategies (e.g., agricultural extension) should be invested in or not (hypothetically speaking) to increase implementation. While quantitative analyses such as econometrics can illustrate the *elasticity* or sensitivity certain variables have upon populations, system dynamics allows the observation of both elasticity and *plasticity* of variables. In this study, data collected from institutional inquiry (via focus group discussions), DCEs and CSM-runs informed the SDM to mimic a social and environmental climate farmers made choices and operated in.

Causal loop diagrams (CLDs) inform the development of SDMs. These diagrams identify the driving linkages behind a system. Many times, these drivers are referred to as feedback loops. Feedback behavior will exponentially increase/decrease or counter any growth in a stock. The population of a stock such as a pool of SCP implementers, is then unaffected by any endogenous factor added to the system. CLD exercises used during soil management workshops argued that identifying these loops is quintessential to developing and understanding the behavior of SDMs (see **Figure 28**) (Inam et al., 2015).

Figure 28 - Individual causal loops diagrams digitized in Vensim



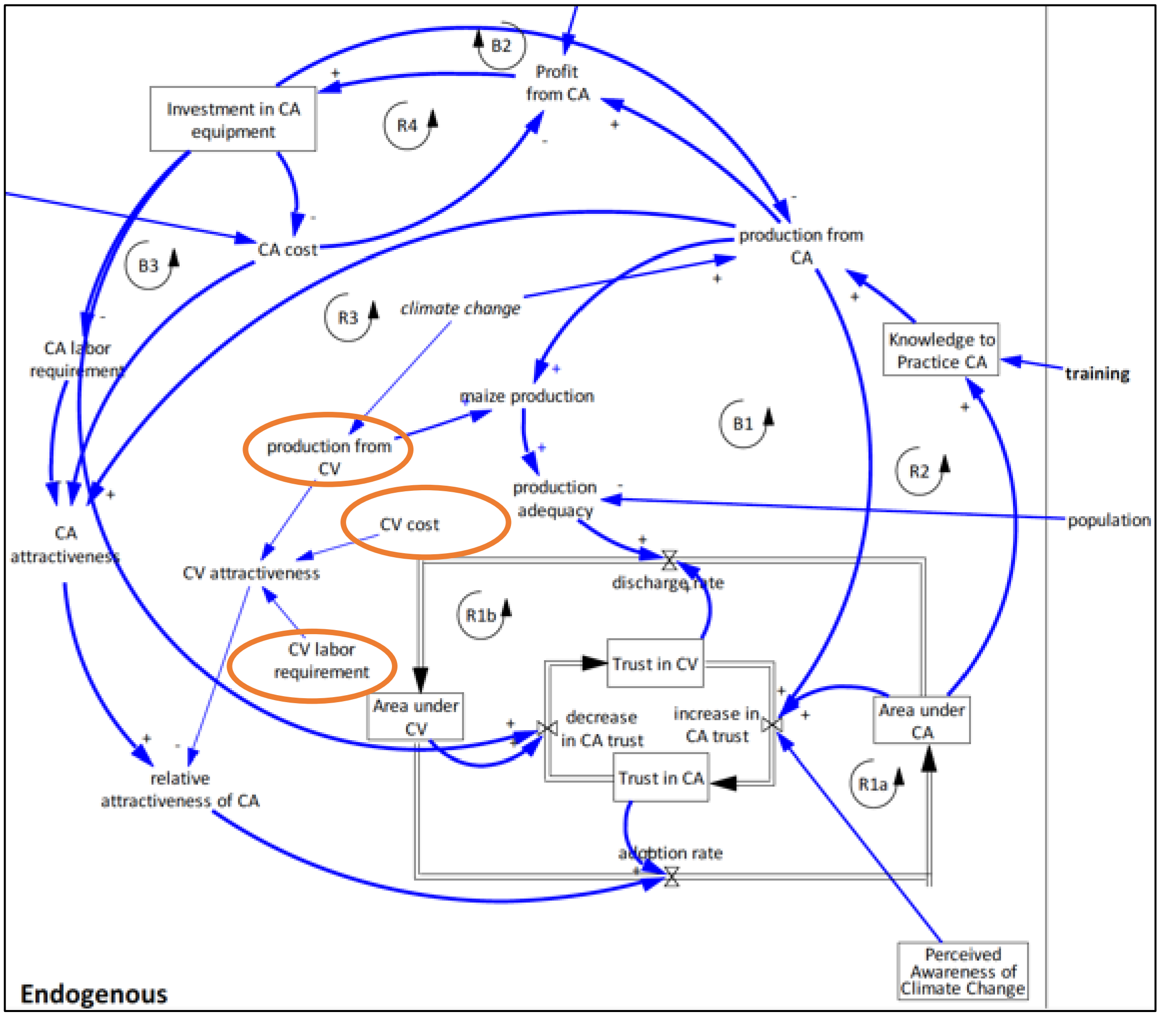
Source: Inam et al., 2015

Prior to the workshop, the researcher met with workshop attendees to discuss the topic of *S. asiatica* emergence across Central Malawi. The purpose of these informal meetings was to briefly discuss the biology behind *S. asiatica* and the status of farmers affected by emergence in the central region. During these discussions, attendee-opinions were gathered about their beliefs of the natural/financial/social causes behind *S. asiatica* emergence. From this point, the researcher explained how their insights informed CLDs. After the attendee was briefed about systems modeling and how CLDs were structured, attendees were then asked to draw their own CLD which explained *S. asiatica* emergence. The CLD could include natural, social and financial parameters. It is advised to explain SDMs (e.g., what is a stock, what is a flow) and conduct CLD drawing activities prior to mediated modeling workshops to streamline SDM building activities (van den Belt, 2004)

At the workshop, participants were separated into three groups – researchers, lead farmers and AEDOs; researchers and private sector employees (e.g., fertilizer salesmen and women); researchers and policy makers. At least one researcher was purposefully put in each group to facilitate the construction of the model. Given the lack of familiarity with system dynamics, researchers helped streamline the construction of each model for each group. The separation of stakeholders into three separate groups is an imperative first step given that they may view the problem differently and develop disparate CLDs (Van den Belt, 2004). First, each group was asked to define *S. asiatica* emergence as a problem in the central region as well as its primary causes. Based on these presentations, groups identified which sector of emergence they would develop a wider SDM for. Lead farmers and AEDOs chose to develop a sector with physical and natural parameters that affected emergence at the field level; private sector employees chose to develop a sector with financial and social parameters that affected SCP adoption; policy makers chose to develop a sector with financial and social parameters that affected the development and dissemination of SCPs.

Once groups and their modeling responsibilities were defined, they were asked to collaboratively design and present CLDs that mimicked emergence across a one-hectare field cultivated by a smallholder. Specifying a boundary for attendees to model in, such as a smallholder field, facilitates which parameters to (or not to) include (Van den Belt, 2004). Next, groups used CLDs to construct an SDM that initially included parameters from the EPA level they believed directly affected emergence. After constructing the SDM they could add parameters from the district level they believed affected emergence, and finally, the country level. Attendees were asked to parameterize their model in this manner as to not overwhelm them with the insurmountable factors that could affect emergence, hindering their completion of a SDM (Van den Belt, 2004). This is a common method which has been used in the past to parameterize an agricultural technology adoption SDM. **Figure 29** illustrates how certain parameters such as “climate change” and “population growth” are located outside model boundary. Thereafter, groups presented and fielded questions regarding their SDM. Finally, the researcher made plans with attendees of how to collect data for applying equations and values to their parameters. In addition, the researcher received input from attendees how to connect and combine these SDMs into a single model using Vensim. Vensim is a simulation software used to develop, analyze and package dynamic feedback models.

Figure 29 - CA indicates conservation agriculture practices and CV indicates conventional farming practice



Note: B# and R# indicate balancing and reinforcing behavior, respectively, in the model
Source: Amelia et al. (2014)

4.3.3 Data collection

Data collection was carried out in a consecutive manner with each method's findings informing the development of the following method's instrumentation. Focus group discussions were first facilitated to assess which SCPs farmers were aware of and/or had implemented before. Focus group discussion were also carried out to unveil the attributes farmers considered prior to implementing a SCP. These data informed the development of questionnaires and DCEs. After data from focus group discussions, questionnaires and DCEs were collected, a CSM was developed to evaluate the most popularly implemented SCPs. The most popular SCPs were uncovered by analyzing questionnaire data. Then, a mediated modeling workshop was held with farmers and other stakeholders (e.g., *S. asiatica* researchers) to structure and parameterize a SDM. This mixed method approach used to parameterize an SDM has been carried out previously to model agricultural technology adoption (Amelia et al., 2014). Raw data and findings from all previous methods were used to apply values/equations to parameters in the SDM.

4.3.2.1 Site description

Household surveys were conducted over a 3-week period from August-September 2017 using questionnaires and DCEs in two central districts of Malawi- Dedza and Ntcheu. Dedza and Ntcheu are located in the Kasungu Lilongwe Plain (14.1667°S, 34.3333°E) and Rift Valley Escarpment (14.7500°S, 34.7500°E), respectively. Within these districts, four extension-planning areas (EPAs) were selected for data collection, namely Linthipe, Kandeu, Nsipe and Golomoti. These EPAs were specifically chosen based on the growing challenge of *S. asiatica* reported by farmers in recent years (Atera et al., 2012). Hence, the study was highly relevant to the region and its current farming population.

The CSM was developed from observing *S. asiatica* emergent rates at Chitedze Research Station. Chitedze is located on latitude 13.59° S, and longitude 33.38° E, Lilongwe, Malawi. The site is 1146 meters above sea level, has a mean annual temperature of 20^{o}C and mean annual rainfall of 892 mm. Mean maximum and minimum temperatures are 24^{o}C and 16^{o}C respectively (MoAFS, 2007). The experiment was conducted from December 2017 to March 2018 at the Chitedze Research Station in Malawi in order to evaluate the effects of tillage and cowpea-intercropping had on *S. asiatica* emergence in maize based systems. Soils used for the experiment were collected from farmer-managed plots from July 20-22, 2017. Farmers were affiliated with the Conservation Agriculture project funded by Total Land Care (TLC) and CIMMYT-Harare in partnership with the Ministry of Agriculture in Malawi. The mediated modeling workshop was conducted at the same research station on September 14, 2017.

<u>4.3.2.2 Selection of participants</u>

For focus group selection, Agriculture Extension Development Officers (AEDOs) were given lists of farmers from the Africa RISING program and participants were randomly selected from each gender. AEDOs purposefully selected 6-8 men and 6-8 women per focus group to avoid one gender from dominating the discussion and to capture a diverse dialogue. The focus group quota was set to 12-15 participants to ensure each participant had ample opportunity to share his or her opinion (Fern, 1982). Each discussion lasted between 60-80 minutes, was recorded and transcribed after. Discussions took place in or near an extension office. Participants were compensated with a soda and bread to discuss *S. asiatica* control practices with the researcher and his enumerator.

A stratified sample of 215 households (n=215) was taken from the Africa RISING's farmer roster (N = 298) across four EPAs (Linthipe, Golomoti, Nsipe, Kandeu) to determine who would be surveyed in the Striga Emergence Questionnaire and DCEs. First, a stratum of 125 participants were purposefully selected consisting of households that expressed *S. asiatica* as primary challenge to productivity. After these households were removed from the roster, farmer names were segregated into their respective EPAs. Given the budget constraints of this study, only 50-60 *Striga* Emergence Questionnaires and DCEs were carried out per EPA. Taking this budget into account, the first names of the household heads were put in ascending order alphabetically and the remaining balance was taken to fill a quota of 50-60 questionnaires per EPA. For example, in Linthipe, 36 farmers were purposefully selected and removed from the EPA's roster, then households were alphabetized, and the first 24 names were selected to make a total of 60 famers. After eliminating households for which data were missing or incomplete, 51 households were selected from Linthipe, 59 from Golomoti, 52 from Nsipe and 53 from Kandeu.

The CSM was calibrated from *S. asiatica* seedlings that emerged from farmer soils. The farmers (n=15) participated in the project funded by Total Land Care (TLC). The project advocates for minimal disturbance of the soil, retaining crop residues on the soil surface during- and off-season and/or rotating legumes. After forming a cooperative (10-12 farmers), cooperatives in communities are given several inputs (fertilizer, maize seed, cowpea seed) by TLC to assist with beginning one or all farming practices. The pot experiment yielded 360 pots, allowing for 360 potential observations of emergent rates.

For the mediated modeling workshop, two male and two female farmers from each EPA were selected to participate. These farmers were lead farmers in the Africa RISING program. Lead farmers are generally charged with training other farmers (among many other responsibilities) about new agricultural technologies. In addition, they sometimes manage demonstration plots with these technologies. Two Agriculture Extension Development Officers (AEDOs), one male and one female, were selected from each EPA to participate. The AEDOs were largely involved in the Africa RISING project and the training of its participants since 2013. One officer from each EPA assisted with organizing the focus groups. In addition to farmers and AEDOs, two crop scientists, two ministry of agriculture officials and two agricultural input salesmen (e.g., seed, fertilizer) were selected to participate in the workshop as well. These stakeholders were invited specifically for their insights about *Striga spp*., its research, policy and SCP distribution. Opinions offered by each participant gave a complete perspective of the weed; from the farmer field; to the research lab, to the market, and finally to the government. Workshop attendees were compensated with a per diem rate of 4000MKW, lunch and traveling stipend. Traveling stipends varied depending on distance.

4.3.4 Data analysis

4.3.4.1 Summary statistics

Parameters in the SDM informed what summary statistics were needed from the questionnaires and DCEs. In addition, parameters in the SDM informed which climate data to take that was imbedded in the CSM. Also, emergence rate results based on SCP scenarios were taken from the CSM as well. These data and results were later synthesized into equations and/or values for purposed of applying them to parameters in the SDM. The following topics and their respective sources are listed in **Table 20**.

Table 20 - Source used for parameter equation/values.

Topic	**Source**
Yield thresholds which led to adoption or dis-adoption of SCP	1. Random parameter logistic regression in willingness to pay space (estimates made from Discrete Choice Experiments) 2. #35-41 (*Striga* Questionnaire)
Contact rate between farmers based on positive or negative results received from implementing a SCP	1. #27/31B, 27C/31C, 27D,31D (*Striga* Questionnaire)
Percent that receive a negative or positive outcome from implementing a SCP	1. #27/31B (*Striga* Questionnaire)
Implement a SCP based on word-of-mouth, agricultural extension, observation of other farmer fields	1. #25B/29A, 25A/29A, 26A/20A (*Striga* Questionnaire)
Rate of negative or positive outcome observed	1. #25B/29A, 26a/30A, 25B/29B (*Striga* Questionnaire)
Relationship between field parasitized with *Striga* and knowledge about Striga	1. #8-14 (*Striga* Questionnaire)

Table 20 (cont'd)

Striga attachment rate to maize in response to different SCPs	1. Scenario runs (Cropping Systems Model) 2. Literature (Rusinamhodzi et al., 2012)
Maize yield percent loss/gain based on rainfall and attachment	1. (Cropping Systems Model) 2. Literature (Jayanthi et al., 2013)
Number of fields with/without *Striga*	#14-15, 20 (*Striga* Questionnaire)
Percent implementers continued/discontinued SCP after receiving positive/negative results	#26D/30C, 26F/30E, 26G/30F (*Striga* Questionnaire)
Time required prior to hearing, seeing or receiving information about SCP	#34B, 34C, 34D (*Striga* Questionnaire)

4.3.4.2 Sensitivity and scenario analyses

A sensitivity analysis was used to evaluate how subtle changes in parameters of the SDM affected *S. asiatica* emergence and/or SCP adoption. Sensitivity analyses are used to investigate the resistance and resilience of simulated outcomes against certain events (Patten, 2013). In this model, for example, rainfall was reduced to assess if reduced maize yield affected trust in SCP, as well as its use and subsequent *S. asiatica* emergence rates across the region. In addition, different implementation rates of different SCPs were adjusted to see what emergent rates would play out across the region over time. In addition to the sensitivity analysis, different parameters were adjusted to reflect policies and management strategies. Scenario analyses are typically conducted in dynamic models to investigate the relationship between model outcomes and variable parameters (Patten, 2013). For example, fertilizer subsidies can be initiated in the SDM to determine if input purchases would reduce the implementation of cowpea-maize intercropping practices, increasing the emergence of *S. asiatica*.

4.4 Findings and discussion

There are several parameters in the SDM which required an assessment where and who farmers sourced their information about SCPs. This information was used to determine if that source influenced their implementation of one or multiple SCPs. In this section, summary statistics elaborate on these sources in terms of their effect on implementation, dis-implementation, reimplementation and abandonment of SCPs. Afterward, the manner in which the SDM was constructed at the mediated modeling workshop is explained. Next, how its different components of adoption (e.g., reimplementation) were used to parameterize the SDM. Thereafter, several sensitivity and scenario analyses are presented and discussed to determine what level of emergence might play out according to status quo trends. Historical trends from the literature were sourced to verify these findings. Finally, hypothetical scenarios were run and their results are discussed.

4.4.1 Summary statistics

Farmers implemented a number and combination of treatment and/or preventative SCPs. Treatment practices consisted of timely weeding, disposal in a deep pit and micro-dosing the affected area with maize bran, ash, fertilizer and/or manure. Preventative practices consisted of mulching, minimum tillage and/or crop rotation/intercropping with legumes. On average, household implemented two SCPs on their farm. The practices were implemented across one to two fields cultivated with maize. These fields were generally between 0.05-2.65 hectares. The preventative practices farmers implemented to address *S. asiatica* agree with Vanlauwe et al. (2010) assessment that SCPs typically consist of applying soil amendments, organic materials and mineral fertilizer to replenish soil nutrients.

As a whole, 57.7% of farmers reported that *Striga spp.* emerged on one or more of their fields cultivated with maize. Higher knowledge scores about the *Striga spp.* lifecycle were not associated with lower percentages of fields with *S. asiatica* (see **Table 21**). Being that the score could range from 0-12 and the average score was 5.27, farmers had a low understanding about the identification, parasitism and lifecycle of *Striga spp*. Among these three areas (each having 4 questions), participants scored the highest in identification and lowest in parasitism. Those with lower knowledge (n=40), average knowledge (n=94) and higher knowledge (n=24) varied little in the number of SCPs they implemented. Participants with average or higher knowledge (i.e., a score of 5-12) implemented a slightly higher number of SCPs ($\bar{x}$=4.1) when compared to their counterparts ($\bar{x}$=3.7) who assumed lower scores (0-4). This finding coincides with wider argument that as adoption intensifies (e.g., more SCPs implemented), knowledge about the technology and its desired effects (e.g., emergence reduction) increase as well (Alene et al., 2000).

Table 21 - Participant characteristics according to Striga spp. prevalence on HH farm

*Participant and farming practice characteristics	Low % fields with Striga (n=35)	Medium % fields with Striga (n=63)	High % fields with Striga (n=60)	Aggregate average (n=158)
Knowledge (1-12)	4.82	5.52	5.25	5.27
Treatment practices (#)	2.29	1.90	1.98	2.02
Preventative practices (#)	2.08	1.89	2.15	2.04
*Maize yield (kg/ha)	2,008	1,454	1,456	1,548

*Note: Low, medium and high percentages of fields infested with *Striga spp.* were considered as 0-34%, 35-67% and >68%, respectively. Out of 158 households surveyed in the Central region, 23%, 44% and 33% of fields had low, medium and high infestations, respectively.
**Note: Maize yield (per hectare) varied dramatically, ranging from 400 kg/ha to 4000 kg/ha, but the average was approximately 1500kg/ha. The mean yield seemed to exceed yields (approximately 1000 kg/ha) farmers received the 2016 season. This commonly occurs when yield cuts are extrapolated into kg/ha, which is what the study did.

Higher knowledge scores, however, were not associated with lower percentages of fields parasitized by *Striga spp*. Further analysis among participants with a low percentage of fields with *Striga spp*. emergence revealed that 68.2% had implemented between 4-7 SCPs whereas 25.4% and 49.8% of participants cultivating a medium and high percentage of fields with *Striga spp*. emergence implemented 4-7 practices. Long-term *Striga spp*. management, in many cases, requires the implementation of a combination of SCPs rather than just one to two; therefore, it seems plausible there would be a lower percentage of fields with *Striga spp*. emergence associated with participants that implemented a higher number of SCPs (Ransom, 2000; Reda et al., 2005).

A much clearer relationship is evident in **Table 21** between average maize yields and the percentage of fields which had *Striga spp*. emergence. Households which cultivated fields with 0-34% emergence (n=35) had close to 500 kg difference (33.3% loss) in average maize yields than those with 35-67% (n=63) or >68% (n=60). This finding agrees with previous estimates where maize yield losses attributed to Striga *spp*. attachment range between 30-100% in low input systems (Parker, 2009). These losses, in many respects, are influenced by the extent of emergence across an entire field versus or just in various patches. Among the households that reported emergence (n=147) in their fields, 80.2% (109) and 38.6% (17) experienced patchy and full emergence across their fields, respectively. Lower yields ($\bar{x}$ =795 kg) were experienced among households with full emergence versus those that reported spotty emergence ($\bar{x}$ =1,075 kg).

Participants mentioned several sources they heard or learned about SCPs. The primary sources included word-of-mouth (via family member, market vender/patron, organization member, other farmer), agricultural extension (via AEDO), observation (via farmer field, demonstration trial) and advertisement (via radio, pamphlet, private agent). Word-of-mouth was the overwhelmingly popular source farmers heard and where SCPs were implemented from, followed by agricultural extension, observation, and finally, advertisement. The high percentage of learning attributed to word-of-mouth coincides with similar studies that have assessed information source influence over the implementation of agricultural technologies (Kopainsky et al., 2012). The order of the sources in this study, specifically agricultural extension ranking higher than observation, does not agree with other studies necessarily (Stone, 2007). One reason for this difference is that agricultural extension was included as word-of-mouth in these studies. In addition, in the study SCPs may have been in fields but were not noticed by study participants due to their low knowledge of *Striga spp*. and its related practices.

Table 22 - Sources SCPs were heard and implemented from

Source	Received information about SCP (n=153)	Implemented a SCP after receiving information (n=143)
Word of mouth	153 (96.8%) -------------------->	143 (90.5%)
Agricultural extension	109 (69.0%) -------------------->	97 (61.4%)
Observation	75 (47.5%) -------------------->	59 (37.3%)
Advertisement	16 (10.1%) -------------------->	9 (5.7%)
Aggregate average	153 (96.8%)	143 (90.5%)

Apart from rankings, it is important to assess the difference between the percentage of participants that heard about a SCP from a specific source and the percentage of those that actually implemented the same SCP later from the same source. Some refer to this difference between hearing and implementing as trust (Adesina & Baidu-Forson, 1995). Trust in an agricultural practice can appreciate and depreciate quickly from the high frequency of farmers sharing positive and negative outcomes from implanting a practice (Kopainsky et al., 2012). Hence, it is important to consider these percentages to assess later why there may be a sharp decline in SCP implementation, for example, due to a single season with negative outcomes, even if there were numerous consecutive seasons with positive outcomes previous to this event. In **Table 22**, there is a 6.6%, 11.1%, 21.4% and 43.8% decrease from participants hearing about a SCP and implementing a SCP via word-of-mouth, agricultural extension, observation and advertisement, respectively. These results indicate there is a low trust in advertisement where there is a high trust in word-of-mouth. One primary consideration in this calculation (i.e.,

% Receive Information about SCP 1 from Source A ÷ % Implement SCP 1 from Source A) is that participants heard about a SCP quite often from multiple sources as opposed to one source exclusively.

Word-of-mouth assumed the highest percentage of implementation across all SCPs in **Table 23**. The SCPs listed in **Table 23** were among the most commonly mentioned. Manual weeding, tillage and burning were excluded from the table to determine SCPs that have been introduced more recently. Observation assumed the second highest percentage of implementation among maize bran and ash application practices, but agricultural extension assumed the second highest percentage of implementation among the remaining practices. Difference in these percentages may be attributed to a number of reasons, including the trust and frequency of agricultural agents that visit villages which were surveyed in this study. In addition, maize bran and ash application have not been studied as extensively as their counterparts in the realm of *Striga spp*. control, perhaps because the quantity and quality of these controls' inputs are difficult to measure (Franke et al., 2006). Literature regarding this practice is more extensive in West African studies (Emechebe et al., 2004). Limited studies and literature may be a reason for why less extension has promoted ash and maize bran application as a SCP, and consequently, why there is less implementation among study participants.

Table 23 - Popular SCPs implemented across information sources

Source that informed farmer about SCP	Manure applic.	Maize bran applic	Ash applic	Herbicide applic	Crop residue incorp.	Maize-legume tech.	Fert. micro-dose	Total (aggreg. average)
Word of mouth	82 (83.7%)	9 (90.0%)	6 (85.7%)	26 (86.7%)	31 (93.9%)	38 (95.0%)	83 (83.8%)	143 (90.5%)
Extension	49 (50.0%)	4 (40.0%)	1 (14.3%)	16 (53.3%)	22 (66.7%)	25 (62.5%)	50 (50.5%)	97 (61.4%)
Observation	32 (32.7%)	6 (60.0%)	4 (57.1%)	16 (53.3%)	12 (36.4%)	12 (30.0%)	32 (32.3%)	59 (37.3%)
Advertisement	2 (2.0%)	0 (0.0%)	0 (0.0%)	1 (3.3%)	1 (3.0%)	1 (2.5%)	3 (3.1%)	8 (5.6%)
Total & aggregate averages	98 (62.0%)	10 (6.3%)	7 (4.4%)	30 (19.0%)	33 (21.9%)	40 (26.5%)	99 (65.3%)	143 (90.5%)

Note – Farmers heard and implemented a SCP typically from more than one source; therefore, column aggregate averages should not be treated as summed percentages. Farmers typically implemented more than one SCP from each source; therefore, row aggregate for each source should not be treated as summed percentages.
Note – Row aggregate averages were calculated by dividing the "total number of famers who heard a SCP from a source" by those same "farmers that implemented the SCP" after receiving information from that same source.

Different SCPs received higher percentages across different sources of information. Maize-legume technology (95.0%) and crop residue application (93.9%) assumed the highest percentages of implementation via word-of-mouth. The same trend was found via agricultural extension. These findings coincide with the wider effort being led in Malawi to promote such SCPs to address land degradation, although they are generally part of a wider package of practices that fall under conservation agriculture (Andersson & D'Souza, 2014). Different implementation trends emerged under observation and advertising. Crop residue and maize-bran application assumed the highest implementation percentages (60.0% and 57.1%, respectively) via observation**.** Herbicide and micro-fertilizer dose application assumed the highest implementation percentages (3.3% and 3.1%, respectively) via advertising**.** Higher percentages of implementation via advertising, though minimal, may be a result of private dealers vending agricultural inputs. Fertilizer micro-dose application assumed the highest aggregate percentage of implementation (65.3%) followed by manure (62.0%). Fertilizer may have been implemented to control *Striga spp*. considering its secondary benefits (e.g., maize yield increase) as well as its previous success across Malawi via FISP (Dorward & Chirwa, 2011). Manure, on the other hand, may have assumed the second highest percentage of implementation among participants because it possesses benefits akin to fertilizer micro-dose application. As a final point, focus group discussions revealed that farmers popularly implemented these types of practices not necessarily to reduce *Striga spp*. emergence, but to buffer maize against it. As evidenced by focus group transcripts, the application of manure provided a temporary pool of phosphorus for uptake to delay the onset of attachment (Kabambe et al., 2008).

> *"It increases fertility so maize can run away from Striga attack." (Linthipe – Male Participant 1)*
> *"When you apply manure, it will grow faster. So by the time Striga grows, the maize will have run past Striga before it can attack. (Linthipe – Male Participant 6)*

Various SCPs delivered a number of positive outcomes for participants that implemented them. Apart from the obvious, such as lower *Striga spp*. emergence in the short-term or long-term (94.4%), participants noted they received higher maize yield in the short-term or long-term (75.3%), increased soil fertility (70.8%), lower overall weed biomass (10.8%) and increased soil-water retention (10.0%). These results compliment earlier findings from focus group discussions as well as the literature where implementation of a SCPs was largely driven by maize yield and soil fertility benefits (Ajayi et al., 2007). Across positive outcomes (see **Table 24**), manure (71.4%) and ash application (71.4%) were viewed as the most effective technologies in lowering *Striga spp*. emergence. Researchers expected participants to choose maize-legume technologies (e.g., intercropping, rotation) to outcompete other SCPs in terms of *Striga spp*.

reduction. Partialness to other SCPs may be a symptom of participants not seeing or using newer practices. In addition, there may be other barriers to implementation of maize-legume SCPs such as land scarcity and fears of reducing maize-sowing density, and consequent maize yield (Silberg et al., 2017).

Table 24 - Common outcomes received by implementing SCPs

Benefit Received	Manure app.	Maize bran app.	Ash app.	Herbicide app.	Crop residue incorp.	Maize-legume tech.	Fert. micro-dose	Total (aggreg. average)
Lower Striga emerg.	70 (71.4%)	7 (70.0%)	5 (71.4%)	10 (33.3%)	16 (48.5%)	26 (63.4%)	11 (11.1%)	135 (94.4%)
Higher maize yield	55 (56.1%)	7 (70.0%)	0 (0.0%)	4 (13.3%)	17 (51.5%)	23 (56.1%)	56 (56.7%)	98 (75.3%)
*Higher soil fertility	48 (49.0%)	2 (20.0%)	1 (14.3%)	0 (0.0%)	18 (54.6%)	20 (48.8%)	50 (50.5%)	92 (70.8%)
Lower overall weed biomass	1 (1.0%)	1 (10.0%)	0 (0.0%)	10 (33.3%)	1 (3.0%)	0 (0.0%)	1 (1.0%)	14 (10.8%)
More water retention	1 (1.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (3.0%)	0 (0.0%)	1 (1.0%)	13 (10.0%)
Aggregate positive outcome	88 (92.8%)	10 (100%)	7 (100%)	29 (96.7%)	31 (93.9%)	35 (85.4%)	89 (89.9)	130 (82.3%)
Draw-back Received	Manure app.	Maize bran app.	Ash app.	Herbicide app.	Crop residue incrop.	Maize-legume tech.	Fert. micro-dose	Total (aggreg. average)
Higher Striga emerg.	6 (6.12%)	1 (10.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (0.6%)	6 (6.1%)	20 (71.4%)
Lower maize yield	1 (1.0%)	0 (0.0%)	1 (14.3%)	0 (0.0%)	0 (0.0%)	1 (2.4%)	1 (1.0%)	15 (53.6%)
Aggreg. negative outcome	19 (19.4%)	3 (30.0%)	0 (0.0%)	3 (10.0%)	8 (24.2%)	9 (22.0%)	19 (19.2%)	28 (17.7%)

Note – Increased soil fertility also included reduced erosion/improved soil structure/texture. Increased maize yield also included aggregate food increase

Note – Percentages calculated for positive and negative outcomes were calculated by dividing the number of individuals who mentioned the outcome according to a SCP divided by the total number of those that mentioned implementing a practice. For example, 6 individuals mentioned a negative outcome of implementing manure application as a SCP. A total of 98 participants implemented manure application. 6/98 = 6.1%

Apart from *Striga spp*. control, herbicide delivered the highest percentage of weed biomass reduction benefits (33.3%), maize-bran delivered the highest percentage of maize yield increase benefits (70.0%), fertilizer micro-dose application delivered the highest percentage of maize yield benefits (56.7%), crop residue incorporation delivered the highest percentage of soil fertility and soil-water retention benefits (54.6% and 3.0%, respectively). Researchers expected participants to choose fertilizer micro-dose application to surpass other SCPs in terms of maize yield benefits being that it is a N-based input largely responsible for yield increases (Denning et al., 2009). The SCP delivered the second highest percentage of maize yield benefits for participants (56.7%). A higher percentage associated with maize-bran application may be attributed to the small number of participants that implemented the SCP (n=10). For example, if just four participants mentioned they received weed biomass reduction benefits, the SCP would deceivingly appear as the SCP that delivered the highest percentage weed biomass reduction.

Participants of the study mentioned that they received several drawbacks from implementing one or more SCPs. Higher *Striga spp*. emergence in the short or long-term was cited as the most popular drawback (71.4%) to implementing a SCP. Lower maize yield in the short or long-term was cited as the second most popular drawback (53.6%). Maize bran assumed the highest percentage of higher *Striga spp*. emergence (10.0%) and ash application assumed the highest percentage of lower maize yield (14.3%). These percentages may be a reflection the small number (28 out of 158) of negative outcomes mentioned by participants. While these reports may appear encouraging for SCP disseminators, minimal responses about negative outcomes may be attributed to fear of losing agricultural extension and/or inputs from the NGO the researcher was affiliated with during the study (Africa RISING). Such occurrences are commonly cited in the literature (Hensher, 2010). Oddly, little to no participants mentioned labor increase, pest attraction (n=1) or input cost/availability (n=3) as a drawback from implementing a SCP. These were common reasons mentioned in focus group discussions and cited in the literature for discontinuing or not implementing a SCP associated with maize-legume intercropping (Chinsinga & Poulton, 2014). The survey may have not captured these observations.

Maize yield assumed the highest percentage of positive and negative outcomes received by implementing a SCP. A more in-depth analysis revealed that maize yield gains and losses were also the leading reasons for continuing and discontinuing a SCP. For example, among the 80% of participants that mentioned they received a positive outcome from implementing a SCP, only 20% remained after removing observations associated with maize yield increase. In addition, among the 20% that received a negative outcome, only 5% remained after removing observations associated with maize yield losses. These findings concur with published and unpublished literature that cite staple food yield losses as the primary reason for discontinuing SFM technologies such as conservation agriculture and maize-pigeon pea maize intercropping (Grabowksi et al., 2018; Kopainsky et al., 2012).

Table 25 - Extent of positive and negative outcomes shared with peers

	Positive outcome	Negative outcome	Average
% HH's share	46.2%	20.1%	33.2%
Avg. # of people share	9.9	2.0	6

Participants shared their positive and negative outcomes with fellow farmers, cooperatives and other points of contact differently. More than double the percentage of participants shared their positive outcomes ($\bar{x}$=.46) than their negative outcomes ($\bar{x}$=.20) via word of mouth (see

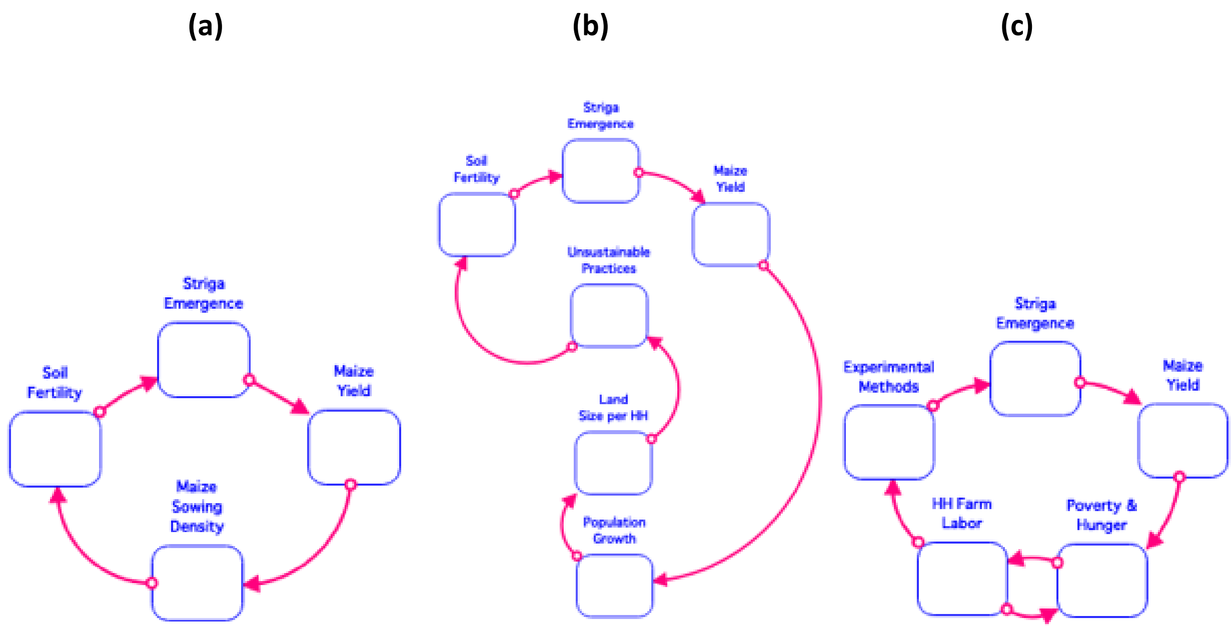
Table 25). Furthermore, participants, on average, shared nearly five times more the number of individuals with positive outcomes ($\bar{x}$=9.9) than negative outcomes ($\bar{x}$=2.0). There are a number of reasons for why individuals may have been more prone to sharing information about the positive outcomes of using a SCP rather than sharing information about negative outcomes. For instance, focus group participants mentioned that seeds could be transferred from farm to farm. Hence, an information sharer could be motivated to inform their neighboring farmer how to control *Striga spp*. to avoid emergence on their farm. On the other hand, farmers may have been ashamed or reluctant to share information due to various taboos (Ngwenya & Hagmann, 2011). The lop-sided differences between positive and negative information sharing did not necessarily agree with previous adoption literature (Friedlander et al., 2013). Literature seems to cite that farmers are more willing to share their challenges with a new agricultural technology rather than the benefits it provides.

4.4.2 Participant causal loop diagrams

Participants were asked to develop CLDs at the mediated modeling workshop prior to composing SDMs. To streamline activities, the researcher facilitated a discussion to determine the overarching feedback loops which increased or reduced emergence. Initially, many participants mentioned emergence was driven by the degradation of soil. When asked what drove soil degradation in region, many participants highlighted the growing problem of decreasing land size due to population growth. Consequently, average household farm sizes decreased, sowing density increased to compensate for planting space lost. As a result, soil fertility decreased from intensified practices, creating more favorable conditions for *Striga spp.* emergence. In addition, many participants mentioned as more maize fields were parasitized by

Striga spp., more seeds were transferred from farm to farm. Without fallowing or the application of organic inputs to rectify degraded lands, the problem would persist. Based on this discussion, three CLDs were drawn (see **Figure 30**) to guide SDM development during the second half of the workshop. These CLDs were created in a systems modeling software called Stella.

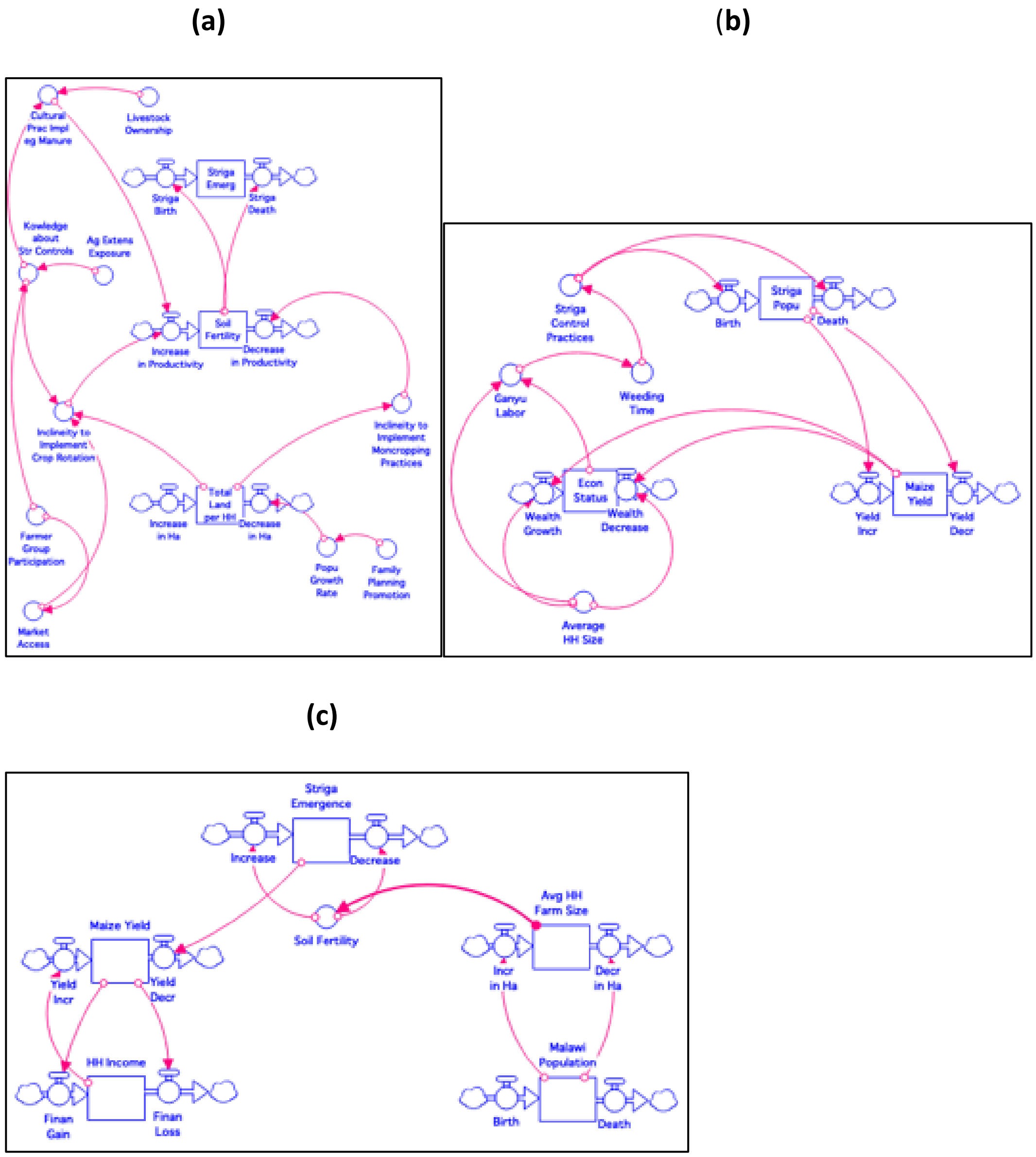
Figure 30 - Causal loop diagrams created by farmers and AEDOs (a), private sector participants (b) and policy makers (c)



4.4.3 Participant system dynamics models

Based on the CLDs shown in **Figure 30,** the three groups created three SDMs. As much as researchers tried to help streamline the development of these SDMs, it became evident during the workshop that the facilitator had not prepared participants well enough. Systems thinking can be a difficult concept to grasp in such a short time period, but obligating research participants to develop a SDM in a single meeting can be even more challenging. Never the less, **Figure 31** illustrates SDMs they developed. While they may not appear extensive, key parameters show what participants felt drove emergence. Based on the SDM in **Figure 31(a)**, farmers and AEDOs believed that knowledge about SCPs catalyzed the use of traditional practices to control *Striga spp*. In addition, affiliation with cooperatives increased the flow of information to discuss and implement SCPs such as maize-legume crop rotation. Further implementation decreased the cost of inputs as cooperatives could supply and buy seed from the SCP implementers. **Figure 31(b)** illustrates that the private sector believed the current state economy in Malawi drove the emergence of *Striga spp*. Therefore, as wealth grew from maize yield increases, more funds could be allocated to casual labor (also referred to as ganyu labor) to assist with weeding and the implementation of SCPs. While it is not shown in their SDM, group members mentioned to increase maize yield, agricultural input subsidies would need to be put in place. **Figure 31(c)** demonstrates that policy makers held the belief that *Striga spp*. emergence was largely driven by larger households, shrinking land holdings and consequent land degradation. All groups identified that maize yield was the primary determinant of SCP implementation.

Figure 31 - System dynamics models created by farmers and AEDOs (a), private sector participants (b) and policy makers (c)

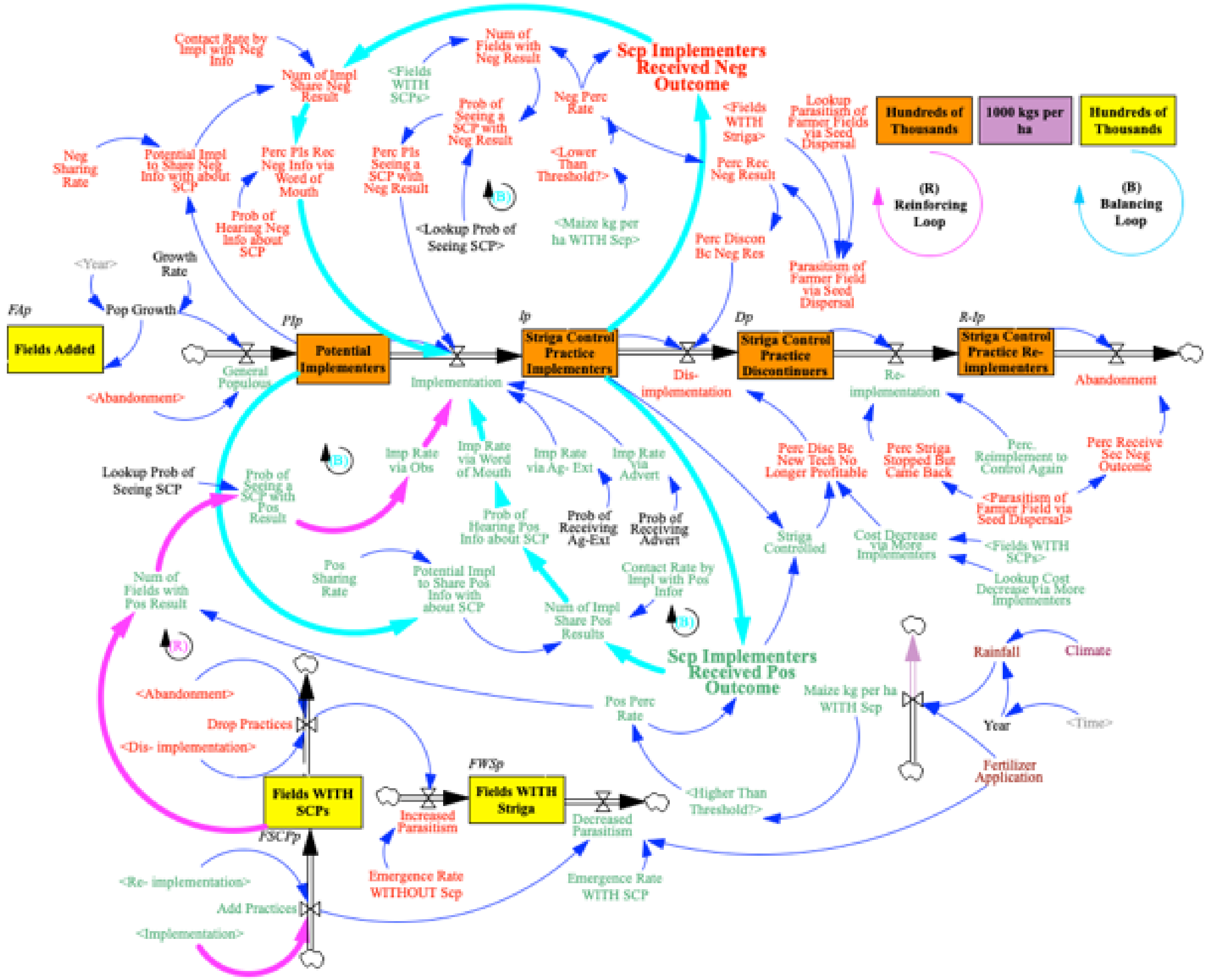


Note: All models were drawn and presented at the workshop and later created in systems modeling software named Stella

4.4.4 System dynamics model

A SDM was developed (see **Figure 32**) to simulate the interaction between SCP implementation and *S. asiatica* emergence. A SCP in the model is associated with integrating legumes (*Vigna unguiculata*) within a maize-based system. The structure of the model was based on the data collected from the mediated modeling workshop (e.g., SDMs, discussions) and adoption models found in the literature (Turner et al., 2016). The parameters of models were applied with values and equations based on data collected from household surveys. These values and equations are outlined in **Appendix 2**. The core structure of the model embodies a diffusion process (refer to **4.3.1 Theoretical Framework** for further explanation). In the SDM, households from the general population can choose to implement a SCP making them a "Striga Control Implementer". Then they can remain with the SCP, discontinue (making them a "Striga Control Practice Discontinuer"), take the SCP back up again (making them a "Striga Control Practice Re-Implementer") or abandon the SCP all together.

Figure 32 - System dynamics model of Striga emergence and control practice implementation



Note: The implementation of the SCP that was analyzed specifically was maize-cowpea intercropping given the scope of this dissertation. In addition, the species that was analyzed was *S. asiatica* given its specificity to the region. The rates of its emergence and control are according to CSM estimations.

The uptake or suspension of a SCP is driven by numerous outcomes, most notably maize yield. Hence, the percent of households that receive positive and negative outcomes is based on whether a maize yield threshold exceeds what a household is willing to sacrifice for lower *S. asiatica* emergence. In this model, maize yield is a function of SCP implementation, rainfall and fertilizer application. Other outcomes influenced the percent of positive and negative outcomes households received (refer to **4.4.1 Summary Statistics** for further explanation). Implementation is driven by the positive and negative outcomes shared via word of mouth, and observation. For example, as more fields with SCPs are seen, if optimal maize yields are met, more potential implementers can see these positive results and encourage implementation. The growth of implementers increases the population of fields with SCPs, decreasing the cost of inputs as more legume seed becomes available locally. Oppositely, if more fields become infested with *S. asiatica*, emergence can increase exponentially due to the spread of seed from neighboring fields. The aforementioned paradigms are examples of feedback behavior. Feedback behavior is identified in the SDM with pink and turquoise arrows and largely guide its behavior.

4.3.4.1 Sensitivity

In a base case run (where all parameter values/equations are taken directly from survey data) SDM behavior indicates that dis-implementation overwhelmed implementation (see **Figure 33[a]**), consequently leading to higher *S. asiatica* emergence in the future (see **Figure 33[b]**). Initially, there is a rise in the population of implementers given that favorable rainfall affords satisfactory yields from SCPs, but afterward, consecutive years of low rainfall (see **Figure 33[c]**) during the growing season (e.g., year 4,5,9) dissuades potential implementers from employing

SCPs in their fields. Seasons in the second half of the 20-year time period bring better yields, slow rebounding implementation, but with so many fields parasitized prior, emergence carried over into other fields. This sensitivity analysis indicates maize yield is a driving factor of implementation and dis-implementation, regardless of the other benefits offered by the SCP. This finding concurs with previous studies that modeled SFM adoption, finding maize yield to dominate implementation (Amelia et al., 2014). This type of behavior seen in the model, particularly the exponential spread of *S. asiatica,* agrees with previous studies that measured the dispersal of seed via livestock (Berner et al., 1994). Being that the central region allows free grazing of ruminant livestock, seed dispersal is carried out in this manner. Had the model been run in an area with no livestock, the spread of seed to neighboring fields via water or wind would not have been as high (van Delft et al., 1997).

Figure 33 - Implementation (a) and Striga emergence (b) base on rainfall (c)

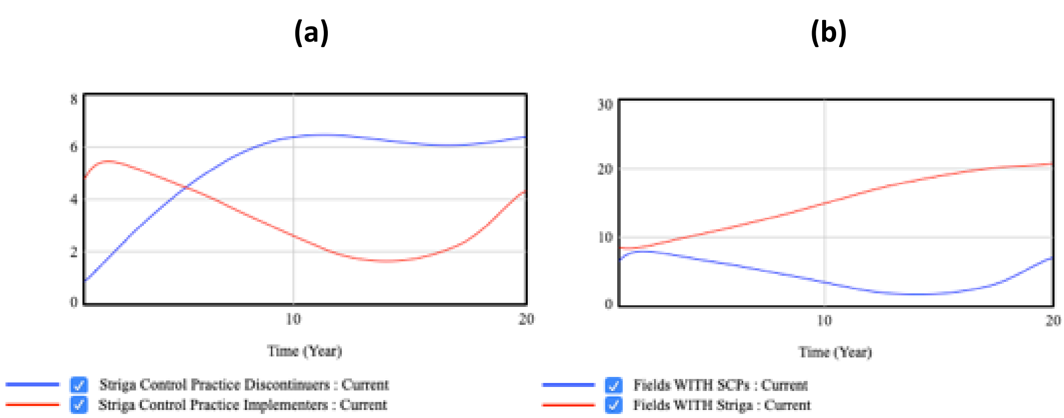
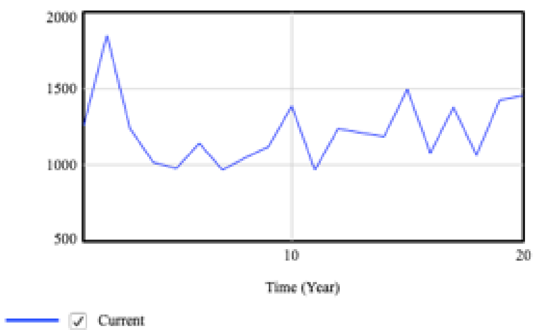


Figure 33 (cont'd)

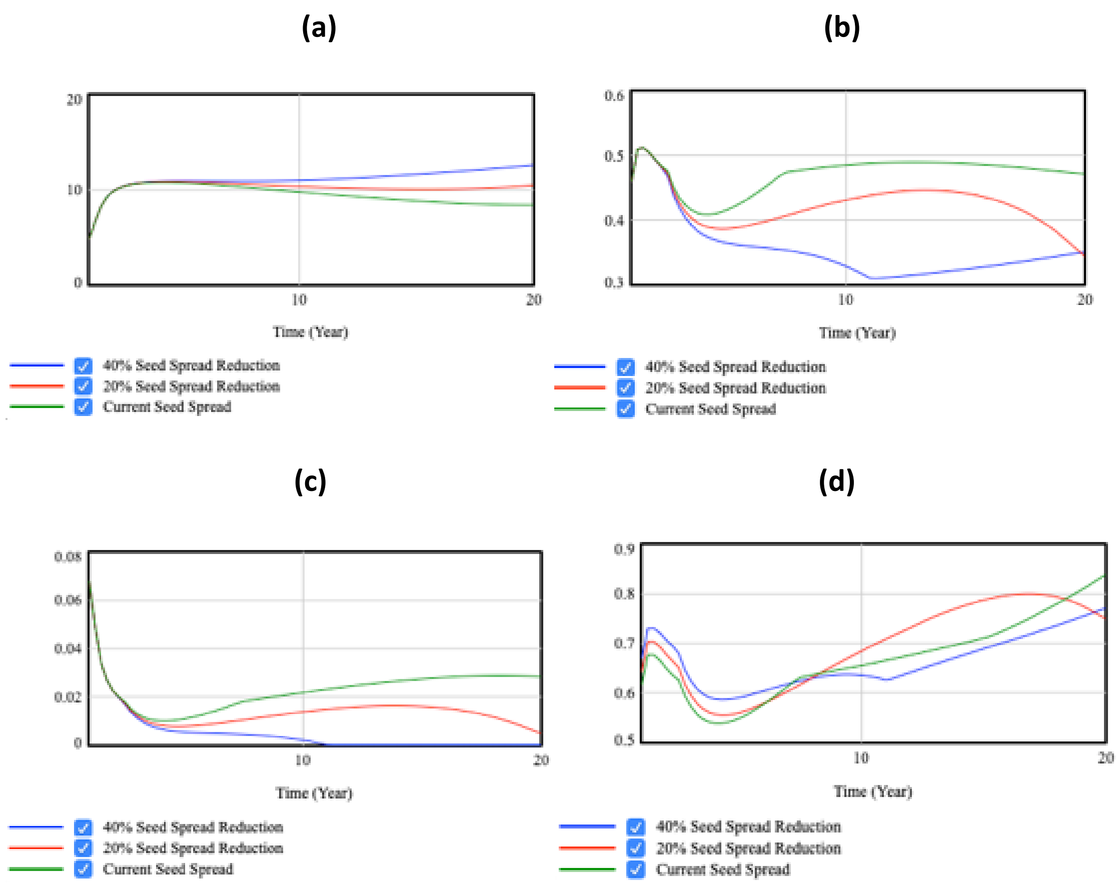
(c)



Note: The Y-axis of figure a and b is scaled to hundreds of thousands (100,000)
Note: The Y-axis of figure b is scaled to millimeters. The observations are based on rainfall data the Dedza district of Malawi received over the past 20 years during the growing season (November to April)

A sensitivity analysis was carried out between seed spread and the discontinuing population (e.g., di-implementers, abandoners) to understand the compounding effect seed transfer had various stocks. To do this, different seed dispersal rates were loaded in the model with 20% reductions relative to the fields infested with *S. asiatica.* In the first example, (see **Figure 34[a]**), a noticeable difference between the implementer population does not begin until year 10. In year 3, however, a noticeable difference begins almost immediately with abandoners discontinuing SCPs because of re-emergence. In **Figure 34(b)**, the population of discontinuers decreases dramatically and almost depletes the population by year 11. The same type of behavior occurs with abandoners that discontinued SCPs because of input costs (see **Figure 34[c]**). While the aggregate population of both types of abandoners does not exceed 60,000 individuals, keeping them at minimum allows the implementer stock to sustain a population between 1 and 1.3 million households, all of which cultivate fields with SCPs, and consequently, reduce the population of fields with *S. asiatica* overtime (see **Figure 34[d]**). As fields decrease overtime, approximately 78,000 still remain after 20 years due to the persistent seedbank. This finding corroborates with other emergence studies that investigate the transfer of seeds based on reduced flowering rates. In one study, van Delft et al. (1997) mentions that even when two to three *Striga hermonthica* plants per m^2 were left to seed, this population kept the seedbank high enough for seeds to transfer into neighboring fields 25 meters away.

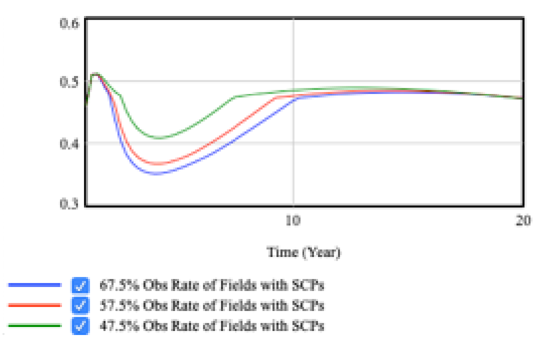
Figure 34 - Sensitivity of implementer (a), discontinuer (b), abandoner (c) and parasitized field (d) populations to seed spread rates of Striga spp.



Note: In the survey, 14% of households mentioned they had *Striga spp.* had emerged in their fields, so a 20% reduction equated to 11.2% seed spread and a 40% reduction equated to 8.4% seed spread.
Note: The Y-axis of figure a, b and c is scaled to hundreds of thousands (100,000)

A final sensitivity analysis was conducted to understand the relationship between observation rates and the dis-implementation stock. The observation rate is defined as the percent of potential implementers that see a field with a SCP. The dis-implementation rate is affected by the number of fields potential implementers see with positive or negative results. The rate was augmented in 20% increments (from 47.5% base-case value), reflecting an S-curve. A low rate with few fields with SCPs equated to 14.2%:95,000 fields, an average rate with the current fields having a SCP equated to 47.1%:661,000 and a high rate (reaching a saturation point) equated to 91.0%:900,000-2,000,000. In **Figure 35,** with an observation rate of 67.5%, the population of discontinuers drastically drops only after one good season of rainfall, returning to the base-case population not until year 15. This finding illustrates how strong of an effect field observation (of positive results) can have on dis-implementation. If optimal rainfall were to play out across 2-3 years in the beginning this model, dis-implementation would behave in an opposite manner. The delay in dis-adoption due to favorable rainfall is well-documented in the literature, particularly with hybrid-rice varieties (Diagne, 2006). In a similar fashion, the authors argue that a short period of consecutive seasons which receive optimal yields will increase adoption of agricultural technologies as well as delay dis-adoption rates when negative climatic events occur.

Figure 35 - Sensitivity of dis-implementer population to observation rate

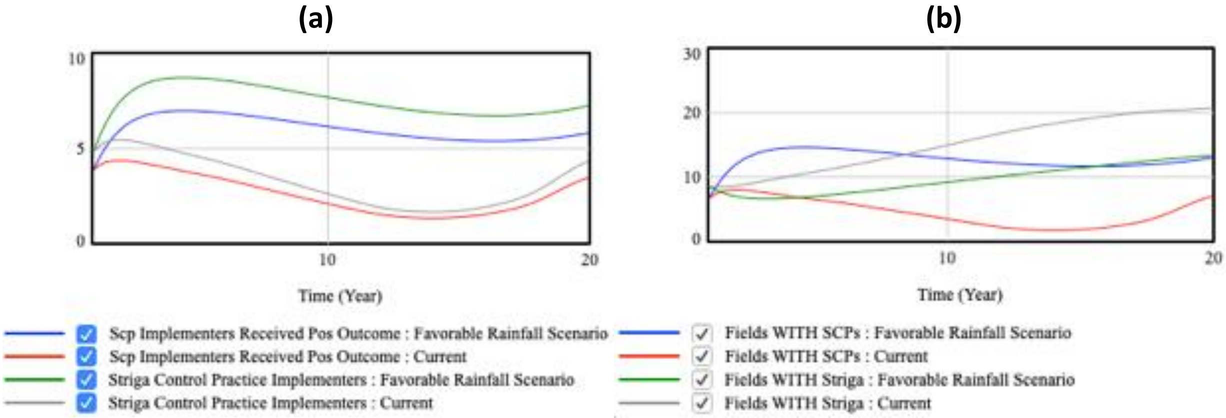


Note: The Y-axis of figure is scaled to hundreds of thousands (100,000)

4.3.4.2 Scenario runs

Several environmental and policy scenarios were run in the SDM to determine if and how the disconcerting rise of emergence could be curbed in the future. In the first scenario (**Figure 36**), the rainfall parameter was adjusted so fields with SCPs could reach a yield no yield losses occurred. As expected, the implementer population remained above its starting population of 477,000 (**Figure 36[a]**). Even though optimal maize yields were met, some implementers still received negative outcomes, (see "Neg Perc" explanation in **Appendix 2**) such as the reoccurrence of S. *asiatica* emergence. This reoccurrence pulls the positive outcome stock down below 300,000 households. Still, with so many implementers, the population of fields with SCPs almost reaches 1.5 million (as compared to 800,000 in the base case run) (see **Figure 36[b]**). With so many fields having SCPs, emergence remains below 1.4 million fields across 20 years (as compared to 21 million fields in the base case run). The 20-year outcome of 1.4 million fields having *S. asiatica* is concerning given the high number of fields which have SCPs. According to the survey, 35% of implementers reported still having *S. asiatica*. This rate of parasitism validates the model in year 4 where approximately 1.6 million fields having SCPs corresponds to approximately 600,000 fields with *S. asiatica*. This finding also coincides with studies that compare emergence rates in maize-cowpea fields against sole maize fields (Musambasi et al., 2002). The increase in *S. asiatica* emergence across 20 years, regardless of SCP field population, may not be because of ineffective control by implementers, but mis-management by discontinuers, increasing the likelihood of seed transfer.

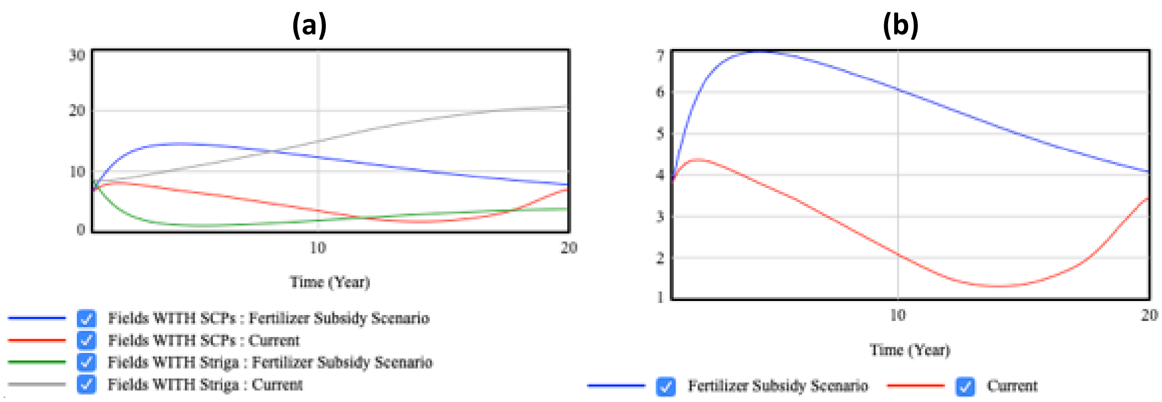
Figure 36 - Implementer (a) and emergence (b) population response to favorable rainfall



Note: The Y-axis of figure a and b is scaled to hundreds of thousands (100,000)

Findings from the CSM (developed in Essay 2) revealed that cowpea-maize intercropping managed *S. asiatica* emerging to only a certain extent. Suicidal germination induced by the legume decreased the surface seedbank, but did not address attachment effectively, allowing emergence to persist. As illustrated in the previous figure (**Figure 36**), additional practices are needed to reduce emergence via decreased attachment. Therefore, a fertilizer subsidy scenario was run where all household received 66 kg of NPK fertilizer to apply to their two fields. The national Ministry of Agriculture advises 33 kg of NPK per ha. In this scenario, the population of fields with *S. asiatica* behaves in an opposite manner relative to fields with SCPs, remaining below approximately 120,000 fields from year 2 to year 7 (see **Figure 37[a]**) at the peak of implementation (1.4 million fields with SCPs). Large reductions in emergence (>80%) in intercropping + fertilizer treatments are common relative to controls trials (Carsky et al., 2002). While the population of implementers that receive a positive outcome climb to 700,000 by year 3, there is a negative linear trend afterward (see **Figure 37[b]**). This downward trend in the SDM is not attributed to implementers receiving negative outcomes, but it is a result of the decreasing population of implementers. Reasons for why the population of implementers begins decreasing in year 6 (see **Figure 37[a]**) cannot be explained by the SDM. This downward trend of implementation may be a result of fertilizer subsidies crowding out SCPs (Ricker-Gilbert et al., 2011). That is, subsidized fertilizer may be offering households a more economical and less arduous alternative to sustain maize yield (rather than trying to manage *S. asiatica*), obligating them to discontinue legume intercropping. Unfortunately, the household survey did not collect data which could not parameterize the SDM to simulate crowding out.

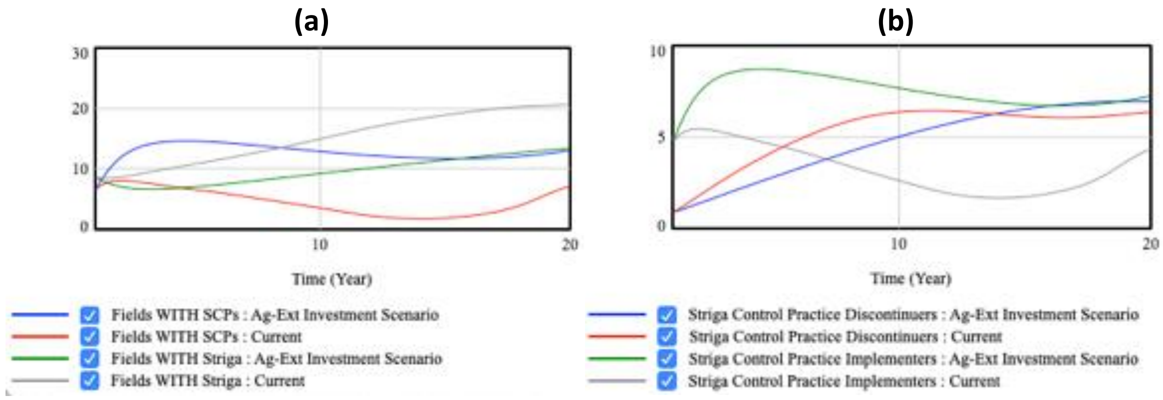
Figure 37 - Emergence (a) and implementer population that receives a positive outcome (b) in response to fertilizer subsidy



Note: The Y-axis of figure a and b is scaled to hundreds of thousands (100,000)

There are four parameters that guide the implementation rate. Word of mouth and observation can influence implementation positively and negatively, while advertising and agricultural extension can only influence implementation positively. Only 5.7% of implementers mentioned they employed a SCP after learning about it via advertising. Implementers, however, were much more trusting with agricultural extension (61.4%). This difference in trust is common across adoption studies being that farmers have more faith in a person they can speak with rather than one they are hearing over a radio (among many other reasons) (Van Rijn et al., 2012). Among the 61.4% of households that implemented a SCP via extension, 69.0% had learned about the SCP via extension. To mimic a policy scenario where more agricultural extension was invested in to disseminate SCPs, the learning parameter was increased from 69.0% to 90.0%. In the scenario, the implementer population increases to approximately 1.4 million and remains between this upper bound and 1 million for the remaining 15 years (see **Figure 38[a]**). Both the "Ag-Ext Investment Scenario" and "Current" curves illustrate the same behavior as they react to different rainfall and lower maize yields. A larger difference is seen between the "Fields WITH Striga". In the "Ag-Ext Investment Scenario", "Fields WITH Striga" is approximately 40% lower than the "Current" population. In **Figure 38(b)**, the discontinuer population does not increase as quickly as the "Current" population, but actually exceeds the population in 20 years. There are several reasons for why implementers would discontinue their SCP more often after receiving agricultural extension in the long-run. One primary reason for this is that a larger population of implementers offers more households that can dis-implement and feed into the discontinuer stock. Another reason could be that household lose trust in agricultural extension agents after their SCPs do not perform as well as they expected. This could be due to any number of reasons such as drought. The loss in trust, however, is not parameterized in the model because the survey did not collect this type of data.

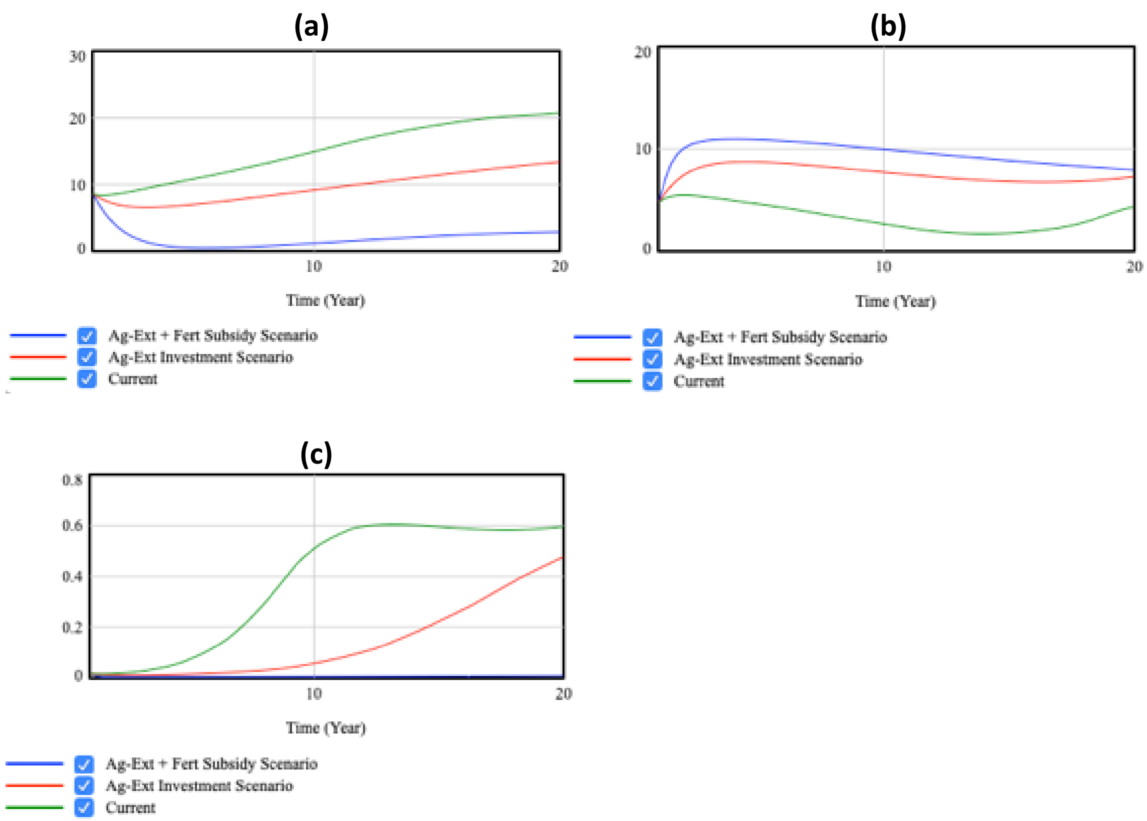
Figure 38 - Emergence (a) and implementer (b) population response to increased agricultural extension



Note: The Y-axis of figure a and b is scaled to hundreds of thousands (100,000)

The previous two scenario analyses have demonstrated two key points. First, fertilizer application can provide an integrated effort to reduce *S. asiatica*, but not necessarily increase the stock of implementers. Second, by not supporting this population with increased efforts of SCP dissemination (via agricultural extension), the corresponding population of fields with SCPs decreases, increasing emergence in later years. As shown in **Figure 39(a)**, the combination of fertilizer subsidies and increased agricultural extension can reduce emergence from 2 million fields to under 200,000 quickly. In some years (e.g., year 5), the population of fields with *S. asiatica* falls to almost zero. In **Figure 39(b)**, an aggregated effort to increase maize yield (even under variable rainfall) while encouraging more households to implement SCPs via extension will delay the onset of *S. asiatica*, limiting the spread of seed. The rate of abandonment remains below 5,000 households in aggregated effort runs (see **Figure 39[c]**). The behavior in response to this scenario, in terms of emergence and abandonment, echoes the larger argument that only long-term aggregate efforts that span across 3-5 years can reduce the parasitism of *S. Striga* (Ejeta, 2007; Oswald, 2005; Ransom, 2000).

Figure 39 - Emergence (a), implementer (b) and abandoner (c) response to fertilizer subsidy & increased agricultural extension



Note: The Y-axis of figure a, b and c is scaled to hundreds of thousands (100,000)

4.4 Conclusions

The following study developed a SDM to simulate the dynamic behavior of *S. asiatica* emergence under various variables such as rainfall and SCP implementation. Emergence was tested under various environmental and policy scenarios. The SDM differed from previous dynamic adoption models in that it was first parameterized by the very smallholders it intended to simulate. Second, parameters were applied with values and equations that were calculated from adoption data collected from those same smallholders. Third, the model integrated crop model data to ensure its estimations about *S. asiatica* emergence with respect to SCP implementation were accurate. Finally, it used choice model data to create yield thresholds households were unwilling to accept from implementing SCPs, created parameters from these thresholds, estimated dis-implementation rates based on these thresholds being met or not. A meta-analysis of agricultural technology adoption argues the need to model the dynamic exchange between implementation and technology performance (Marenya & Barrett, 2007). Yet, those researchers argue few studies have modeled this exchange. This study sought to fill that gap.

The SDM highlights several critical findings for *S. asiatica* researchers and practitioners, particularly those studying emergence in Malawi. First, under current dissemination and implementation rates of SCPs in the central region, approximately 75% of households that cultivate maize will be parasitized *S. asiatica* in the next 7-10 years. Second, to address this growing problem, an aggregated effort of agricultural extension and supply of inorganic inputs (e.g., fertilizer) must be delivered to the smallholders over the course of 3-5 consecutive years. Fourth, without a sustained effort to supply inputs and extension, either *S. asiatica* seeds will spread to other farmer fields that have not been parasitized yet, input costs will dissuade farmers to discontinue SCPs or erratic rainfall will reduce yields to a point where Malawian households are not willing to accept and are obligated to discontinue SCPs. Lastly, human and weed response to aggregated control efforts (e.g., intercropping + fertilizer subsidy + extension) are dynamic. There are points in time in the SDM where fertilizer, intercropping and extension could decrease emergence to an acceptable threshold. This finding indicates regional efforts to control *S. asiatica* do not necessarily need to invest in them for 20 consecutive years. Rather, these policies must be crafted to be dynamic (perhaps resilient) so as to respond to dis-implementation rates and corresponding emergence.

While the study provided valuable insights as to how to address emergence in Central Malawi, it had several limitations. First, the SDM may have been too sensitive to rainfall given that maize-cowpea intercropping systems have shown to increase soil fertility and increase water retention (Lunduka et al., 2012). These two points are not only cited in the literature but mentioned by the survey participants who implemented them. Increased soil fertility and water retention has shown to buffer maize yield against climatic shocks such as drought (Lunduka et al., 2012). Hence, implementers may not have discontinued as sharply as shown in the base case runs of the SDM. Second, the SDM could not account for increased dis-implementation rates in response to fertilizer subsidies. To address this shortcoming, additional studies must investigate the perverse consequences input subsidies may have on the implementation of SCPs. Third, the SDM was parameterized with a yield threshold informed by a choice experiment conducted at one point in time. These preferences may change over times. Thus, this parameter must be more dynamic (as opposed to being applied with static values) to make more robust estimations. These thresholds may decrease as population growth exponentially increases and landholdings respond in opposite fashion.

Model behavior has several implications for practitioners and researchers who wish to address the plight of *S. asiatica* emergence in central Malawian. Given the extent of erratic rainfall, inorganic inputs are needed to sustain maize yields within intercropping systems during initial years (Denning et al., 2009; Jayanthi et al., 2013). During this time, implementers can consecutively cultivate these SCPs to suppress *S. asiatica* and prevent the spread of seed to neighboring fields. In addition to these subsidies, agricultural extension is needed to increase *Striga spp*. knowledge, which can encourage implementation of SCPs (Sileshi et al., 2008). Third, aggregated efforts that decrease emergence and/or increase SCP implementation must be evaluated annually. As evidenced by the SDM, these strategies may bring emergence to a relatively low threshold, but feedback behavior from dis-implementation can override what reductions were made. New strategies are needed to maintain emergence at a low enough threshold so that seeds are not transferred from field to field, sparking an outbreak of emergence. The aggregated scenarios run in the SDM were done so by increasing or decreasing rates. These rates are linear, not dynamic. Therefore, aggregated efforts must be as dynamic as the weeds they wish to address.

APPENDICES

APPENDICES

APPENDIX 1. Enumerator Demonstrating Choice Tasks

APPENDIX 2. Justification of Values/Equations Applied to Parameters for System Dynamics Model Of Striga Emergence and Control Practice Implementation

Stocks			
Parameter	*Elaboration about name*	*Equation or value*	*Explanation*
FAp	Initial fields added population	[redacted]	[redacted]
Fields Added	Fields added to the potential population which could have a SCP	[redacted]	[redacted]
Pip	Initial potential implementer population	[redacted]	[redacted]
Potential Implementers	The available households that could implement a SCP	[redacted]	[redacted]
IP	Initial implementer population	[redacted]	[redacted]
Striga Control Practice Implementers	Households that implement a SCP in their field	[redacted]	[redacted]
Dp	Initial discontinuer population	[redacted]	[redacted]
Striga Control Practice Discontinuers	Households that discontinue a SCP in their field	[redacted]	[redacted]
R-Ip	Initial Re-implementer population	[redacted]	[redacted]
Striga Control Practice Re-implementers	Households that implement a SCP in their field after discontinuing initially	[redacted]	[redacted]
FSCPp	Initial fields with Striga control practice population	[redacted]	[redacted]

			[redacted]
Fields WITH SCPs	Fields with Striga control practices in them	[redacted]	
FWSp	Initial fields with Striga population	[redacted]	
Fields WITH Striga	Fields where Striga has emerged	[redacted]	
Flows			
Parameter	*Elaboration about name*	*Equation or value*	*Explanation*
General populous	The incoming population	[redacted]	[redacted]
Implementation	All potential households that implement SCPs		[redacted]
Dis-implementation	All potential households that discontinue SCPs		[redacted]
Re-implementation	All potential households that re-implement SCPs		[redacted]
Abandonment	All potential households that abandon SCPs		[redacted]
Add Practices	SCPs added to new fields		[redacted]
Drop Practices	SCPs removed from older or new fields		
Increased Parasitism	Striga emerging on new fields		

Decreased Parasitism	Striga eradicated from new or existing fields	[redacted]	[redacted]
Maize Kg per ha WITH SCP	Average maize yield per hectare with a maize-legume SCP	[redacted]	[redacted]
Parameters attached to stocks			
Parameter	*Elaboration about name*	*Equation or value*	*Explanation*
Scp Implementers Received Neg Outcome	Implementers that received a negative outcome from the SCPs	[redacted]	[redacted]
Scp Implementers Received Pos Outcome	Implementers that received a positive outcome from the SCPs	[redacted]	[redacted]
Potential Impl to Share Neg Info with about SCP	Potential implementers that received negative news about SCPs	[redacted]	[redacted]
Potential Impl to Share Pos Info with about SCP	Potential implementers that received positive news about SCPs	[redacted]	[redacted]
Num of Fields with Pos Result	The number of fields with SCPs that received a positive outcome	[redacted]	[redacted]
Parameters attached to flows			
Parameter	*Elaboration about name*	*Equation or value*	*Explanation*
Pop Growth	Population growth	[redacted]	[redacted]
Impl Rate via Obs	Implementation rate via observation	[redacted]	[redacted]
Impl Rate via Word of Mouth	Implementation rate via word of mouth	[redacted]	[redacted]
Impl Rate via Ag - Ext	Implementation rate via agricultural extension	[redacted]	[redacted]
Impl Rat via Advert	Implementation rate via advertising	[redacted]	[redacted]
Perc PIs Rec Neg Info via Word of Mouth	Percent of potential implementers that receive negative	[redacted]	[redacted]

	information about a SCP via word of mouth		
Perc PIs Seeing a SCP with Neg Result	Percent of potential implementers that see a negative outcome from a SCP	[redacted]	[redacted]
Perc Discon Bc Neg Res	Percent of implementers discontinue because of a negative outcome	[redacted]	[redacted]
Perc Disc Bc New Tech No Longer Profitable	Percent of implementers discontinue because the SCP is no longer profitable or too costly	[redacted]	[redacted]
Perc Striga Stopped But Came Back	Percent of implementers that received Striga emergence again	[redacted]	[redacted]
Perc Reimplement to Control Again	Percent of implementers that implemented a SCP after discontinuing initially	[redacted]	[redacted]
Perc Receive Sec Neg Outcome	Percent of implementers received a second negative outcome	[redacted]	[redacted]
Emergence Rate WITHOUT Scp	Striga emergence rate on fields without a SCP	[redacted]	[redacted]
Emergence Rate WITH Scp	Striga emergence rate on fields with a SCP	[redacted]	[redacted]
Fertilizer Application	An action of micro-dosing or broadcasting fertilizer	[redacted]	[redacted]
Rainfall	Annual rainfall	[redacted]	[redacted]
Other Rates and Converters			
Parameter	*Elaboration about name*	*Equation or value*	*Explanation*
Year	Each year	[redacted]	[redacted]
Growth Rate	Population growth	[redacted]	[redacted]
Prob of Hearing Neg Info about SCP	The probability of hearing negative information about a Striga control practice	[redacted]	[redacted]

Neg Sharing Rate	The number of individuals implementers share their negative outcomes with	[redacted]	[redacted]
Contact Rate by Impl with Neg Info	The percent of individuals implementers share their negative outcomes with	[redacted]	[redacted]
Num of Impl Share Neg Result	The contact rate based on the potential implementers available to share the information with	[redacted]	[redacted]
Prob of Seeing a SCP with Neg Result	The probability of seeing a field with a Striga control practice that received a negative outcome	[redacted]	[redacted]
Num of Fields with Neg Result	The number of fields with a negative result	[redacted]	[redacted]
<Lower Than Threshold>	A yield threshold exceeded that farmers are unwilling to accept from implementing a SCP	[redacted]	[redacted]
Neg Perc Rate	The percent of implementers that receive a negative outcome	[redacted]	[redacted]
Perc Rec Neg Result	The percent of implementers that receive a negative outcome contingent upon seed dispersal	[redacted]	[redacted]
Lookup Parasitism of Farmer Fields via Seed Dispersal	Seed spread based on the number of fields that have Striga	[redacted]	[redacted]

Parasitism of Farmer Fields via Seed Dispersal	Seed spread based on the number of fields that have Striga	[redacted]	[redacted]
Lookup Prob of Seeing SCP	The increase or decrease of seeing a field with a SCP	[redacted]	[redacted]
Prob of Seeing a SCP with Pos Results	The increase or decrease of seeing a field with a SCP that received a positive outcome	[redacted]	[redacted]
Pos Share Rate	The number of individuals implementers share positive information about their outcomes with	[redacted]	[redacted]
Prob of Hearing Pos Info about SCP	The probability of receiving positive information from implementers	[redacted]	[redacted]
Num of Impl Share Pos Results	The number of implementers that share positive information	[redacted]	[redacted]
Prob of Receiving Ag-Ext	The probability of learning about a SCP via agricultural extension	[redacted]	[redacted]
Prob of Receiving Advert	The probability of learning about a SCP via advertising	[redacted]	[redacted]
Contact Rate by Impl with Pos Inform	The percent of individuals that learned about a SCP via word of mouth	[redacted]	[redacted]
Pos Perc Rate	The percent of SCP implementers that receive a positive outcome	[redacted]	[redacted]
<Higher Than Threshold?>	Whether or not an implementer receives a maize yield above a	[redacted]	[redacted]

	threshold their willing to accept		[redacted]
Striga Controlled	The percent of implementers controlled or decreased Striga from implementing a SCP	[redacted]	[redacted]
Lookup Cost Decrease via More Implementers	The percent of implementers discontinue due to the cost of implementing a SCP	[redacted]	[redacted]
Cost Decrease via More Implementers	Same as above	[redacted]	[redacted]
Climate	Annual rainfall	[redacted]	[redacted]
<Time>	Specifies how timesteps occur	[redacted]	[redacted]

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CHAPTER 5: CONCLUSIONS

The dissertation took an alternative approach, bridging the social and natural research methods, to evaluate *Striga asiatica* emergence in smallholder cropping systems across central Malawi. The literature review used to inform several experiments in the dissertation indicates two disciplines have studied this issue extensively, but to much of a respect, separately. The two disciplines, being the natural sciences and the social sciences, have often used a reductionist approach to evaluate and propose interventions for addressing parasitic weed emergence. For instance, in the natural sciences, different components of a *Striga spp.* control practice (SCP) are changed one at a time (e.g., herbicide application rates) to determine how effective they reduce emergence. In the social science world, different socioeconomic variables are fitted in a regression, for example, run and replaced one at a time to determine their effect on the adoption of SCP involving cowpea-maize intercropping. While these approaches have contributed greatly to the body of knowledge regarding SCPs, they often fall short in providing appropriate strategies for emergence being that it is a dynamic and multifaceted problem. Perhaps these linear approaches have largely been relied upon because there has been a high level of agreement in the scientific community about the problem of *Striga spp.,* and with it, a high level of agreement how to address it. Currently, however, emergence still persists under old solutions and is likely to get worse across SSA, particularly in Malawi, unless they are modified. This is not to blame the scientific community for the scourge *S. asiatica* has had over the region, but rather to highlight the limitations these approaches have had given their misunderstandings about the problem. Hence, this dissertation employed a dynamic research approach to assess the *wicked* problem of *S. asiatica* emergence, rather than proposing a solution first and evaluating its effectiveness later. First, the dissertation assessed what tradeoffs farmers were willing, but particularly, not willing to make to implement a SCP. Second, it evaluated their efficacy, but particularly, their lack of control over various stages of the weed's lifecycle. Third, it assessed how implementation, but rather dis-implementation, increased due to sudden negative climatic events.

These results from the three empirical studies should not be interpreted as all negative news for smallholder farmers in Malawi. Rather, it should serve as an indicator of *where* to begin addressing low adoption rates of SCPs, *which* lifecycle stages (of *S. asiatica*) SCPs should address and *what* streams of information agricultural policies should focus their efforts on. In essay one, quantitative and qualitative analyses highlighted that smallholders are not as concerned about the labor or *S. asiatica* reductions SCPs offer, but more so the soil fertility, maize yield and legume yield they deliver. The first study revealed that farmers were willing to implement SCPs with legumes because they offered soil fertility improvements, but not ones which would increase their current labor requirements. Being that the "High Legume Yield" attribute assumed the highest coefficient of significance at the 1% level, farmers may be more concerned with SCPs that offer more food security, as compared to ones that provide soil fertility improvement or reductions in labor requirements. The second study indicated (according to the cropping systems model [CSM]) that while attachment was the largest driver of emergence, all stages must be addressed to eradicate the weed. While a combination of fertilizer application and traditional practices appeared to be more effective than intercropping, the addition of legumes induced suicidal germination and shading, completing the process of eradication. There are human and financial tradeoffs for implementing these SCPs. These tradeoffs must be considered before developing and disseminating SCPs as a packaged control strategy. The third study illustrated that climatic shocks can push yields below a threshold farmers are unwilling to sacrifice for implementing a SCP, and as a result, abandon and share this information with fellow farmers, dissuading their implementation.

Conclusions made in each of the three empirical studies yield several applications for future *S. asiatica* management in Central Malawi. First, large consideration must be taken in crafting SCPs which deliver benefits smallholders are most concerned about, and furthermore, those benefits must reach a certain threshold if the SCP will bear a certain maize-yield penalty. Malawian smallholders are unlikely to employ a SCP if initial maize yield falls below 15% of what they would normally receive under status quo practices. These sacrifices are specific to different farmer types (e.g., male, female). Accounting for heterogeneous preferences affords better policy recommendations for which attributes to invest in for specific smallholder groups. Second, delaying the onset of attachment with modified traditional practices, such as the repeated micro-dosing of manure at planting stations, could assist the financially-constrained farmer. In addition, varying planting station depth (e.g., poking holes in ridges and sowing >30 cm) can provide an economic avenue for decreasing attachment as well as coating seeds with herbicide if fertilizer is too expensive or unavailable. These are just a few practices among many that should be offered to farmers given what little choices they currently have. Promoting one practice, even if its economical, does little for the socioeconomically diverse community of smallholders that live across several environmentally distinct landscapes in Malawi.

Third, input gained from farmers for purposes of optimizing crop models is invaluable. These models are developed for their benefit, hence their contribution to instrument development makes for a more robust model.

Further research is needed to understand the wicked problem of *S. asiatica* emergence across Malawi. First, more studies must be conducted to understand the barriers and drivers of SCP decisions. One barrier might be the lack of knowledge about *S. asiatica* among farmers, specifically regarding how each SCP reduces emergence. Creating the connection between a practice and its *effect* on a pest can, in many cases, increase uptake of technologies. Second, additional greenhouse trials should be conducted using farmer soils to observe emergence rates across practices. Later, these rates can validate and/or calibrate CSM behavior. The greenhouse trial was conducted in this study because too few studies could be sourced to parameterize and validate the CSM. *Striga spp.* research in sub-Saharan Africa has particularly focused on the emergence and control of *Striga hermonthica* given its emergence across West Africa. Given what success has come from this body of literature, if research wishes to address *S. asiatica* emergence in Southern Africa, more efforts will need to be led to study this species given its specificity to the region. Third, SDM behavior remains to be validated with panel adoption data. Such studies are limited in the region, particularly regarding SCPs. More long-term studies should be conducted to assist with validating dynamic models.

Several times during this dissertation, certain quantitative analyses failed to explain quantitative results. Time and again though, complimentary methods, such as the thematic analysis of focus group discussions, clarified these initially confounding results. Many times, these methods are discounted or absent in quantitative analyses for one reason or another.

This study added evidence to the argument that mixed methodological approaches may better inform the development and data collected from farming household surveys and CSMs. Furthermore, analysis of these data are able to be extrapolated (by using quantitative methods) while highlighting their context-specific nuances (by using qualitative methods). These mixed method approaches should be applied to understanding wicked problems such as *S. asiatica* emergence across Central Malawi. Numerous SCPs in the region have shown to reduce emergence significantly, but implementation of them has been minimal. On the other hand, numerous SCPs have been modified and implemented by smallholders to manage *S. asiatica,* yet their effectiveness has been minimal. System dynamics modeling (SDM) can bridge the gap between these two conundrums and offer new avenues to explore and determine policies which can encourage the implementation of more effective SCPs, and hopefully, reduce emergence across the landscape.