SPATIAL AND TEMPORAL CONTEXT-DEPENDENCE IN THE PUSH-PULL SYSTEM

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Ecological intensification is a set of practices and principles aimed at managing biodiversity to maintain or enhance crop yields while reducing negative environmental impacts of conventional agriculture. One of the most successful examples of ecological intensification is the push-pull system developed by the International Centre of Insect Physiology and Ecology (ICIPE) for cereal crops in Africa. First developed in the 1990s, the push-pull system utilizes two companion crops alongside a cereal grain (most often maize) to reduce pressure from insect pests and parasitic weeds, enhance soil quality, and dramatically improve yield. While the push-pull system provides significant benefits to growers, its impacts also vary for reasons that are not well-understood. Working closely with our collaborators at ICIPE, SLU, and Lund University, we examined different drivers that could influence the effectiveness of the push-pull system. We found that push-pull fields which had been established for longer had stronger pest suppression and higher yield. Interestingly, the pest suppression benefits showed some evidence of spilling over to neighboring control fields, meaning that the longer a push-pull field was established, the lower the pressure

on its neighboring control field as well. We also found that push-pull was resilient across weather and landscape gradients. While push-pull's effect was slightly weaker in certain conditions (including in landscapes with a high percentage of surrounding agriculture), push-pull fields always outperformed control fields by significant margins. Finally, we found that biological control services in push-pull fields could vary with both time within the growing season and surrounding landscape context. Early in the growing season push-pull fields had higher levels of pest egg predation than control fields, but later in the season this pattern reversed on farms surrounded by more natural area. Overall, we find that even where push-pulls benefits may vary, they are robust across time, landscape context, and weather context, and are likely to remain so in the future. More broadly, we consider our results encouraging for ecological intensification in general, showing that ecologically intensified systems may be robust over extended timespans, across a range of environmental conditions, and against novel invasive pests.

BIOGRAPHICAL SKETCH

Tim Luttermoser grew up in South Euclid, Ohio, just outside of Cleveland. He attended Charles F. Brush High School and spent many formative hours at the Cleveland Museum of Natural History and Cleveland Metroparks. His undergraduate degree at Hiram College was in Biology, with minors in Environmental Studies and Philosophy. While at Hiram, he performed summer research on forest community and ecology with Michael Benedict, and designed his own research project on burying beetles with Amy Braccia and Matt Hils. Tim's senior thesis, supported by Nick Hirsch, was based on his work in the pollination ecology REU at Oregon State University led by Sujaya Rao and Andy Moldenke, focusing on the nesting habits of a native bee in mountain meadows. After undergrad, Tim spent a summer in California working in Claire Kremen's lab with Hillary Sardiñas on pollination ecology and ecosystem services in sunflower. He then got an MSc at Purdue University with Grzegorz Buczkowski and Gary Bennett focused on ant behavioral ecology, before returning to the world of ecosystem services and agroecology for a PhD in Entomology at Cornell. Tim was active in Jugatae (the Entomology graduate student organization) and several department mental health and equity initiatives.

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Fittingly, to all those who know me, I'm finalizing this section with just a few hours to spare before the deadline. I could fill another 50 pages with everyone who

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Are pests adapting to the push-pull system?

Ecologically intensified farms in Kenya maintain successful pest control over time

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Abstract

Ecological intensification utilizes biodiversity to maintain agricultural yields while reducing negative environmental impacts. While pest management is a common goal of ecological intensification, studies examining ecologically intensified pest management systems over longer time scales are rare. Using the push-pull system in Western Kenya, we examine whether pest abundance (for both insects and parasitic weeds) and yield vary with time since a given push-pull field was established. With a total of 1880 data points from 476 unique farmers and 24 cropping seasons, we found that pests declined with time since establishment in both push-pull and nearby control fields, while yield improved with time since establishment in push-pull fields. Although this study did not directly address mechanisms, it seems likely that pests in the push-pull system are not successfully adapting to overcome its pest management effects given the continued declines in pest abundance over time. Our data suggest that ecologically intensified agriculture may be resilient against pest adaptation over time, maintaining consistently high yields.

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1. Introduction

As a response to sustainability concerns of conventional agriculture, the paradigm of 'ecological intensification' has been proposed. In this framework, anthropogenic inputs such as pesticides and synthetic fertilizers are replaced using carefully managed biodiversity to maintain or improve ecosystem services, including productivity (Bommarco et al., 2013; Cassman, 1999; Doré et al., 2011). By managing farms and landscapes in ways that maintain ecosystem services such as nutrient cycling and biological pest control, ecological intensification maintains or increases yields while reducing the negative environmental impacts of conventional agricultural practices (Garibaldi et al., 2019; Kleijn et al., 2019; Tittonell and Giller, 2013). Adding wildlife habitat or nectar-producing plants near field edges has been shown to maintain or increase yield compared to conventionally managed fields (Gurr et al., 2016; Pywell et al., 2015). However, it remains unclear how these systems develop over longer time scales. Depending on the specific context, there are reasons to expect that ecological intensification could have diminishing returns or fail over time, or that ecologically intensified farms may in fact see stronger benefits the longer they are maintained.

One major concern with ecological intensification practices for pest management is that pests

may adapt to those practices. Pesticide resistance is a common problem in agriculture and public health (Liu, 2015; Nauen and Denholm, 2005; Ranson et al., 2011), and can evolve rapidly under certain conditions (Fardisi et al., 2019; Gordon et al., 2014). Overall, resistance to biological control by macro-organisms is expected to be less likely and slower to develop, due to the potential for coevolutionary arms races, lower overall selection pressure compared to pesticides, and varying selective pressures from multiple control agents (Tomasetto et al., 2017). That said, examples of cultural and biological control failing due to pest adaptation do exist. Parasitoid control of larch sawfly, *Pristiphora erichsonii*, failed after 27 successful years when the sawfly immune system evolved to better resist attack, although another strain of the parasitoid successfully re-established control (Goldson et al., 2014). Western corn rootworm, *Diabrotica virgifera virgifera*, a major maize pest in North America, was controlled for many years by rotating maize and soybean annually. However, some populations of Western corn rootworm adapted to oviposit in soy fields, damaging the maize planted the following year (Gray et al., 2009). Tomasetto et al. (2017) found that Argentine stem weevil, *Listronotus bonariensis*, was more likely to evolve resistance to its parasitoid control agent in plots containing a type of grass grown nationwide at high intensity, compared to in plots containing a less common pasture grass. While it is encouraging that cases of pests overcoming biological and cultural control techniques are rare in the literature, these examples demonstrate the potential for pests to adapt to a variety of pest management approaches.

In other situations, ecological intensification may be resilient against pest adaptation, or even become more effective over time. Associational resistance has been shown in a variety of systems (Barbosa et al., 2009), in which different plant species grown together reduce pest

pressure through a variety of mechanisms. Some of these mechanisms, such as accumulation of natural enemies, improvements to soil nutrients, or changes to microclimate (light intensity, temperature, humidity), could have stronger beneficial effects the longer a companion cropping system is in place. Particularly with regard to natural enemies, perennial plantings are expected to provide better nesting opportunities for beneficial arthropods even outside of a cropping season (Ganser et al., 2019; Kremen, 2020). When perennial companion crops are present for longer timespans, colonization by weakly dispersing arthropods and higher trophic levels is more likely (Boetzl et al., 2021). Additionally, intercropping can increase soil carbon and nitrogen over time (Cong et al., 2015), which may increase the yield of the main crop regardless of any pest pressure.

An ideal system to test whether pests can be expected to adapt to ecologically intensified systems, or whether such systems may in fact become more effective over time, is the push-pull cropping system. The push-pull system was developed to control pests of maize in Kenya, primarily stemboring moths (*Chilo partellus* and *Busseola fusca*). The name of the system comes from the mechanism by which it controls the moths: a “push” plant, usually a member of the *Desmodium* genus, is planted in between maize rows, while a “pull” plant, either Napier grass (*Pennisetum purpureum*) or signalgrass (*Brachiara* cv. Mulato-II) is planted around the perimeter of the maize field (Khan et al., 2008; Maass et al., 2015). Volatile chemistry from both push and pull plants mislead adult female moths to oviposit on the pull plant rather than the maize, reducing stemborer infestation in push-pull fields compared to fields planted with maize alone (Khan et al., 2007, 2006, 2001). Despite being preferred by adults, both Napier grass and signalgrass are poor hosts for stemborer larvae, with larval mortality exceeding 90% (Khan et al.

2007, Cheruiyot et al. 2018). Furthermore, *Desmodium* spp. produce root exudates which induce suicidal germination of seeds of the parasitic striga weed, in which the seed germinates but is unable to elongate its roots and subsequently dies, reducing the striga seed bank (Odhiambo et al., 2011; Tsanuo et al., 2003). Striga seeds disperse at relatively short distances, within 12m from the parent (Berner et al. 1994), so push-pull fields are not necessarily re-colonized quickly by striga. *Desmodium* spp. are also nitrogen-fixing legumes which improve soil nitrogen availability for maize (Ndayisaba et al., 2021). First established in the 1990s, over 280,000 farmers have adopted the push-pull system as of 2021 (push-pull.net). Push-pull maize fields increase yields compared to non-push-pull fields by 200-300% on average (Kfir et al., 2002; Midega et al., 2015), and have been shown to have a variety of economic benefits for farmers (Chepchirchir et al., 2018; Kassie et al., 2018).

Due to the history of establishment and adoption, at any given time there is a broad range of fields which have been operating under push-pull management for varied number of years. This provides a perfect test case to examine whether the effect of the push-pull system on pests, either stemborer or striga, may be weakening or strengthening over time. While testing adaptation directly can be difficult, by using existing data on pest pressure in the push-pull system we are able to examine whether there is a correlation between how long a field has been in use and pest pressure on that field. Higher pest pressure in older push-pull fields would imply pest adaptation and motivate more directed studies of the mechanism of adaptation itself. Conversely, if the effect of the push-pull system is shown to be improving over time, this could motivate research on the specific mechanisms allowing the system to either maintain or improve its effectiveness over time. In this study, we examine 12 years of data (24 cropping seasons) on pest abundance

and yield in push-pull and non-push-pull fields across Western Kenya to determine whether the ability of the push-pull system to control pest populations and improve yields of maize has changed over time. We predicted that if pests had adapted to the push-pull system, the system would be less effective at controlling pests and at increasing yield the longer it had been under push-pull management. If on the contrary the push-pull system relies on ecological mechanisms that make the system more robust over time, we predict that the push-pull system will become more effective at controlling pests and at increasing yield over time.

2. Methods

2.1 Dataset

In collaboration with farmers, extension agents of the International Centre of Insect Physiology and Ecology (*icipe*) have been collecting data on pest pressure and yield from a large number of farms with push-pull and non-push-pull fields across Western Kenya (Midega et al., 2015). In total, the dataset analyzed here includes 476 farms across eight regions of Western Kenya, covering 24 cropping seasons from 2005 through 2016 (see Fig. 1). These regions are largely defined by pre-2010 subcounty boundaries (Kenya's political districts underwent a major reorganization in 2010). At each farm, the same farmer managed one push-pull and one non-push-pull field planted with maize. Non-push-pull fields varied, some being maize monocultures while others were intercropped with groundnuts, greengrams, or other local crops. However, none of the non-push-pull fields had a perimeter crop of Napier grass or signalgrass, and none contained *Desmodium* as an intercrop. For the rest of this manuscript, we will refer to the non-

push-pull fields as “control,” despite these variations. All control fields were within 100m of their respective push-pull field. Sites were sampled in both the short rains (October-January) and long rains (March-August) growing seasons, although not every farm was sampled at every time point. Briefly, to measure pest abundance for both stemborers and striga, 100 maize plants were randomly selected in each field four weeks after crop emergence and tagged for follow-up observations after a further six weeks. During this second observation period, stemborer damage was quantified as the percentage of maize plants damaged per 100 plants, and striga was quantified as the number of emerged striga within 15cm of the base of the plant per 100 plants. Yield was calculated after sun-drying grain to 12% moisture content, and weights were converted to tonnes/hectare, with maize yields in the push-pull fields accounting for the entire area including the area occupied by the companion pull plants. In two seasons, some regions experienced extreme drought causing them to have pest measures but no yield measures; these data points were utilized for all pest analyses but excluded from the yield analysis.

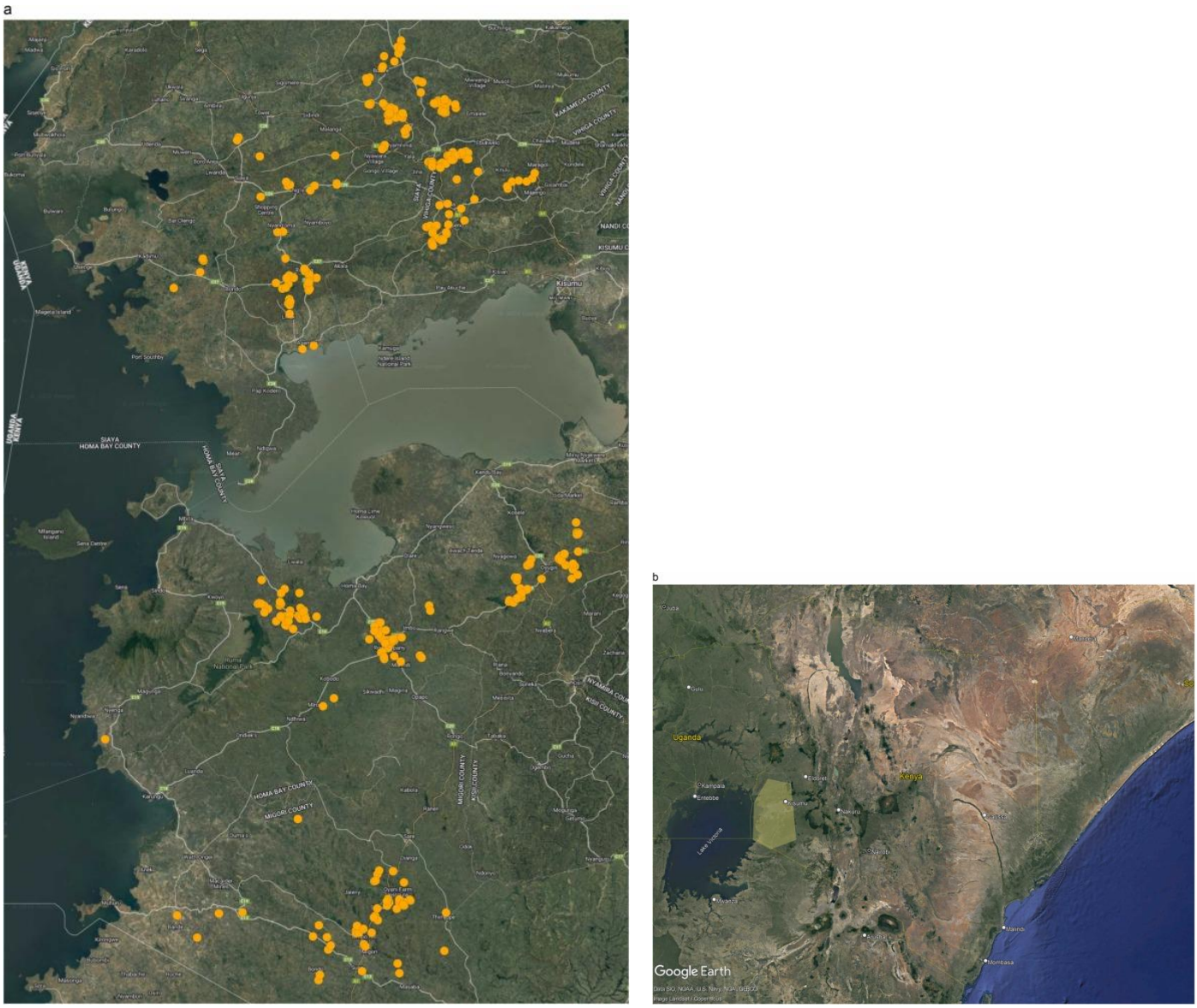

Figure 1. (A) 394 of the total 476 farms, showing farms with reliable GPS coordinates in the dataset. (B) The yellow polygon shows roughly the extent of our field sites within Kenya.

2.2 Data Cleaning

The initial dataset included a total of 784 unique farmers and 2613 data points. A given season's data for any farm was removed if any cell contained impossible values, such as non-integer

values for stemborer or striga abundance. Two farms which had a yield of 18 t/ha in the control field were removed as likely data entry errors, as this value was nearly double the next highest yield recorded in any field. Farms were removed if they were sampled twice (or more) in the same season, as we could not ensure that the same push-pull field was being sampled consistently across all seasons. Any farmer maintaining multiple fields at different sites was removed, as we could not be confident that data labeling was consistent. Any farm for which *icipe* could not confirm the initial season of planting push-pull was removed, as was any farm for which the reported initial season of planting was after a season in which we had data from that farm.

After data cleaning was completed, the dataset consisted of 476 unique farmers and 1880 data points. Farms' initial year of push-pull planting ranged from 1999 to 2016, with the median year of initial planting being 2007. The number of observations on a given farm ranged from 1 to 16 (mean 3.83, standard deviation ± 3.05). Due to sampling heterogeneity, we grouped data based on year since establishment. Sampling points at farms with less time since establishment were much more common, with the largest age bracket being 2 seasons since establishment (n = 216). 18 farms were sampled at 18 seasons since establishment. All age bins >18 seasons since establishment had fewer than ten farms. (Fig. 2) For all analyses, we excluded data points where a given farm had been under push-pull management for more than 18 seasons due to this. Thus, there were 24 total seasons of data containing farms which first established push-pull at different times, and within those 24 seasons, only data points for farms under push-pull management for 0-18 seasons were used.

Of these 476 farmers, we had reliable GPS coordinates for 394 farmers. All farms were used for main analyses, but these 394 were used for an additional analysis to check for spatial autocorrelation (Appendix A).

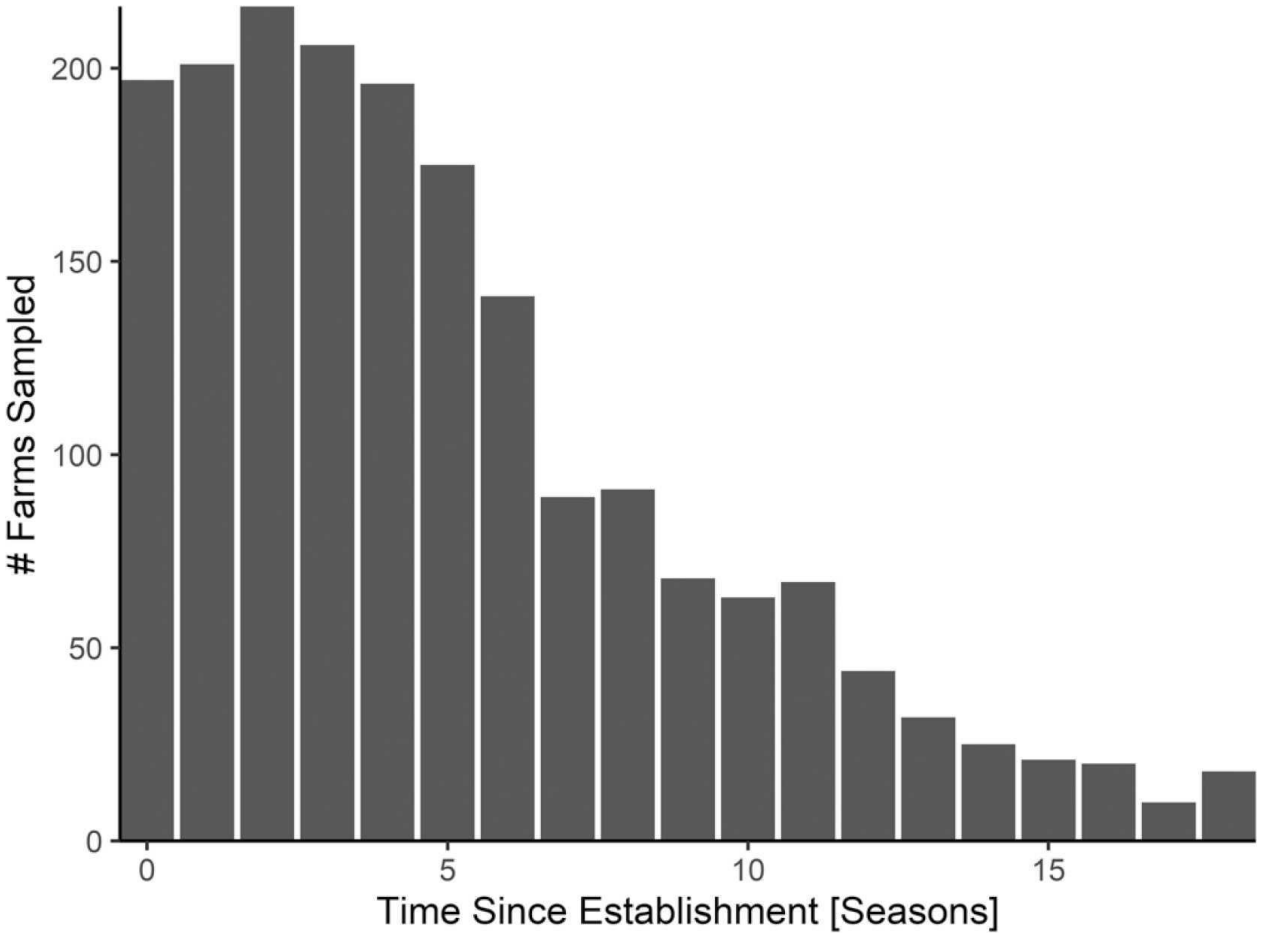

Figure 2. Number of farms sampled at each given time since establishment.

2.3 Data Analysis

In order to analyze whether the push-pull system's impact on pest pressure had changed over time, we used linear mixed effects models in R using *glmmTMB* (R Core Team 2021,Brooks et al. 2017). We built three models, one each for stemborer abundance, striga abundance, and yield.

In all models, our fixed effects were the number of seasons a field had been under push-pull management, termed "time since establishment," management treatment (push-pull or control), and an interaction effect between the two. All models had the same random effects structure: farmer identity, to account for repeated sampling at the same sites; nested within geographic region, as a proxy for soil and/or climate conditions that were not directly measured at our sites.

Preliminary analysis showed that models including season type (short rains vs long rains) were not more parsimonious than models which ignored it (Δ AIC > 2 for all cases), so we did not include season type as a covariate or random effect (Aikake 1973). To ensure that any effect of field age was not due to farms with poor performance dropping out of the dataset, we calculated the relative yield benefit of push-pull in the first three seasons since planting:

$$yield\ effect = \frac{push\text{-}pull\ yield - \ control\ yield}{control\ yield}$$

We then split the dataset into the top 25% highest and lowest 25% yield benefits in these first three seasons, and tested whether the maximum age associated with a given field was different between these two subsets with a t-test. If farms stopped using push-pull due to poor performance, we would expect the maximum age in our dataset to be lower for the bottom 25%. There was no significant difference in maximum age between the top and bottom quartile ($t = 1.14$, $p = 0.26$).

The number of farms varied greatly from season to season due to logistical constraints (minimum 17, maximum 165). As more farms established the push-pull system over time, the dataset was weighted towards younger fields with relatively few examples of fields established for longer periods of time. To account for this, we used permutation testing. Permutation testing is a

statistical technique useful for data which may not meet assumptions of normality (Manly 1997). Rather than assuming a particular null distribution of test statistics, the data collected is randomized a large number of times and the relevant statistical models run on the newly randomized data. Test statistics from those models are then used to create the null distribution of what a particular dataset would look like if no relationship between variables truly existed, and the test statistic from the model using the real data is compared to this distribution to determine a p-value and significance (Manly 1997). Specifically, we created 9,999 permutations to generate the null distributions for each model. Each permutation randomly arranged the dependent variable (stemborer abundance, striga abundance, or yield) while maintaining the dependent structure of our random effects. In other words, we randomized the observations within each farmer, while keeping the total distribution associated with a given farmer consistent. This has shown to be more reliable for permutation tests in models with repeated measures (Winkler et al., 2015).

3. Results

Stemborer abundance was significantly reduced by the push-pull treatment and decreased the longer a farm had a push-pull field (Table 1, Fig. 3). This did not only occur in push-pull fields, but was actually marginally more pronounced in the control fields of farms where push-pull management had been used for a longer time (Table 1, Fig. 3).

Striga abundance was significantly reduced by the push-pull treatment and decreased the longer a farm had a push-pull field, similarly to stemborer abundance (Table 1, Fig. 4). Striga abundance decreased in both push-pull and control fields with time since establishment, and

decreased significantly faster in control fields (Fig. 4).

Yield was significantly increased by the push-pull treatment (Table 1,Fig. 5). Yield increased slightly with time since push-pull establishment in push-pull fields, but not control fields (Table 1, Fig. 5).

Table 1: Model Summary Statistics. All p-values were obtained with permutation testing with 9,999 permutations. Estimates and z-values presented for "treatment" are for the effect of the push-pull treatment.

Dependent	**Predictors**	**Estimate**	**df**	**z-value**	**p-value**
Stemborer Abundance	Intercept	19.509	7	21.03	-
	Treatment	-15.006	7	-38.97	$p < 0.001$
	Time since establishment	-0.324	7	-6.33	$p < 0.001$
	Treatment*Time since establishment	0.148	7	2.52	0.0014
Striga Abundance	Intercept	408.053	7	15.29	-
	Treatment	-363.039	7	-34.83	$p < 0.001$
	Time since establishment	-6.998	7	-5.69	$p < 0.001$
	Treatment*Time since establishment	4.645	7	2.92	$p < 0.001$
Yield	Intercept	2.034	7	17.5	-
	Treatment	2.331	7	55.1	$p < 0.001$
	Time since establishment	0.004	7	0.73	0.632
	Treatment*Time since establishment	0.027	7	4.1	$p < 0.001$

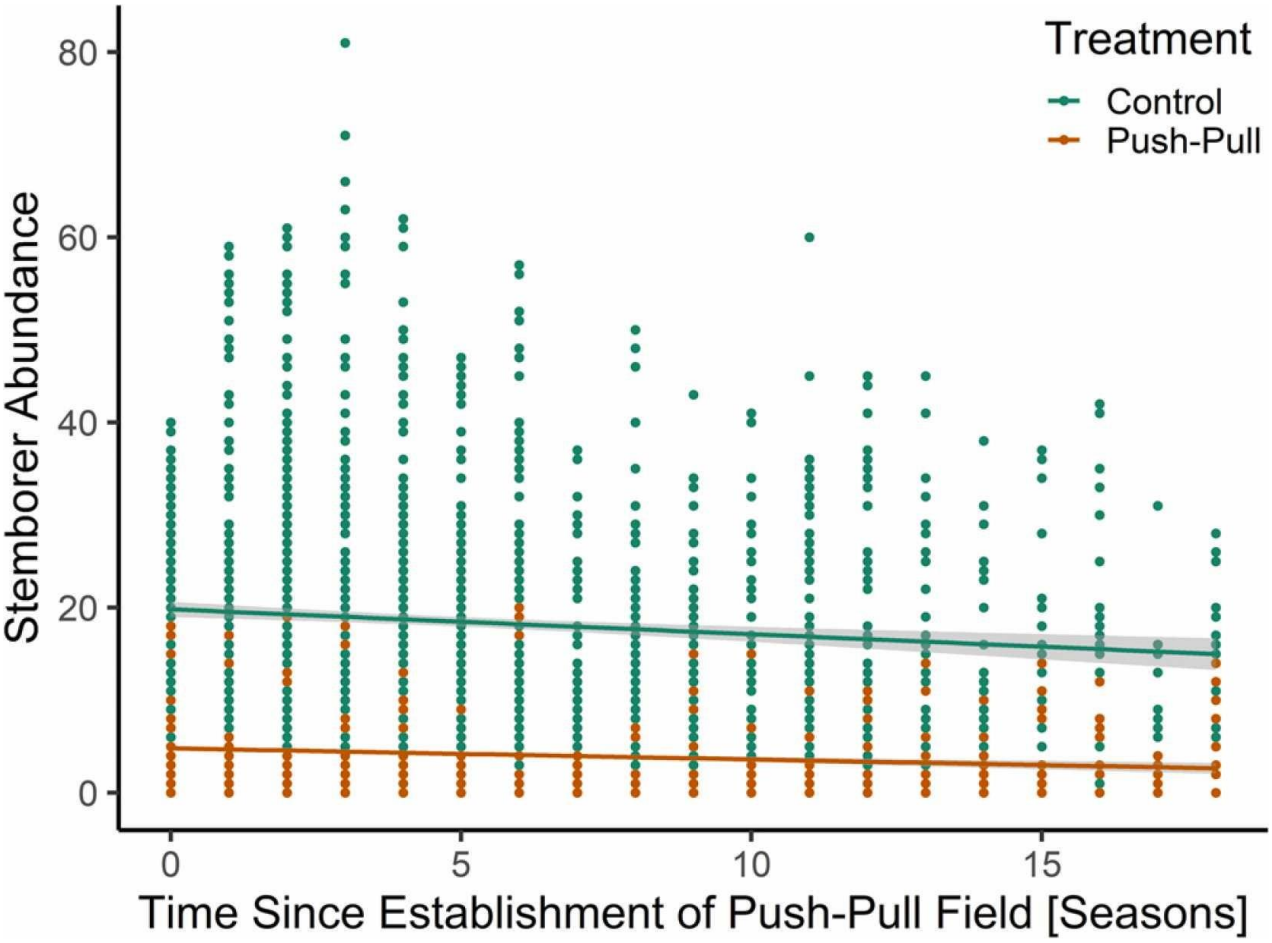

Figure 3. Stemborer abundance in push-pull and control fields on farms where the push-pull system has been in use for varying amounts of time. Field age is reported as the number of seasons that a farmer had established a push-pull field on their farm. Stemborer abundance reduced with time since establishment in all fields, but the slope was marginally steeper for control fields (green, y = 19.5–0.32x) than for the push-pull fields (orange, y = 4.5–0.17x).

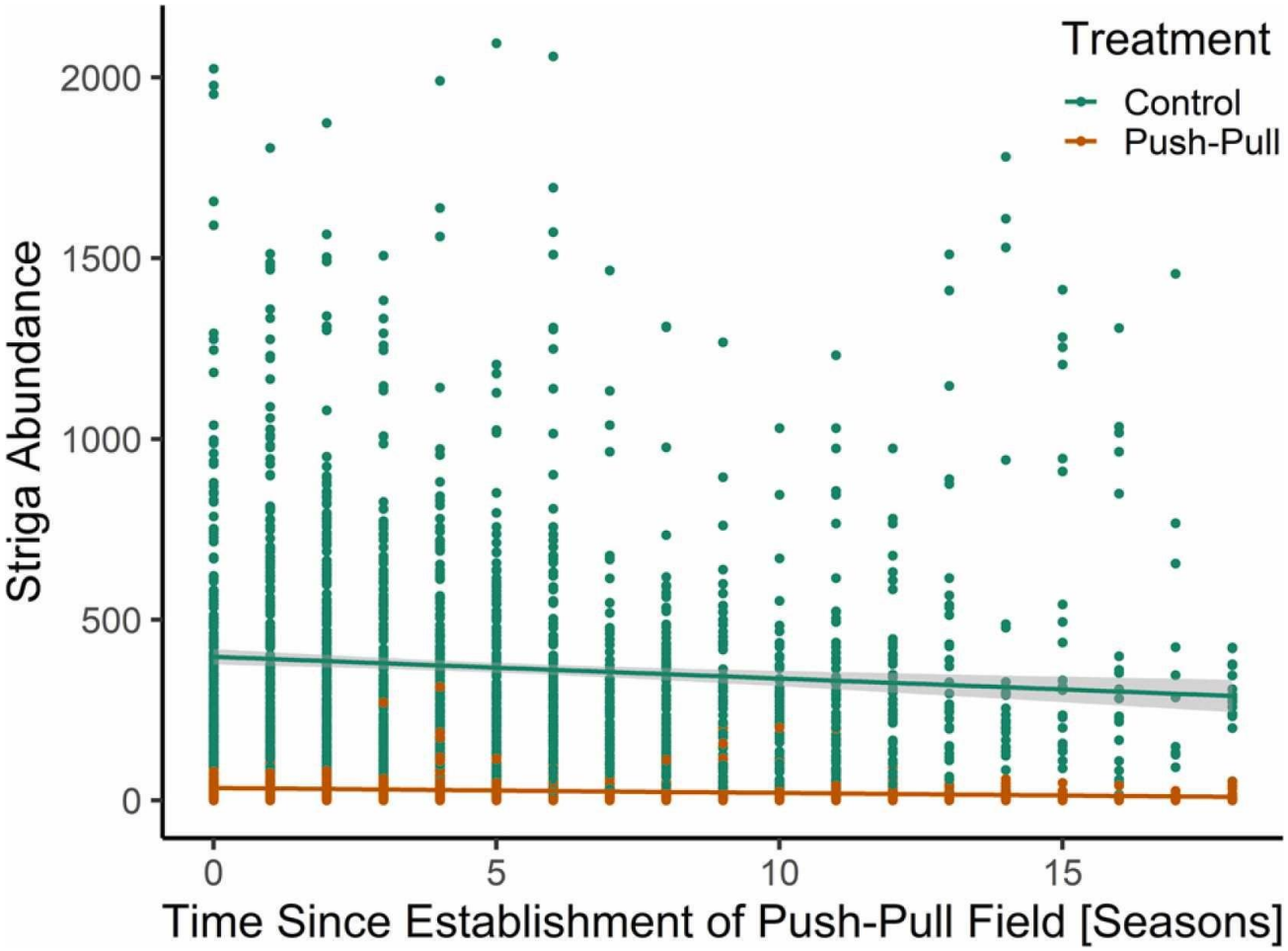

Figure 4. Striga abundance in push-pull and control fields on farms where the push-pull system has been in use for varying amounts of time. Time since establishment is reported as the number of seasons that a farmer had established a push-pull field on their farm. Striga abundance was suppressed in all fields, but the slope was steeper for control fields (green, y = 408.05–6.99x) than for push-pull fields (orange, y = 45.01–2.35x).

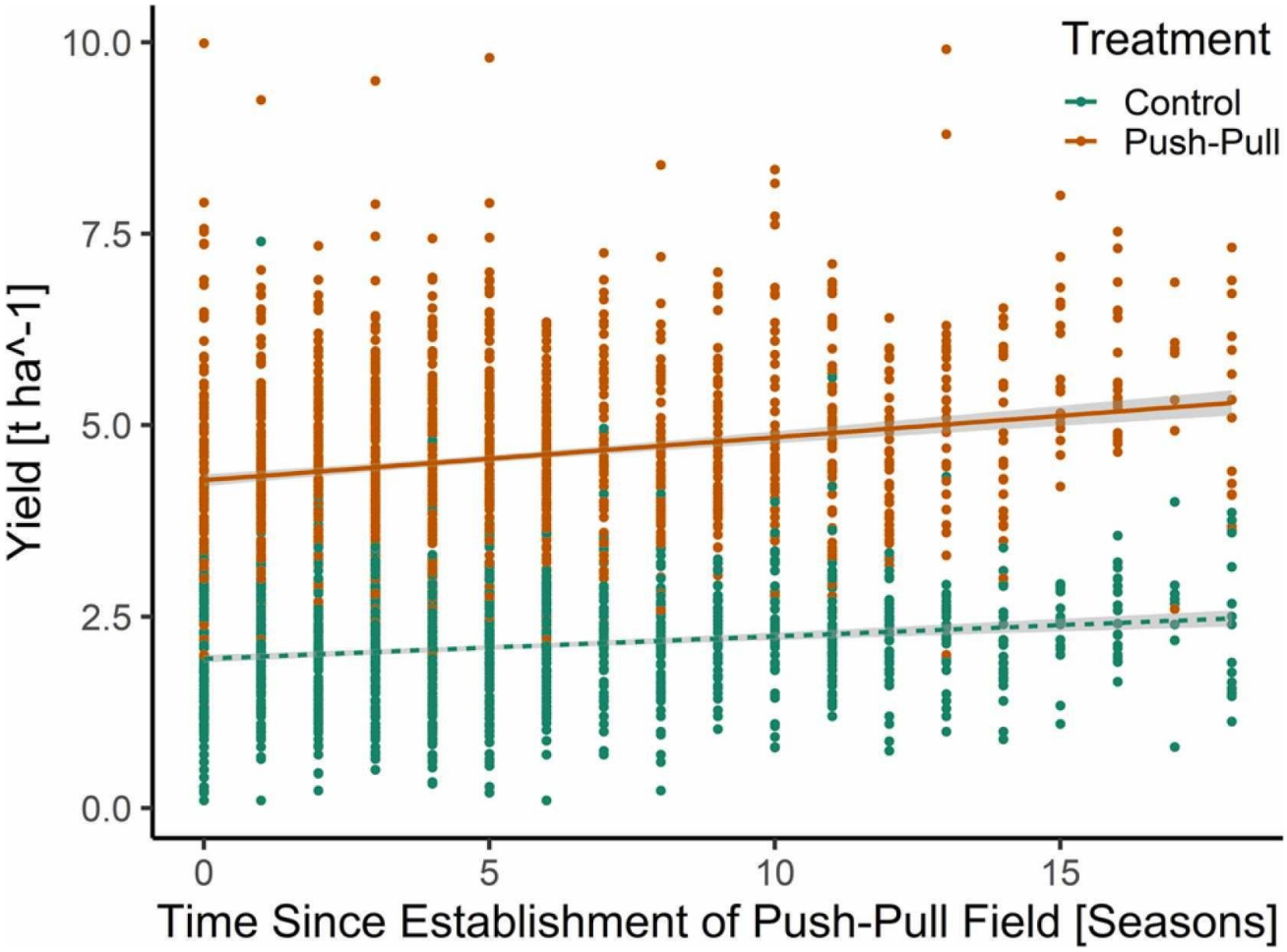

Figure 5. Yield in push-pull and control fields with increasing time since push-pull establishment. Time since establishment is reported as the number of seasons that a farmer had established a push-pull field on their farm. Yield increased in push-pull fields with time since establishment (orange, $y = 4.33 + 0.029x$) fields.

4. Discussion

The aim of our study was to determine how ecologically intensified systems may develop over time. Specifically, we use the push-pull system in Kenya as a model system to investigate if the beneficial effects of this ecological intensification practice changes with increasing time since

the initial planting. Based on agroecological theory and previous research, we could expect the following very different outcomes: 1) that pests are adapting to overcome the system, 2) that the push-pull system maintains a consistent effect, or 3) that the effects of push-pull become stronger as certain benefits build over time. We found that the benefits of the push-pull system remained robust or even became slightly stronger with time since establishment. Furthermore, we are confident that this effect is explained by time since push-pull establishment, not by farmers with poor push-pull performance dropping out of the dataset or the calendar time point itself (Appendix B).

Although the exact mechanism driving increased benefits of push-pull over time is unclear, research in both push-pull and other ecologically intensified systems suggests at least three likely possibilities: 1) Beneficial communities of natural enemies often build up over time after changes in local management, which can manifest as increased abundance, richness, and/or attack rate (Birkhofer et al., 2008; Denys and Tscharntke, 2002; Krimmer et al., 2022). 2) *Desmodium spp.* in push-pull fields suppress the overall striga seed bank over time, limiting striga damage in future growing seasons (Khan et al., 2008). 3) Ecologically intensified fields may build improved soil fertility (Thierfelder et al., 2013b, 2013a) or soil-mediated changes in plant defenses (Blundell et al., 2020; Mutyambai et al., 2019) with increased time since implementation. In reality, the changes we observe are very likely due to a combination of processes. Consistently, push-pull has a strong yield benefit which improves over time.

While questions about the mechanisms remain, particularly with regard to the effects seen in control fields (see below), we found that the push-pull system improved upon its strong impact

on pest reduction and yield increases with time since push-pull establishment. Although the effect sizes were small, a conservative reading still shows that pests are not overcoming the push-pull system. Within the twelve-year time span of the total dataset, our oldest fields had been under push-pull management for nine years. In our system this represents 18 growing seasons, at least 27 generations of *Busseola fusca* (Critchley et al., 1997), and 45 or more generations of *Chilo partellus* (Khadioli et al., 2014). Given that pesticide resistance, in contrast, can evolve in just one or two generations (Fardisi et al., 2019; Gordon et al., 2014), it is encouraging to see the push-pull system remain durable over the time period sampled here.

4.1 Benefit to Control Fields

Interestingly, we found that with increased time since push-pull establishment, a given field's paired control also had lower pest populations. From these data, it is hard to say why exactly this would be the case, but we propose potentially overlapping mechanisms which could be tested.

First, it is possible that the improvement in control fields is not a direct effect of the push-pull system itself, but rather due to push-pull farmers improving their practices generally alongside adopting push-pull. Push-pull fields require less labor to maintain once they are established (Diiro et al., 2021; Murage et al., 2015), which may allow more time to be devoted to weeding and maintaining other fields. Farmers who adopt agroecological practices often have regular contact with extension services, participate in agroecological trainings, and develop formal and informal peer networks to share information and discuss best practices (Amudavi et al., 2009; Bezner Kerr et al., 2018; Kangmennaang et al., 2017; Khan et al., 2008; Madsen et al., 2021). Thus, reduced pest pressure in control fields with increasing time since push-pull implementation

may reflect push-pull farmers' allocation of labor and access to information on management practices.

Second, some benefits of the push-pull system may spillover locally to nearby maize fields. Volatile chemicals emitted by the companion crops and any potential build-up of natural enemy communities could all contribute to reducing stemborer pressure on nearby fields. With fewer striga plants in a push-pull field, there may be fewer striga seeds entering the seed bank of nearby fields as well, reducing overall striga pressure over time.

4.2 Comparison to Other Pest Management Systems

Unlike the examples of failed biological and cultural controls previously cited (Goldson et al., 2014; Gray et al., 2009; Tomasetto et al., 2017), the push-pull system relies on multiple overlapping mechanisms of pest management and soil improvement. It may be that pests are unable to adapt to overcome the particular mechanisms utilized in this system or that not enough time has elapsed since the implementation of push-pull practices. Another possibility is that multiple overlapping mechanisms themselves are more robust to pest development of resistance and can maintain their usefulness for longer periods.

4.3 Fall Armyworm

It is worth noting that the data used for this study was collected before fall armyworm (*Spodoptera frugiperda*) arrived in Kenya in 2017. A devastating pest of maize, sorghum, rice, and several other crops, fall armyworm has spread quickly across Africa since its first detection in Nigeria in 2016 (Zacarias, 2020). The push-pull system has so far successfully protected

against fall armyworm, reducing fall armyworm damage by over 80% and maintaining yields 2-3 times higher than control fields even in the presence of this new pest (Hailu et al., 2018; Midega et al., 2018a; Njeru et al., 2020). However, this new invasive pest could significantly change the dynamics of the system moving forward. Continued monitoring will be necessary to determine how these patterns change in the future.

4.4 Conclusion

Our results are encouraging for the resilience of ecological intensification more broadly. Over a large number of farms and several growing seasons, we see that the benefits of an ecologically intensified agricultural system do not degrade with time since establishment, and in fact improve slightly over time. We also intriguingly found possible benefits of ecologically intensified fields to other fields nearby, whether or not they were under the same management scheme. Further studies are needed to determine the relative significance of different mechanisms within the system, as well as how the system is continuing to develop in the presence of fall armyworm. Future studies should also ideally gather data from control fields far from the ecologically intensified treatment, to better distinguish any possible effect of ecological intensification on neighboring fields. Overall, this study provides further evidence for the hypotheses that ecologically intensified farms are less likely to fail due to pest adaptation and more likely to have resilient, or even increasing, benefits over time.

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Ecological intensification is robust across landscape and weather gradients: results from the Kenyan push-pull maize system

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Abstract

Ecological intensification in agriculture aims to manage biodiversity to maintain or improve crop yield, while reducing negative impacts of agricultural management. Ecologically intensified systems have also been shown to perform better in the face of extreme weather and changing climate conditions. Growers often increase local plant diversity as part of ecological intensification, using techniques such as flower strips and companion cropping, but the success of these techniques can depend on diversity in the surrounding landscape. Using data from the push-pull pest management system in Western Kenya, we examined how the interaction between local management, landscape composition, and weather influenced abundance of insect pests and a parasitic weed, as well as maize yield. In total, our dataset contained 182 unique farmers with both a push-pull and control field, sampled opportunistically over four growing seasons. We found that weather factors, such as length and number of dry spells within a growing season, affected pests differently in the long and short rains growing seasons, but that in all cases push-pull maintained strong pest suppression and yield benefit effects. Push-pull fields showed the strongest crop yield benefits in landscapes with less surrounding agriculture, but consistently doubled crop yield (at least) in comparison to control fields regardless of landscape context. Push-pull fields were largely unaffected by weather factors (other than extreme drought), and

across all weather conditions, push-pull fields consistently outperformed control fields. Altogether, push-pull remained a robust local management practice for growers regardless of their local weather or landscape conditions.

Keywords: ecological intensification, climate-smart agriculture, landscape ecology, food security, biodiversity, crop yield, precipitation

Introduction

Ecological intensification is a set of principles and practices aiming to carefully manage biodiversity to maintain or improve ecosystem services in agriculture, including crop yield (Bommarco et al., 2013; Cassman, 1999; Doré et al., 2011). By managing farms and landscapes to maintain ecosystem services such as nutrient cycling, pollination, and biological pest control, growers can reduce anthropogenic inputs such as pesticides and synthetic fertilizers which have negative environmental impacts (Garibaldi et al., 2019; Kleijn et al., 2019; Tittonell & Giller, 2013). Ecological intensification can include a variety of strategies, but many focus on increasing local plant diversity within or nearby crop fields, such as with intercrops and companion crops, wildflower plantings, maintaining forested area near a farm, and similar strategies.

By emphasizing biodiversity to support agricultural systems, ecologically intensified farms may also be more robust to extreme weather events and climate change. The importance of diversity for resilience of natural systems has long been recognized (Elmqvist et al., 2003; Mori et al.,

2013; Walker et al., 1999). Similarly, biodiversity may help agricultural systems to retain important ecosystem functions (including yield) in the face of adverse conditions. For instance, ecologically intensified farms had less erosion and lower economic losses after a hurricane compared to conventional farms (Holt-Giménez, 2002). Organic cropping systems have been found to perform better than conventional agriculture during drought (Lotter et al., 2003; Pimentel et al., 2005), and more diverse crop rotations can increase maize yields in both favorable conditions and unfavorable drought conditions (Bowles et al., 2020). In silvopastoral systems, tree and shrub roots improve water retention in the soil, ultimately helping all plants in the system endure drought conditions (Broom et al., 2013). Conventional agriculture both contributes to climate change, and may be ill-prepared to cope with it – ecologically intensified systems reduce the negative environmental impacts of agriculture, and may be better positioned for success in a changing world.

However, landscape context has been found to influence the success of ecological intensification, particularly for modifications intended to influence beneficial arthropod activity (Batáry et al., 2011; Lichtenberg et al., 2017; Sánchez et al., 2022). In a diverse landscape with abundant resources for beneficial arthropods, adding resources near the field may not have any benefit as the provision of ecosystem services is already high. In simpler landscapes with moderate arthropod diversity, the addition of plant diversity in and around the field should attract those arthropods concentrating the ecosystem services they provide around the field (Tscharntke et al., 2012). A meta-analysis by Batáry et al (2011) confirmed that beneficial arthropod abundance and richness responded to increased plant diversity in moderately simplified, but not more complex, landscapes. Sánchez et al. (2022) also found that the effect of diversified farming on species

richness was highest in landscapes with less natural and semi-natural area within a 1km radius, and that the strength of the effect also varied with the distance from a plot to the closest natural or semi-natural habitat. For beneficial arthropods specifically, the positive effect of diversified farming on richness was strongest in plots that were very far (>1km) from the nearest natural or semi-natural habitat (Sánchez et al. 2022).

To test how landscape context and weather interact with local ecological intensification techniques, we examined the push-pull cropping system for maize in Africa. First developed in Kenya to control insect pests of maize in the 1990s, push-pull has been found to have numerous benefits and is currently used by over 250,000 farmers in several countries across West, East, and Southern Africa (icipe.org). Originally targeting stemboring moths (*Chilo partellus* and *Busseola fusca*), the push-pull system includes both a "push" plant (usually a *Desmodium* species) planted between maize rows and a "pull" plant (either Napier grass, *Pennisetum purpureum*, or Signal grass, Brachiara cv. Mulato-II) planted around the perimeter of the field (Khan et al., 2008; Maass et al., 2015). Volatile chemicals from the push plant repel adult female moths, while volatile chemicals from the pull plants are extremely attractive to them, leading to decreased oviposition on maize and ultimately reduced infestation and damage. The roots of *Desmodium* spp. also produce root exudates which suppress the parasitic striga weed, protecting the maize from a parasitic weed pest as well as the insect pests. Furthermore, *Desmodium* spp. are perennial nitrogen-fixing legumes, which enhance soil fertility and even maize's own plant defenses (Drinkwater et al., 2021; Mutyambai et al., 2019; Ndayisaba et al., 2021). Through the combined impact of these various benefits, push-pull maize fields have 200-300% higher average yield than non-push-pull fields (Kfir et al., 2002; Midega et al., 2015), with several

economic benefits for farmers (Chepchirchir et al., 2018; Kassie et al., 2018).

Despite this extremely large average effect (Luttermoser et al., 2023), the push-pull system can vary significantly in its effectiveness. Midega et al. (2014) found that egg parasitism was strongest in push-pull fields in relatively simple landscapes. In push-pull plots in Ethiopia, stemborer damage was most severe in the simplest landscape regardless of cropping system (Kebede et al., 2018). Kebede et al. (2018) also found a complex interaction between landscape complexity, cropping system, and crop age influencing generalist predator abundance and egg predation activity. While these studies had limited replication, they do provide preliminary evidence that landscape context may influence the success of the push-pull system, and that this effect may be mediated by beneficial natural enemies.

In addition to push-pull and any potential landscape effects, local weather could influence pest and yield dynamics. Striga is sensitive to drought early in its development (Dawoud & Sauerborn, 1994). *Chilo partellus* is less abundant in both too wet and too dry conditions (Patel et al., 2016; Yonow et al., 2017), while *Busseola fusca* relies on humid conditions but is less active during rainfall (van Rensburg et al., 1987). Additionally, Kenya has already begun experiencing negative impacts of climate change, which are expected to continue to worsen (Kogo et al., 2021; Nyang'au et al., 2021). The climate-smart push-pull technology has been developed to perform better in particularly dry areas, both to contend with current droughts and prepare for the anticipated impacts of climate change in the near future (Cheruiyot et al., 2021; Murage et al., 2015). Given that the pests and crop plants may all respond to weather conditions, we expect that local weather may influence the overall effect of the push-pull system.

In Western Kenya, where the push-pull technology was first developed, farmers across the region have adopted the push-pull system in a wide range of contexts. Push–pull fields are embedded in agriculturally-dominated landscapes, are located next to natural areas, or surrounded by a growing urban matrix. Extension agents from the International Centre of Insect Physiology and Ecology (ICIPE) regularly sample these fields for stemborer abundance, striga abundance, and yield, creating a large dataset of pest pressure and yield across several growing seasons. In this study, we use pest and yield data from four cropping seasons (2015 and 2016, long and short rains seasons) to examine whether push-pull remained effective across landscape and precipitation gradients. Due to push-pull's multiple overlapping direct and indirect benefits, we expect that push-pull fields will be robust and maintain low pest abundances and high yields across a wide range of conditions. We predicted that pest abundance will be higher and yield lower on fields surrounded by more agricultural area, but that this effect will be weaker or non-existent in push-pull fields. We also predicted that push-pull fields will consistently perform better than control fields, regardless of weather.

Methods

Summary

Our dataset consisted of 182 smallholder farms in southwestern Kenya, with farmers maintaining both a push-pull and control field at each site. We collected stemborer incidence, striga abundance, and yield data from these fields in 2015 and 2016, representing four growing seasons (two long rains, two short rains). We also classified the landscape surrounding each farm within

a 2km radius using a machine learning method, and collected weather data for each farm from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset (Funk et al. 2014). Using general linear mixed models and structural equations modeling, we analyzed these data to determine how pests and yield in push-pull and control fields responded to landscape and weather gradients.

Dataset

Extension agents of the International Centre of Insect Physiology and Ecology (icipe) periodically collect data from farms with push-pull and non-push-pull fields across Western Kenya (Midega et al., 2015). These farms are maintained by smallholder farmers who collaborate with icipe to allow data collection. Our previous work reported on the data collected from eight regions of Western Kenya from 2005 through 2016 (Luttermoser et al 2023). Due to limitations in the quality of satellite imagery for landscape classification, we limited our dataset for this study to 2015 and 2016, representing two long rains and two short rains growing seasons. At each farm, the same farmer managed a push-pull field and a non-push-pull field planted with maize. Non-push-pull practices varied, while many were maize monoculture, others were intercropped with groundnuts, greengrams, or other local crops. Hereafter, we refer to all non-push-pull fields as "control" fields, although we do acknowledge this variation. None of the control fields had a Napier grass or Signal grass perimeter, and none contained a *Desmodium* intercrop. Control fields and push-pull fields at each site were within 100m of each other.

Farms were sampled opportunistically, that is, not every farm was sampled in every growing season. Sampling occurred in both the short rains (October-January) and long rains (March-

August) growing seasons. 100 maize plants were randomly selected in each field to measure pest abundance for both stemborers and striga. These plants were tagged four weeks after crop emergence, and follow-up observations occurred six weeks after tagging. During the observation period, stemborer damage was quantified as the percentage of maize plants damaged per 100 plants (regardless of damage severity), and striga was quantified as the number of emerged striga within 15cm of the base of a tagged plant. To calculate yield, grain was sun-dried to 12% moisture content and weights were converted to tonnes/hectare. Areas for push-pull fields accounted for the entire area including the area occupied by the perimeter trap crop.

Data Cleaning

We removed any farm for which we did not have reliable GPS coordinates, including any instance where different fields maintained by the same farmer were sampled within our dataset, as we could not verify that the same GPS coordinates were consistently attached to the same data label. We removed the data for a given season for any farmer if a cell contained impossible values, such as non-integer abundance values, as well as two instances of unrealistically high yield which we considered likely data entry errors. In the long rains season of 2016, Bondo experienced extreme drought, resulting in pest measures but no yield measures for 29 of the 107 sites that season; these data points were excluded for all analyses as well. After examining the results of the machine learning method (see below), two sites were noted as particularly poorly characterized. Both were surrounded by primarily agriculture, but classified as >70% developed land, a pattern we did not find at our other sites. These two sites were manually removed from our dataset. This resulted in 322 data points from 182 unique farmers (Fig. 1) over the four growing seasons.

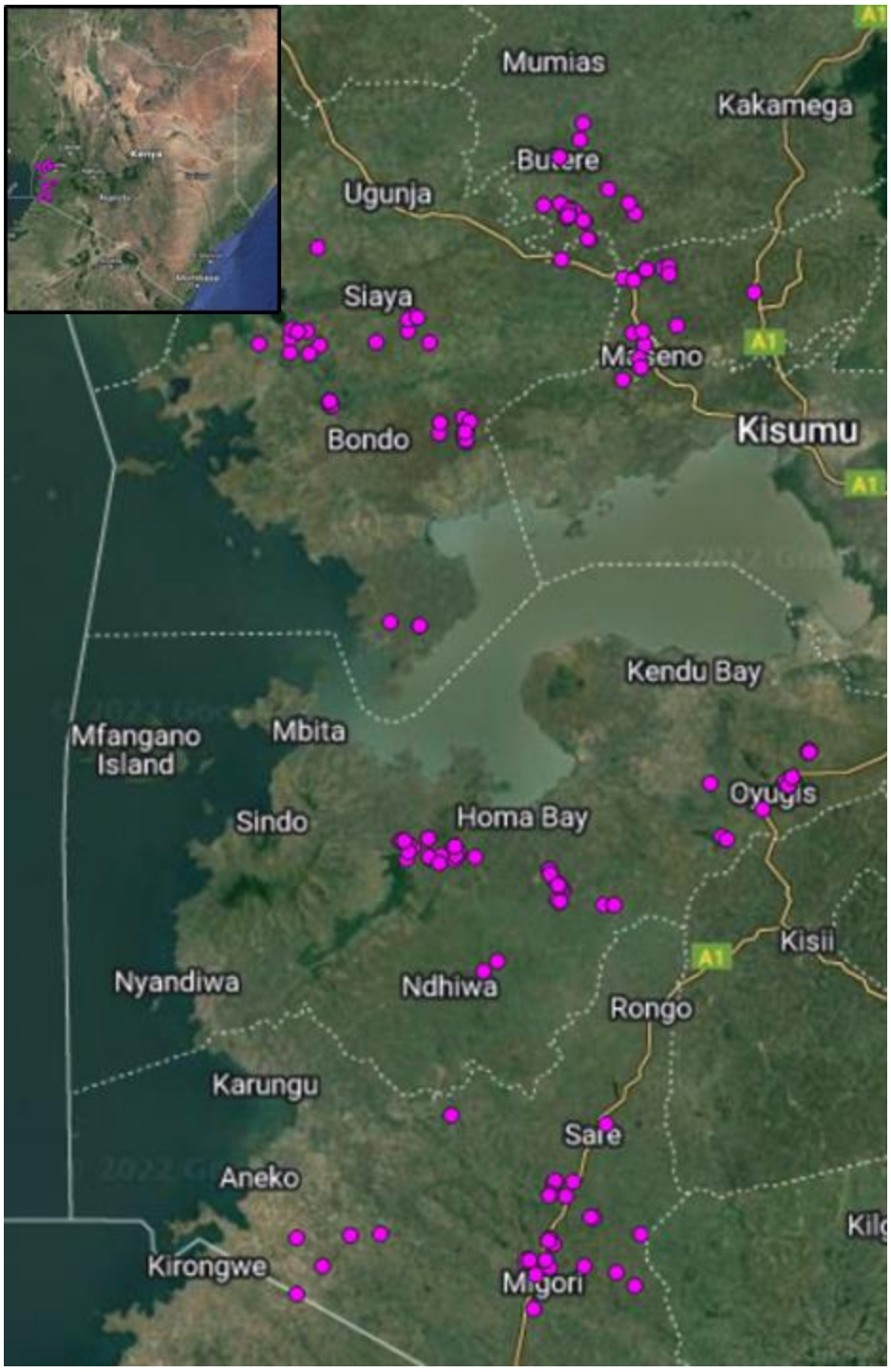


Figure 1. The sites of the 182 farms used for this analysis. Inset: The region of the sites highlighted within Kenya.

Landscape Classification

We classified the landscape surrounding each farm using four categories: agricultural, semi-natural, developed, and open water. First, we classified the landscape in a 1km radius around 22 farms, chosen to maximize the geographic spread within our dataset and minimize overlap between farms. These landscapes were classified manually by drawing polygons in QGIS (QGIS Development Team 2022). Agricultural land tended to have a rectangular shape (though not always), and was either brown (recently plowed), lighter shades of green, or yellow. Semi-natural land tended to be more irregular in shape (though did also include fallow fields in some cases), and was often darker green and of a coarser texture compared to agriculture. Developed land covered more urbanized areas, clusters of buildings (including schools or larger family compounds with several individual homes), and cleared land such as sports fields. Open water was relatively rare, but included Lake Victoria (for those few farms >1km from the lake), larger rivers and streams, and artificial pools sometimes maintained by farmers. These polygons were then used as reference data to train a machine learning approach to classify the landscape surrounding all farms at a 2km radius. Machine learning was used in addition to manual classification due to the size of the dataset.

Figure 2 summarizes the methodology and provides a schematic overview of steps taken to create the land use maps and the polygon shapefiles. A 2km radius around each target farm was identified and was used in all the analyses as the area of interest (aoi) as shown in Figure 2. The Google earth engine (GEE) was used as the data curation, compositing, and classification platform. This platform was used because it processes satellite imagery at the petabyte level on the cloud and aggregates and manipulates these huge datasets without the need to download. In

this task, we used the Sentinel 1 (Synthetic Aperture Radar: SAR) and the optical Sentinel 2 data (of the year 2019), together with their respective vegetation indices. A total of 81 variables were generated, preprocessed, and stacked from the two sensors and were used as predictor variables of the four target classes namely (1) Agricultural, (2) Semi-natural/natural, (3) Developed/ urbanized, and (4) Open water. A total of 3396 reference samples generated from the manually drawn polygons were used to split the reference data in a randomly stratified pattern using the Caret package's 'createdatapartition' method function in R. The original dataset comprised 1782 points for the Agricultural, 927 Semi-natural/natural, 652 Developed/urbanized, and 35 for Open water classes. These data were split into 70% data for training the machine learning application while 30% was retained for validation as a separate dataset. A random forest (RF) machine learning approach was adopted in this classification as it has been proven to successfully handle large datasets as well as to produce very accurate classification results. The RF method available in GEE was used for the classification using the 'aoi' as the target spatial area. The output of the classification was then validated using the 30% dataset. A confusion matrix was generated showing the user's accuracy (UA) and producer's accuracy (PA) for each class and the respective overall accuracy from both the training and test datasets. Simultaneously, a 3 X 3 majority filter was used to reduce noise and speckle from the output raster dataset. The filtered raster was converted to polygon where it was overlaid on a world base map to physically verify the accuracy of the dataset.

While the first attempt at applying a machine learning algorithm to our landscapes generally had high accuracy, accuracy was weakest for semi-natural land cover specifically. To resolve this, we produced additional manual polygons for semi-natural areas to add to the reference data,

specifically around those sites where accuracy was lowest. We also incorporated slope into the second training model, as we had observed that farmers in this region rarely clear hills for fields, and thus most terrain with a significant slope remains semi-natural terrain.

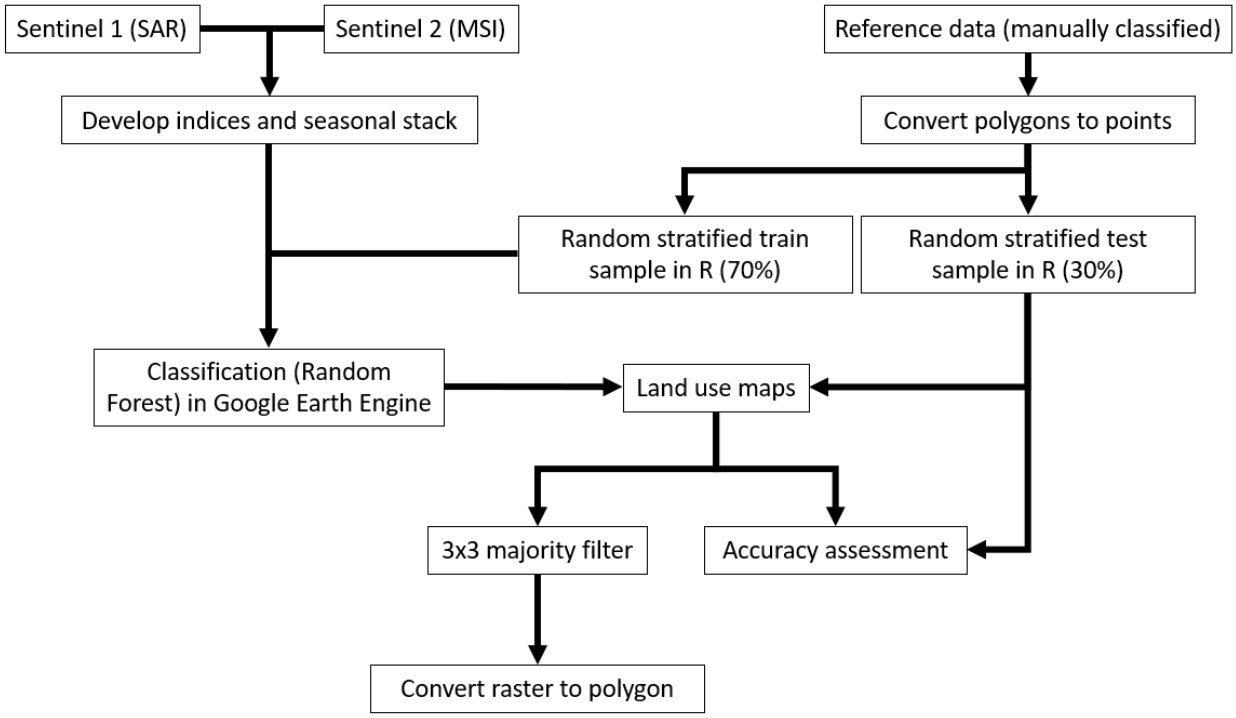


Figure 2: Schematic overview of steps taken to create the land use maps and the polygon shapefiles.

Precipitation Data

We used data of accumulated daily precipitation from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al. 2015) at 0.05° spatial resolution for the period 1981-2019. Following Dunning et al. (2016), we identified the climatological rainy season(s) for each grid point following a stepwise procedure: (1) we computed the climatological mean annual cycle of daily precipitation, from which we identified the dominant harmonic, i.e.,

annual or semi-annual regime, (2) we subtracted the annual mean value from the mean annual cycle of daily precipitation, and (3) using the cumulative daily mean precipitation anomaly, we defined the onset and cessation date(s) for the dominant climatological rainy seasons, one rainy season for the annual regime and the two for the semi-annual regime ("long rains" in boreal spring and "short rains" in boreal fall).

We then used the information on the climatological rainy season(s) to compute different statistics describing the occurrence and the intensity of daily precipitation for individual years at each grid point. A "dry" day is defined as a day with less than 1mm accumulated daily precipitation and a "wet" day if the threshold of 1mm is reached or exceeded. In this study, we use the total amount of rainfall accumulated during the rainy season(s) considering both dry and wet days, the number of dry spells lasting five days or more occurring during the rainy season(s), and the maximum length of a dry spell occurring during the first 20 days of the season(s). For the specific field sites we choose the closest neighboring grid points.

Statistical Analysis

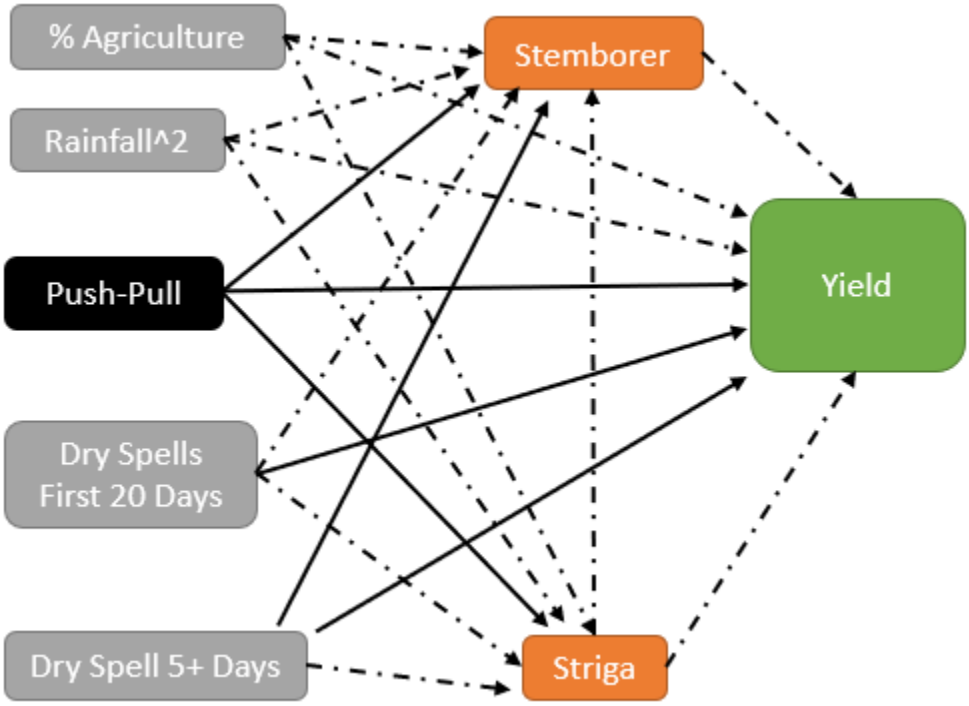
We used linear mixed effects models in R using *glmmTMB* (R Core Team 2021, Brooks et al. 2017) to analyze whether the push-pull system's impacts varied based on landscape context and local weather. Preliminary analysis determined that the patterns of weather variables were significantly different between the long rains and short rains seasons, so all analyses were performed separately for the long rains and short rains seasons.

We used the dredge function of *MuMIn* (Bartoń 20222) to determine which weather variables

were most likely to be relevant. As dredge produced several models with Delta AIC <2 from the best model, any weather variable which appeared in a model within Delta AIC <2 of the best model was included in our analysis, with the exception of the total number of dry days, which was strongly correlated with the number of dry spells lasting five days or more. All other variables were sufficiently uncorrelated (VIF <2). Weather variables retained were the length of the longest dry spell in the first 20 days of the growing season (hereafter "early dry spell length"), the number of dry spells within the growing season lasting five days or more, and total rainfall accumulation as a quadratic relationship (Fig. 3). We included the interaction between landscape context (% agriculture within 2km) and push-pull for pests and yield to determine if landscape context influenced the effectiveness of the push-pull system, and interactions between weather variables and push-pull treatment were included to examine robustness of push-pull across a weather gradient.

All variables were standardized to their z-scores using *mosaic* (Pruim et al. 2017), to account for large differences in numerical scale. All models had the same random effects structure, including farm identity and an exponential spatial position variable to account for spatial autocorrelation. After constructing the models for each individual path within both seasons, we used *piecewiseSEM* (Lefcheck 2016) to estimate coefficients for all paths.

A



B

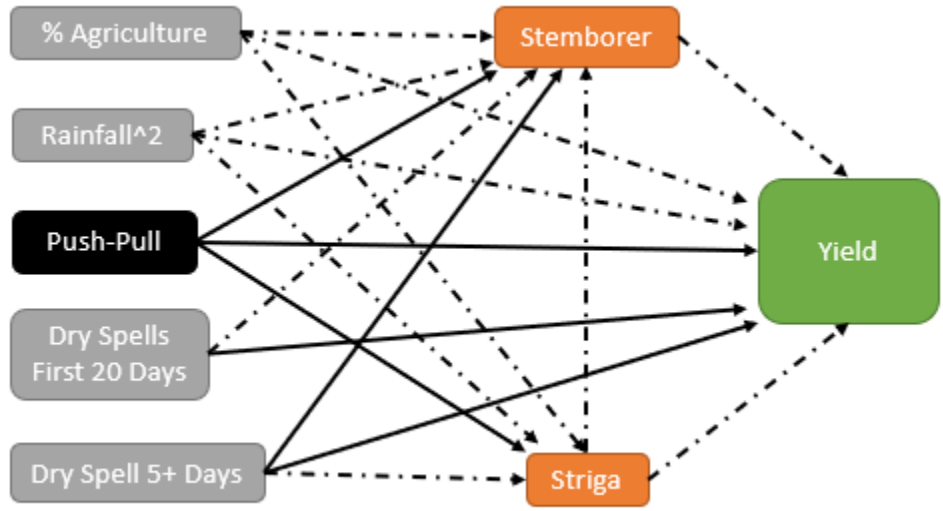


Figure 3. Initial directed acyclic graphs for structural equations modeling of how weather and landscape variables alone, and in interaction with the push-pull system, affect stemborer

abundance, striga abundance and yield in the short rains (A) and long rains (B). Solid lines indicate hypothesized main effects, while dashed lines indicate hypothesized interaction effects with local management (push-pull or control). The direct effect of push-pull on striga, stemborers, and yield is well-documented. Stemborers have also been found to prefer striga-infested fields in some studies. The interaction between landscape complexity and push-pull was included for pests and yield, as one of our main questions is whether any effects of push-pull are landscape context-dependent. Weather variables, including which were included as potential interaction effects with push-pull, were chosen based on the results of a *dredge* analysis as indicated above.

Results

While some paths were not significant, the hypothesized SEM model was supported by the data for the long rains growing season (Chi square = 1.55, df = 1, $p = 0.21$). In the short rains, our best SEM model as suggested by dredge and by testing different directed acyclic graphs (DAGs) was fully saturated (Chi square = 0, df = 0, p = 1). All DAGs in the short rains which removed at least one variable rejected the null hypothesis, and thus performed worse than this model.

In the short rains, stemborer abundance was higher with longer dry spells in the first 20 days of the season in control fields, but stemborer abundance was always low in push-pull fields regardless of the length of the longest early dry spell (z = -2.40, df = 59, p = 0.016; Fig. 4D).

Striga abundance in control fields was lower with increasing number of dry spells lasting at least five days (z = 2.39, df = 59, p = 0.017; Fig. 4F) and longer dry spells early in the season (z =

3.84, df = 59, $p < 0.001$; Fig. 4G), but in push-pull fields striga numbers were consistently low and insensitive to weather variables. Striga was more abundant in control fields with more surrounding agricultural land, but consistently low in push-pull fields regardless of landscape context ($z = -2.38$, df = 59, $p < 0.01$; Fig. 4E).

Yield decreased with striga in the push-pull, while the reverse was observed in the control fields ($z = -2.45$, df = 59, $p = 0.0142$; Fig. 4C). However, the maximum striga counts observed were an order of magnitude lower in push-pull fields than in control fields. Yield decreased with increasing percentage of agriculture in the surrounding landscape in the push-pull fields only, while it was stable, though overall much lower in the control fields ($z = -2.00$, df = 59, $p = 0.045$; Fig. 4B)

During the long rains, stemborers were more abundant when there was a longer dry spell early in the season, but this effect was much stronger for control fields than push-pull fields ($z = -3.84$, df = 179, $p < 0.001$; Fig. 5E). Stemborer abundance was highest at intermediate levels of rainfall, an effect which was stronger in control fields than push-pull fields ($z = 3.06$, df = 179, $p < 0.01$; Fig. 5H). Local management and landscape context statistically interacted in predicting stemborer abundances, but the biological implications of this effect are weak or difficult to interpret ($z = 2.12$, df = 179, $p = 0.03$; Fig. 5G).

Striga was more abundant in fields with more dry spells lasting at least five days, and this effect was slightly stronger for push-pull fields (although push-pull fields still had much lower striga overall) ($z = 3.91$, df = 179, $p < 0.001$; Fig. 5F). Striga abundance was higher at sites with more

surrounding agriculture ($z = 2.07$, $df = 179$, $p = 0.038$), and reduced by push-pull ($z = -21.57$, $df = 179$, $p < 0.001$).

Yield was increased by the push-pull treatment ($z = 10.13$, $df = 179$, $p < 0.001$), and lower when there were more dry spells lasting five days or longer ($z = -4.85$, $df= 179$, $p < 0.001$). Yield was highest in push-pull fields with intermediate levels of rainfall, while yield in control fields did not vary with rainfall ($z = -3.83$, $df = 179$, $p < 0.001$; Fig 5I). Yield was negatively impacted by stemborers ($z = 2.23$, $df = 179$, $p = 0.026$; Fig. 5C) and striga ($z = -5.32$, $df = 179$, $p < 0.001$; Fig. 5D) in both push-pull and control fields, although the interaction effect was significant and the slopes differed. Yield in the long rains was slightly lower in push-pull fields surrounded by more agriculture, while yield in control fields was relatively insensitive to landscape context ($z = -2.784$, $df = 179$, $p < 0.01$; Fig. 5B).

In several cases, the interaction between push-pull and a weather variable was significant because push-pull fields had almost no pests at all. While many weather effects were similar between both short and long rains, striga abundance was lower in control fields with more dry spells of at least five days during the short rains, and higher in control fields with more dry spells of at least five days in the long rains.

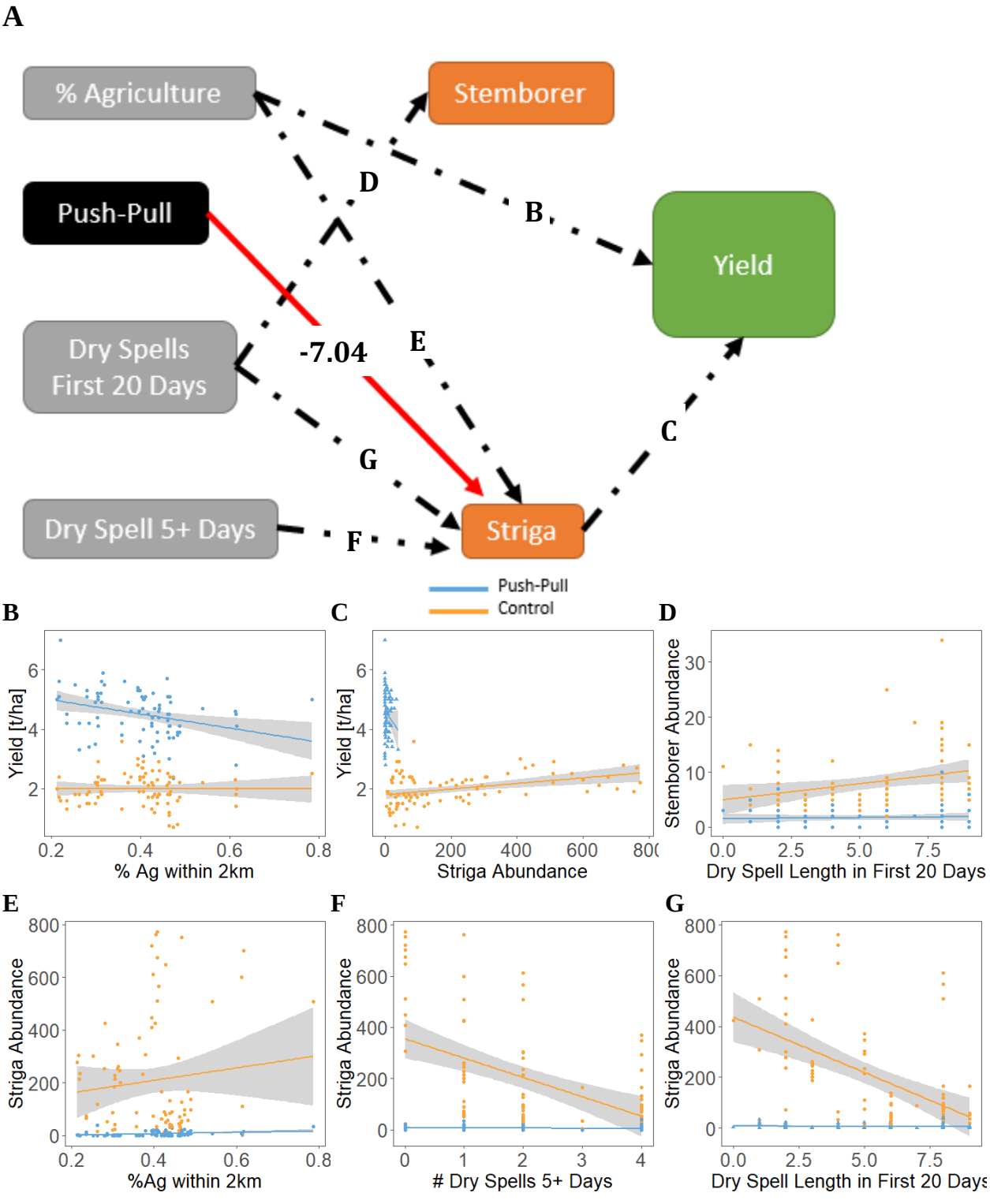
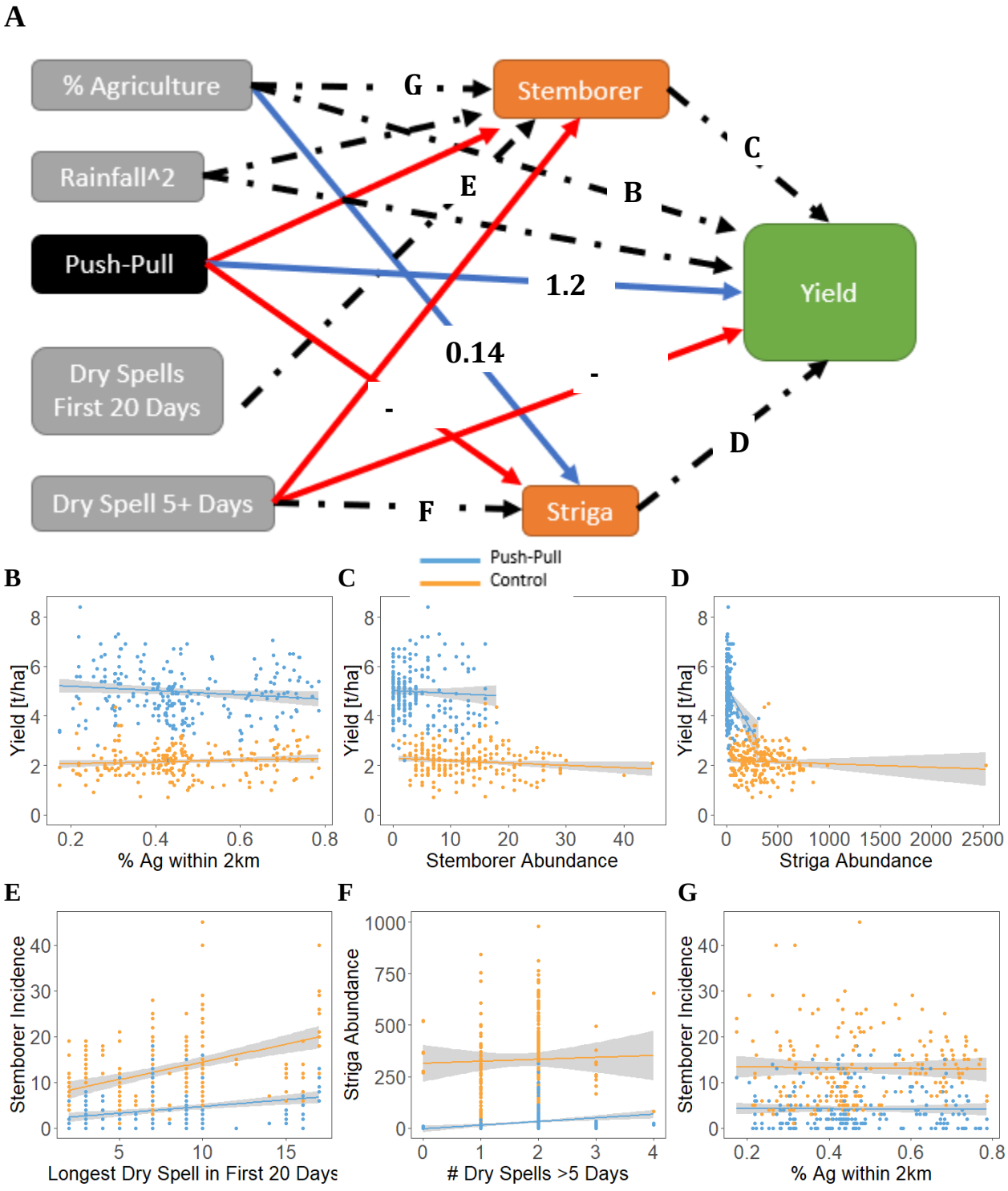


Figure 4 (A) Results from a structural equation model for the short rains season. The red arrow indicates a significant negative effect, and black dashed arrows indicate a significant interaction

of a given factor with the push-pull treatment. Letters in the arrows are related to the panels below indicating the nature of the interaction. All paths related to rainfall were non-significant in the short rains, so rainfall has been excluded from this DAG for simplicity's sake. For (B)-(G), lines denote significant effects with shaded lines denoting 95% confidence intervals. (B) Push-pull fields surrounded by a greater percentage of agricultural land have lower yields than push-pull fields surrounded by less agricultural land, while control fields do not seem to show a response to landscape context. (C) Yield declined with increased striga abundance in push-pull fields, although maximum striga abundance in push-pull fields was much lower than in control fields. Unexpectedly, yield increased with higher striga abundance in control fields. (D) Stemborer abundance increased in control fields when the longest dry spell in the first 20 days of the growing season was longer, but stemborer abundance was consistently low in push-pull fields regardless of dry spell length. (E) Striga abundance increased in control fields with increasing surrounding agriculture, but was consistently low in push-pull fields. (F) Striga abundance was lower in control fields when there were more dry spells lasting at least five days, but consistently low in push-pull fields. (G) Striga abundance was lower in control fields when the longest dry spell within the first 20 days of the growing season was longer, but consistently low in push-pull fields.


A
% Agriculture
Rainfall^2
Push-Pull
Dry Spells First 20 Days
Dry Spell 5+ Days
Stemborer
Striga
Yield
G
E
B
C
1.2
0.14
-
-
D
F
Push-Pull
Control
B
Yield [t/ha]
% Ag within 2km
C
Yield [t/ha]
Stemborer Abundance
D
Yield [t/ha]
Striga Abundance
E
Stemborer Incidence
Longest Dry Spell in First 20 Days
F
Striga Abundance
Dry Spells >5 Days
G
Stemborer Incidence
% Ag within 2km

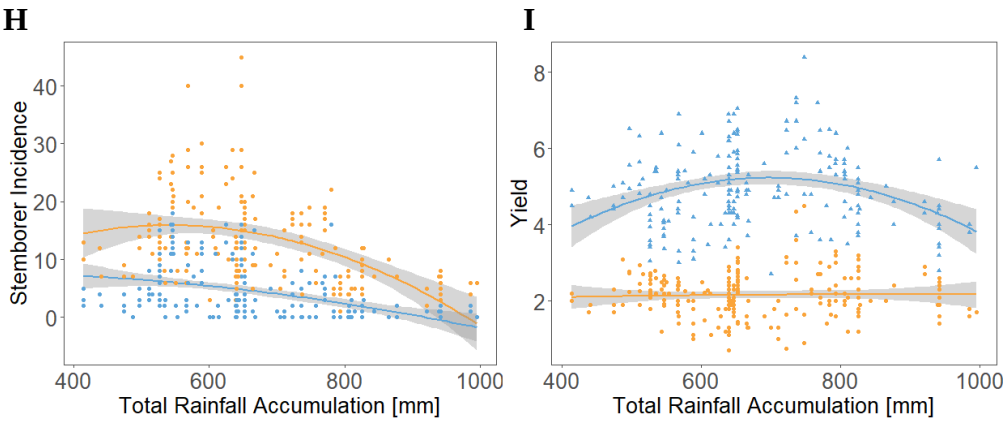


Figure 5. (A) Significant results from the path analysis for the long rains season. Red arrows indicate a significant negative effect, blue arrows indicate a significant positive effect, and black dashed arrows indicate a significant effect as an interaction with the push-pull treatment. (B) Push-pull fields had slightly lower yields when surrounded by more agricultural land, while control fields had slightly higher yields when surrounded by more agricultural land. Neither of these trends were significant on their own. (C) Both push-pull and control fields had lower yield when more stemborers were present, although the maximum stemborer abundance in push-pull fields was much lower. (D) Both push-pull and control fields had lower yield when more striga was present. Push-pull responded more strongly as striga numbers increased, but also had much lower average and maximum striga abundance. (E) Stemborers were more abundant when the longest dry spell within the first 20 days of the growing season was longer, although they responded even more strongly in control fields than push-pull fields. (F) Striga was more abundant in push-pull fields in growing seasons with more dry spells lasting at least five days. Control fields showed a weak trend in the same direction. (G) Our model indicated that stemborer incidence responded to an interaction between field management and surrounding landscape, however, it is not clear what is driving this statistical result. (H) Stemborers were most abundant at intermediate levels of rainfall, and this effect was stronger in control fields. (I)

Yield was highest at push-pull fields in intermediate levels of rainfall, while control fields did not respond to rainfall.

Discussion

The aim of our study was to examine the robustness of ecologically intensified farms across landscape and weather gradients. Based on theory and previous research, we expected push-pull fields to consistently outperform control fields, regardless of landscape context or weather. We also expected that pest pressure would be higher, and yield lower, on control fields surrounded by more agricultural area, but that this effect would be weaker in push-pull fields.

We found that pest responses varied significantly between the short and long rains, but that pest abundance in push-pull was consistently low regardless of season, weather, or landscape context (see also Midega et al., 2015; Njeru et al., 2020). Striga abundance was higher in fields surrounded by a higher percentage of agriculture within 2km (for control fields in the short rains, and all fields in the long rains), which could be due to spillover between agricultural fields. These results align with work on a related species, *Striga asiatica*: within-field density of *Striga asiatica* correlates with the density of neighboring agricultural fields (Scott et al., 2020). Striga is a very common weed of cereal crops, and a good disperser given the large number of seeds and small seed size (Runo and Kuria, 2018), so fields surrounded by a higher percentage of agriculture are likely exposed to a larger striga propagule pressure.

Higher striga abundance had a slightly positive correlation with yield in control fields in the short rains, which is surprising especially given that striga is generally associated with low soil fertility (Samaké et al., 2005; Teka, 2014). While our models assume unidirectionality (striga abundance influences yield, but yield cannot influence striga abundance), this assumption does not fully capture the relationship between pests and crop yield, particularly for a parasitic plant.

It may be that in the short rains of 2015 and 2016, fields with especially poor yields were also poor hosts for striga, driving this relationship.

Stemborers negatively affected yield in the long rains, but did not seem to affect yield in the short rains season, at least for 2015-2016. Kebede et al. (2018) also found that stemborer infestation did not significantly impact yield, suggesting that stemborers are only a major yield constraint under certain conditions.

We found that push-pull was slightly less effective compared to control fields when surrounded by more agricultural area, but that push-pull consistently outperformed control fields by a large margin across our entire landscape gradient. Our results contrast with those of Kebede et al. (2018), who found that landscape effects on yield overrode the effect of push-pull. The benefits of push-pull become stronger with time since establishment (Luttermoser et al. 2023), so this may be due to the difference between established farmer fields and the newly planted experimental plots in Kebede et al.

Our results support the idea that ecologically intensified systems are likely to be robust with regards to weather conditions, perhaps barring extreme drought (all fields in Bondo in Long Rains 2016 had zero yield, regardless of whether push-pull or control). Even where weather conditions did affect yield, push-pull fields consistently fared better than control fields. Our results reinforce other studies which have found that push-pull is likely to remain effective under changing weather conditions (Gugissa et al., 2022; Ndayisaba et al., 2022), as well as results from other ecologically intensified systems (Kremen, 2020; Lotter et al., 2003; Pimentel et al.,

2005).

While previous studies have found ecologically intensified systems to be more effective in landscapes with a higher proportion of agriculture (to a point) (Batáry et al., 2011; Tscharntke et al., 2012, but see Karp et al. 2018), we found that push-pull performed best in landscapes with the least surrounding agriculture. However, in many cases the slopes of our results were shallow, and may not be truly biologically significant. Many previous analyses of the interaction between landscape and local management have focused on the degree to which beneficial arthropods colonize habitat created for them, and thus the degree to which local management change succeeds in increasing ecosystem services provided by beneficials to the crop (Tscharntke et al. 2012). In push-pull the most significant biological control effect is driven by the companion crops directly, and so the pest suppressive effects of this system may be inherently less dependent on the landscape context than many other ecological intensification systems. It is also worth noting that what is a "simple" or "complex" landscape is itself context-dependent. In our system, smallholder farmers maintain very small fields and, for the most part, do not use chemical insecticides or herbicides. There are significant patches of weedy native plants in between and adjacent to fields, and woody hedgerows often separate different farmers' properties. Even in heavily agricultural landscapes in our dataset, there is likely a high degree of plant diversity compared to an agriculturally dominated landscape in North America or Western Europe (particularly for maize fields).

While this study is not explicitly predictive in terms of land use change or climate change, the results suggest that effective ecologically intensified systems may continue to be robust against

future land use and climate changes, as suggested by Luttermoser et al. (2023), at least in the absence of severe drought. Across a wide gradient of land use and weather conditions, the push-pull system reduced pest abundance and significantly increased yield, with the average yield still being roughly double that of control fields even at push-pull's lowest. It will be important to examine how the push-pull system (and other ecologically intensified systems) perform under pressure from new invasive pests, such as fall armyworm (Cheruiyot et al., 2021). Further studies may be able to examine how different types of natural and semi-natural terrain (e.g. woods vs grassland) interact with push-pull, as well as looking at how push-pull interacts with varying temperatures in addition to precipitation.

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Egg predation and herbivore damage vary with landscape context and local management in the Kenyan push-pull maize system

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Abstract

Ecological intensification is a set of ideas and practices for managing biodiversity on and around farms to reduce negative impacts of agricultural management while maintaining or improving yield. Ecologically intensified systems often enhance local plant diversity, sometimes to attract beneficial arthropods such as pollinators and natural enemies of pests. However, the relationship between local management practices and beneficial arthropods can be context-dependent, particularly depending on the diversity of the surrounding landscape. Ecological intensification often enhances beneficial arthropods most effectively in landscapes with relatively little natural land cover nearby. We examined egg predation of fall armyworm (*Spodoptera frugiperda*) in the push-pull maize system in Western Kenya, and tested whether egg predation and herbivore damage were affected by local management (push-pull vs. control), landscape context (% natural area within 1km), and the interaction between the two. We found that push-pull enhanced egg predation earlier in the growing season. Later in the season, the relationship was context-dependent, with push-pull fields having lower egg predation than control fields in landscapes with more natural area nearby. We also found that herbivore damage by both fall armyworm and other Lepidoptera pests was generally reduced by push-pull, and higher in all fields when surrounded by more natural area. While these results suggest that more natural area surrounding a farm may provide ecological disservices in this region, we caution that biological control and

foliar damage both have inconsistent relationships with yield, which we did not measure in this study. We show that beneficial arthropods may respond to ecologically intensified systems that were not initially designed with beneficial arthropods in mind, and that these responses may be context-dependent on both time and surrounding landscape context.

Introduction

Diversity's role in promoting necessary ecosystem services is increasingly recognized, particularly in agriculture (Isaacs et al., 2009; Isbell et al., 2017; Knoke et al., 2016). Many studies have focused on the ecosystem services of pollination and pest management in crop fields, services which are often provided by beneficial arthropods (Egan et al., 2020; Holland et al., 2017; Jonsson et al., 2008). On-farm practices which increase resource diversity, such as flower strips and hedgerows, have been shown to increase beneficial arthropod diversity and abundance (Buhk et al., 2018; Haaland et al., 2011). These practices generally involve deliberate manipulations to increase plant diversity near a crop field, with the goal of attracting or boosting beneficial arthropod populations who will then perform ecosystem services within the field itself. Most of these studies have been focused in European and North American systems, but recent work from the tropics (sometimes utilizing pre-existing gradients of plant diversity) have found similar results (Arnold et al., 2021; Daghela Bisseleua et al., 2013; Tiwari et al., 2020).

The benefits of increasing local diversity in agroecosystems may be dependent on the surrounding landscape. The intermediate landscape-complexity hypothesis suggests that farms with an intermediate level of surrounding non-crop land cover should benefit most from increasing local diversity, especially for practices with a goal of increasing ecosystem services

provided by beneficial arthropods (Tscharntke et al., 2012). Some studies have found this pattern, with strong benefits of local management in landscapes of intermediate complexity, and weaker benefits in both very diverse and very simplified landscapes (Grab et al., 2018; Wilson et al., 2017). However, truly "cleared" landscapes are extremely rare, so this hypothesis is often simplified in practice: the effects of local diversity management, with regards to beneficial arthropods, are expected to be strongest in landscapes with a greater proportion of agriculture and weaker in more diverse landscapes. In very diverse landscapes, additional resources (floral nectar, alternative prey, etc.) may simply be unneeded, while in more agricultural landscapes, local populations of beneficial arthropods are likely to benefit from additional resources (Tscharntke et al., 2012). A meta-analysis by Batáry et al. (2011) largely supports this simplified form of the intermediate landscape hypothesis, showing that on-farm diversification practices increased abundance and richness of arthropods generally and pollinators specifically in simplified landscapes, but not in more complex ones (Batáry et al., 2011).

While there are many studies examining the intermediate landscape hypothesis, most focus on local diversity management which was explicitly designed with beneficial arthropods in mind. We were curious if we would be able to find similar patterns in an agroecological system which increases local plant diversity, but was not (initially) designed to attract beneficial arthropods to the field. Therefore, we performed a study in the push-pull agroecosystem in western Kenya. Established in the 1990s by the International Centre for Insect Physiology and Ecology (ICIPE), the push-pull system utilizes intercropping and companion cropping to control pest damage and increase yields in smallholder fields, primarily maize (Khan et al., 2008). Although first established to control the stemborers *Busseola fusca* and *Chilo partellus*, push-pull has been

shown to also be effective at reducing damage and maintaining high yield during the recent global invasion of fall armyworm (*Spodoptera frugiperda*) (Midega et al., 2018b; Yeboah et al., 2021). While many of the benefits of push-pull arise from the chemical ecology of the companion plants and their effects on pest behavior, there is also evidence that push-pull can increase local predator abundance and parasitoid activity compared to control fields (Midega et al., 2009, 2006).

Following the intermediate landscape complexity hypothesis, we predict that push-pull fields will have higher rates of biological control, as measured by egg predation of *S. frugiperda* eggs, compared to control fields, and that this effect will be stronger in push-pull fields in more simplified landscapes. We also predict that foliar damage by fall armyworm and stemborers will be lower in push-pull fields, and that this effect will be stronger in push-pull fields in more simplified landscapes.

Methods

Field Sites

Our study was performed between May 16 and June 27 in 2018, in Western Kenya. Our sites consisted of 19 farms that contained both push-pull and non-push-pull fields, each farm maintained by one subsistence farmer (Fig. 1). We selected farms along a landscape gradient that ranged from 2.9% to 25.3% natural and semi-natural area within a 1km radius (mean 10.4% ± 6.5%) Our sites were on average 3472m apart, with a minimum of 2000m from all other sites used in the study. The only exception were two farms, which were approximately 400m apart from each other and at least 2km from all other farms. Maize was planted on the farms in late

March or early April.

To determine the percentage natural and seminatural area around each farm, we used satellite imagery from 2017 and 2018 obtained from Google Earth (Google Earth, 2019). With the use of QGIS (QGIS Development Team 2019) we manually categorized the amount of natural and semi-natural land cover within 1km of each farm. Natural and semi-natural land cover was distinguished by color (typically darker green), texture (coarse), and shape (often more irregular than agriculture), and could include both wooded areas and natural grasslands.

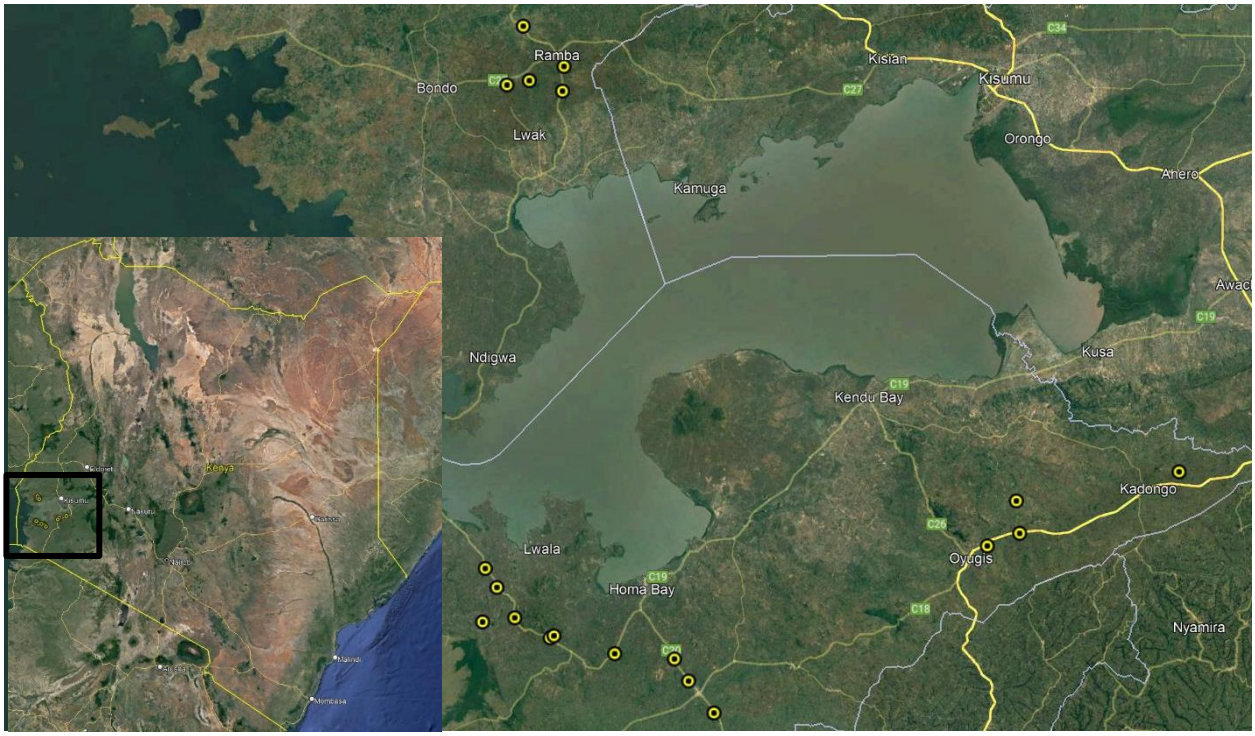

Figure 1. Southwestern Kenya, with our sites highlighted as yellow circles. (Inset) Kenya, with a black rectangle roughly designating the region of the larger map.

Egg Predation Assay

To quantify egg predation we surveyed sentinel fall armyworm eggs placed in the field twice, in May and in June 2018. During our first survey period, the maize was mostly at the tasseling stage (early ear development was present at three farms). During our second survey period, all farms had ears developing. Thus, we will hereafter refer to our sampling periods as during the tasseling and reproductive stages, respectively. For each farm, there was a minimum of 14 days in between sampling dates. On each sampling date, we placed five fall armyworm sentinel egg clutches each in a push-pull and non-push-pull (hereafter "control") field at each farm. Clutches were sourced from a fall armyworm colony maintained by ICIPE, and were deployed in the field less than 36 hours after oviposition. The clutches were oviposited by females onto parchment paper, which was cut to size to contain approximately 50 eggs (mean ± 1SE; 47.4 ± 9.7 eggs per clutch). Eggs were chilled in a refrigerator overnight to reduce the risk of larvae hatching in the field, after confirming that chilling for up to 12 hours did not negatively impact hatch rates. Four clutches were placed on maize plants near the four corners of a field, at least three plants away from the edges of the field. The fifth clutch was attached to a plant near the center of the field. All clutches were placed on the underside of a leaf near the midrib to keep clutch position standardized and similar to what we found in the field. Clutches were only placed on undamaged, green leaves, starting with the second fully extended leaf from the top if that leaf met these criteria. We collected all clutches 24 hours after deployment, transported them to the lab in individual labeled diet cups, and counted the number of eggs remaining.

Parasitoids of fall armyworm (*Chelonus* sp.) were known to be present in the region from our own previous field work. We attempted to measure the rate of parasitoid attack on our egg

clutches by rearing larvae from the egg clutches to pupation. However, we did not recover parasitoids from any clutch, so our results will not discuss this further. We may have failed to find parasitoids because the eggs were out for a short interval and because they were on paper rather directly than on the plant, likely making them less attractive to the parasitoids.

Plant Measurements

To examine the effect of the push-pull system on leaf-feeding lepidopteran damage, we measured ten plants in each field. For each plant, we measured fall armyworm and stemborer damage. Damage was estimated by total percent of leaf area damaged, using damage categories of 0-5%, 5-25%, 25-50%, 50-80%, and 80-100%.

Statistical Analyses

Data were analyzed using mixed linear models in R using the package *glmmTMB* (R Core Team 2018, Brooks et al. 2017). Preliminary analysis revealed that our two sampling periods differed significantly, so we performed all analyses separately for each time period. We tested for spatial autocorrelation for all models by testing the significance of Moran's I with the *moranfast* package (Cooper 2020). All models had non-significant spatial autocorrelation ($p > 0.05$).

Egg predation was analyzed using the binomial of (eggs remaining, eggs removed) as a dependent variable. Plant damage for both fall armyworm and stemborers was analyzed by taking the mean of each damage category (e.g. 37.5% for the 25-50% category), and then taking the mean of plant damage for a given field across all ten plants. For all egg predation and plant damage models, we used the same predictor variables of field treatment (push-pull or control),

the percentage of natural land cover within 1km, and the interaction between treatment and natural area, with farmer identity as a random factor.

Results

On average, roughly half of all eggs were removed from a clutch (mean proportion 0.48 ± 0.34, range 0-1). This was higher in push-pull fields than in control fields in both time periods. During maize tasseling, push-pull management was the only significant predictor of egg removal ($z(17) = 4.422$, $p < 0.001$) (Table 1, Fig. 2). During the reproductive stage, there was an interaction between local management (push-pull or control) and surrounding natural area ($z(17) = -11.974$, $p < 0.001$). At sites with less surrounding natural area, push-pull fields had higher egg predation, while control fields had higher egg predation at sites with more surrounding natural area. An increase in the amount of (semi-) natural area also led to a decrease in the removal of eggs in push pull fields, while in control fields, the tendency was that as the percentage of (semi) natural habitats increased, egg removal also increased (Table 1, Fig. 3).

Herbivore damage was lower in push-pull fields than control fields and higher in fields surrounded by more natural area, with no significant interaction effect between local management and landscape context, for fall armyworm during both maize tasseling and ear development and for stemborers during maize tasseling (Table 2, Fig 4. A, B & C). Both fall armyworm and stemborer damage were higher during the tasseling stage (Fig. 4 A & C) than the reproductive stage (Fig. 4 B & D). During the reproductive stage, stemborer damage was influenced by a significant interaction effect between push-pull management and landscape composition ($z(17) = -1.993$, $p = 0.046$). Push-pull fields had slightly more stemborer damage

than control fields at sites with very little surrounding natural area, while at sites with more natural area, push-pull and control fields had similar levels of stemborer damage (Fig. 4D).

Table 1. Model summary statistics for the effect of local management treatment (control vs. push-pull), the percentage of natural area, and their interaction on sentinel egg removal. Estimates and z-values for the treatment are for the effect of the push-pull treatment.

Dependent	Predictor	Estimate	df	z-value	p-value
Eggs Removed (Tasseling)	Intercept	-0.332	17	-1.360	-
	Treatment	0.402	17	4.422	< 0.001 *
	Natural Area	-3.376	17	-1.673	0.094
	Treatment*Natural Area	-0.130	17	0.162	0.871
Eggs Removed (Reproductive)	Intercept	0.229	17	0.688	-
	Treatment	0.805	17	9.036	< 0.001*
	Natural Area	1.166	17	0.429	0.668
	Treatment*Natural Area	-8.646	17	-11.974	< 0.001*

Table 2. Model summary statistics for the effect of local plant management (control vs. push-pull), the percentage of natural area, and their interaction on plant damage. Estimates and z-values for the treatment are for the effect of the push-pull treatment.

Dependent	Predictor	Estimate	Df	z-value	p-value
Armyworm Damage (Tasseling)	Intercept	4.852	17	1.750	-
	Treatment	-6.278	17	-3.812	< 0.001 *
	Natural Area	60.354	17	2.636	< 0.01 *
	Treatment*Natural Area	-20.454	17	-1.465	0.14
Armyworm Damage (Reproductive)	Intercept	3.037	17	2.112	-
	Treatment	-4.061	17	-5.230	< 0.001 *
	Natural Area	36.161	17	2.232	0.026 *
	Treatment*Natural Area	1.427	17	0.226	0.821
Stemborer Damage (Tasseling)	Intercept	-0.095	17	-0.078	-
	Treatment	-1.813	17	-3.535	< 0.001 *
	Natural Area	39.249	17	3.888	< 0.001 *
	Treatment*Natural Area	-6.355	17	-1.461	0.144
Stemborer Damage (Reproductive)	Intercept	1.206	17	2.514	-
	Treatment	0.802	17	3.260	0.001 *
	Natural Area	-2.134	17	-0.546	0.585
	Treatment*Natural Area	-3.983	17	-1.993	0.046 *

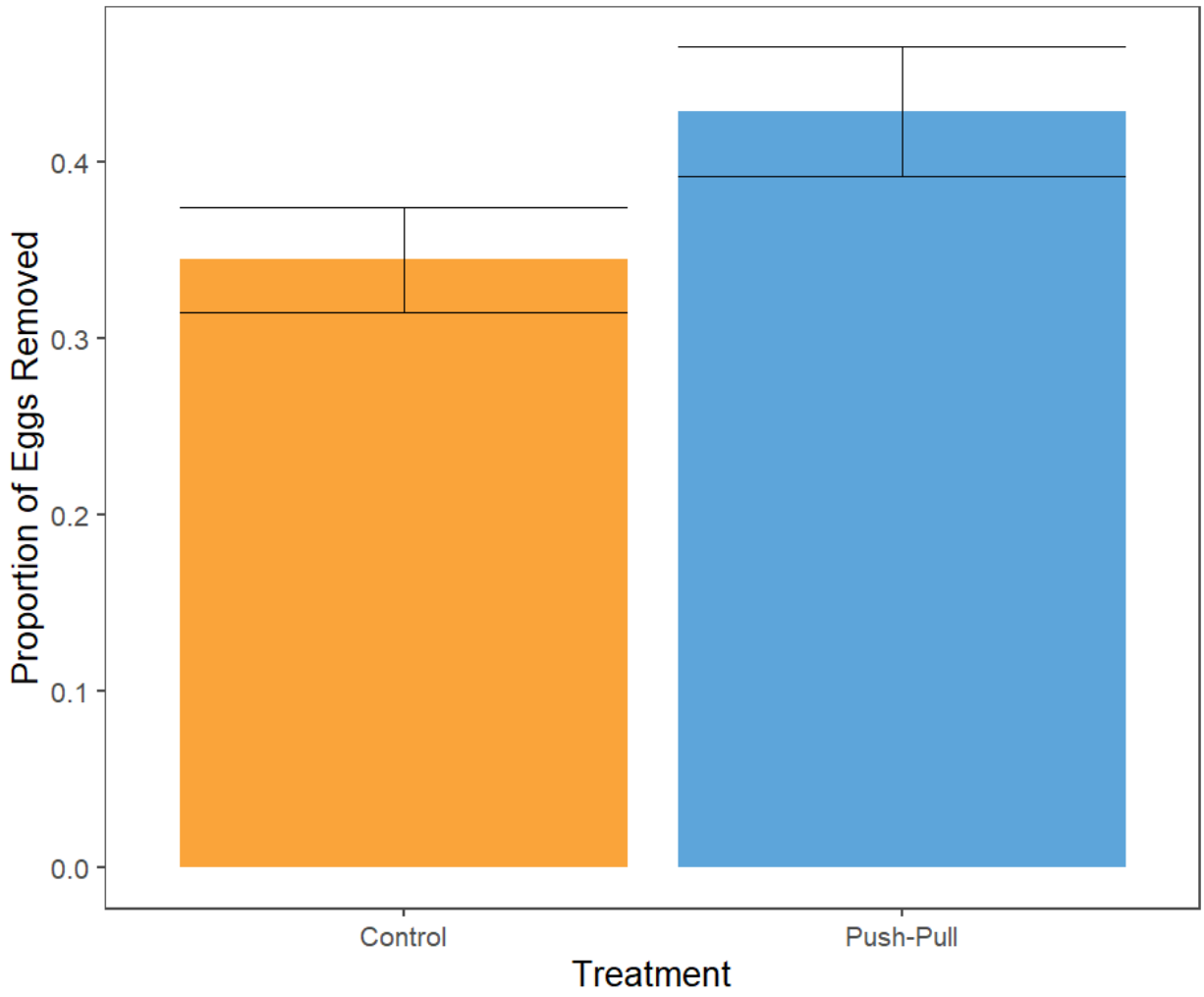

Figure 2. The proportion of eggs removed from maize plants during tasseling in 19 farms with paired push-pull and control fields. More eggs were removed on average in push-pull fields (0.43 ± 0.04) than control fields (0.34 ± 0.03) ($z(17) = 2.547$, $p = 0.011$).

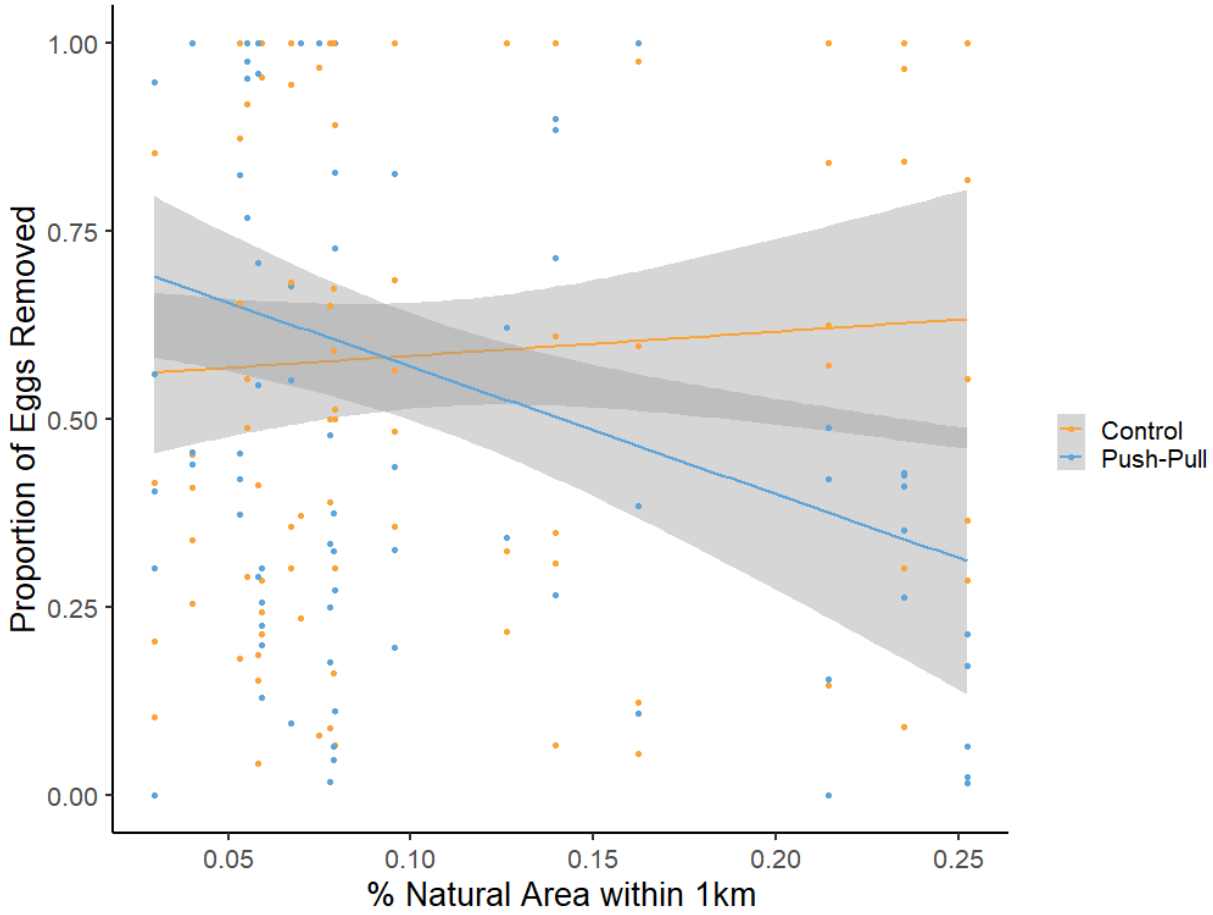

Figure 3. Proportion of eggs removed from maize plants during the reproductive stage in farms along a gradient of landscape composition (percentage of natural area within a 1 Km radius around the farm). There is a significant interaction between the landscape composition gradient and the local management practices. ($z(17) = 11.97$, $p < 0.001$). Shadowed areas indicate a 95% confidence index around the regression line.

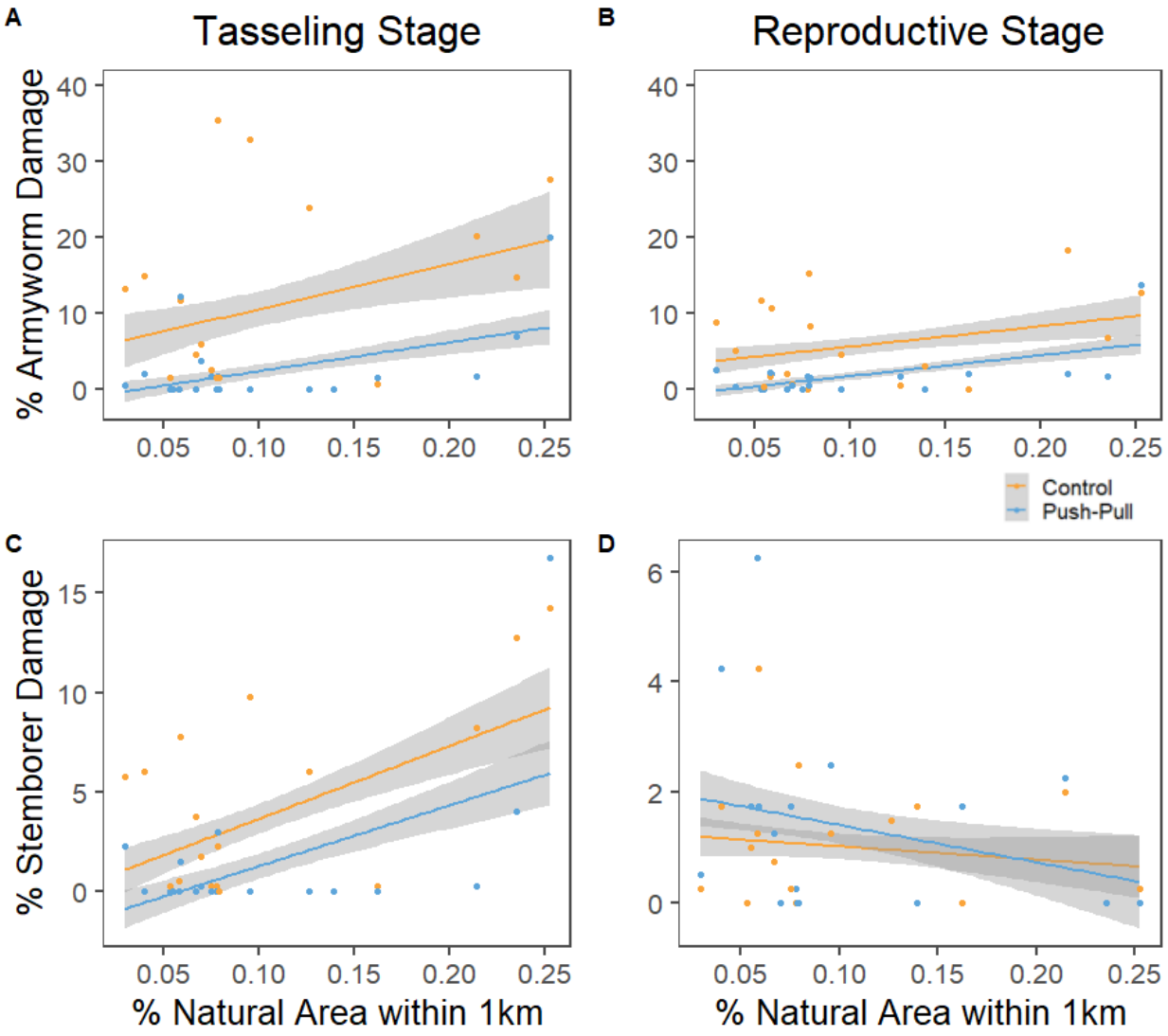

Figure 4. Percentage of herbivore damage by fall armyworm (A & B) and stemborers (C & D) of maize plants during maize tasseling (A & C) and reproductive development (B & D). Shadowed area indicate a 95% confidence index around the regression line. Damage was lower in push-pull fields and higher in fields surrounded by more natural area for both pests in the tasseling stage and for fall armyworm in the reproductive stage. (D) During the reproductive stage, stemborer damage was higher in push-pull fields with very little natural area nearby, but roughly equal between push-pull and control in landscapes with more surrounding natural area ($z(17) = -1.99$, $p = 0.04$). However, stemborer damage was low across all fields, and especially

low during the reproductive stage, so this interaction may not be biologically significant.

Discussion

We found that biological control services as measured by predation of sentinel fall armyworm eggs were usually higher in push-pull fields than control fields, but that this varied with landscape context and timing. During the tasseling stage, local management was the only predictor of egg predation. As maize ears were developing, push-pull fields had higher egg predation in landscapes with less surrounding natural area and lower egg predation in fields surrounded by more natural area, while control fields showed the opposite pattern (albeit with a weaker slope). Biological control at different stages may be important in different ways – in maize fall armyworm causes foliar damage when plants are young, and also directly attacks ears as plants enter the reproductive stage. The effect of push-pull management on egg predation did indeed vary with the surrounding landscape, but not in a way that matched our initial prediction.

Our results highlight the context-dependence of ecosystem services, even within the same fields in the same growing season (Reiss and Drinkwater, 2020; Tamburini et al., 2019). Unlike ecological intensification techniques which were specifically designed to amplify the effects of beneficial arthropods (such as flowering strips and hedgerows), push-pull was primarily designed to amplify benefits associated with the companion crops themselves. It is possible that rather than predators viewing push-pull as an attractive habitat due to plant diversity, push-pull is less attractive due to the lower density of prey (at least later in the season). Predator responses to agricultural pests are often density-dependent (Miksanek and Heimpel, 2020; Rao et al., 2021), and if push-pull reduces pest populations so thoroughly that predators rarely find prey in push-

pull fields, they may prefer to forage in control fields – at least some of the time. We observed lower herbivore damage during the reproductive stage than the tasseling stage across all fields, which likely means that prey densities were lower later in the season – further incentivizing predators to focus their attention on control plots where prey should be more abundant.

Pest responses to surrounding landscape are known to be inconsistent and highly context-dependent (Karp et al., 2018) – while many studies have found lower pest abundance and/or herbivory in fields surrounded by more natural habitat, others have found the opposite pattern (Letourneau and Goldstein, 2001; Zaller et al., 2008). Pests which can utilize resources in natural habitat may be expected to benefit from surrounding natural habitat. While fall armyworm generally prefers cereal grains, it is an extreme generalist able to feed on a wide range of plants (Montezano et al., 2018). *Busseola fusca* and *Chilo partellus* are known to utilize native grasses in the landscape, in addition to crop plants (Calatayud et al., 2014; Haile and Hofsvang, 2002; Mohamed et al., 2004). All three of these pests are likely to move back and forth between agricultural fields and wild plants in the surrounding area, so it is not surprising that herbivore damage was consistently higher on fields surrounded by more natural area. It is worth noting that while we found increasing fall armyworm damage with greater landscape complexity, plant damage does not always correlate clearly with yield (Overton et al., 2021). Future studies in the push-pull system should more explicitly link biological control by beneficial arthropods to yield outcomes.

Overall, stemborer damage was low, likely due to the dominance of fall armyworm (Mutyambai et al., 2022; but see Sokame et al., 2020). Our study took place shortly after fall armyworm's

initial invasion, more recent work has shown stemborers being displaced to alternative food sources like sorghum and also continuing to coexist with fall armyworm within maize fields (Mutyambai et al. 2022, Sokame et al. 2020). Thus, while fall armyworm is now a major driver of crop loss in Kenya (De Groote et al., 2020; Omwoyo et al., 2022), stemborers will continue to be an important crop pest in the region as well.

Our results show that ecological services such as biological control can be influenced by ecologically intensified systems, even when the intensification was not designed to target beneficial arthropods. Furthermore, we show that these effects can be context-dependent depending on timing and the surrounding landscape. The pattern we observed did not fit the prediction of the intermediate landscape complexity hypothesis, likely because the plants used in the push-pull system affect pest density directly, and changes in pest density affected predator behavior. Ecologically intensified systems may affect pest density through a variety of mechanisms, which may in some cases predict contrary outcomes to each other. Future work focusing on pest density in such systems, both those explicitly designed to magnify beneficial arthropods and those not so designed, may be important for optimizing our practices of ecological intensification.

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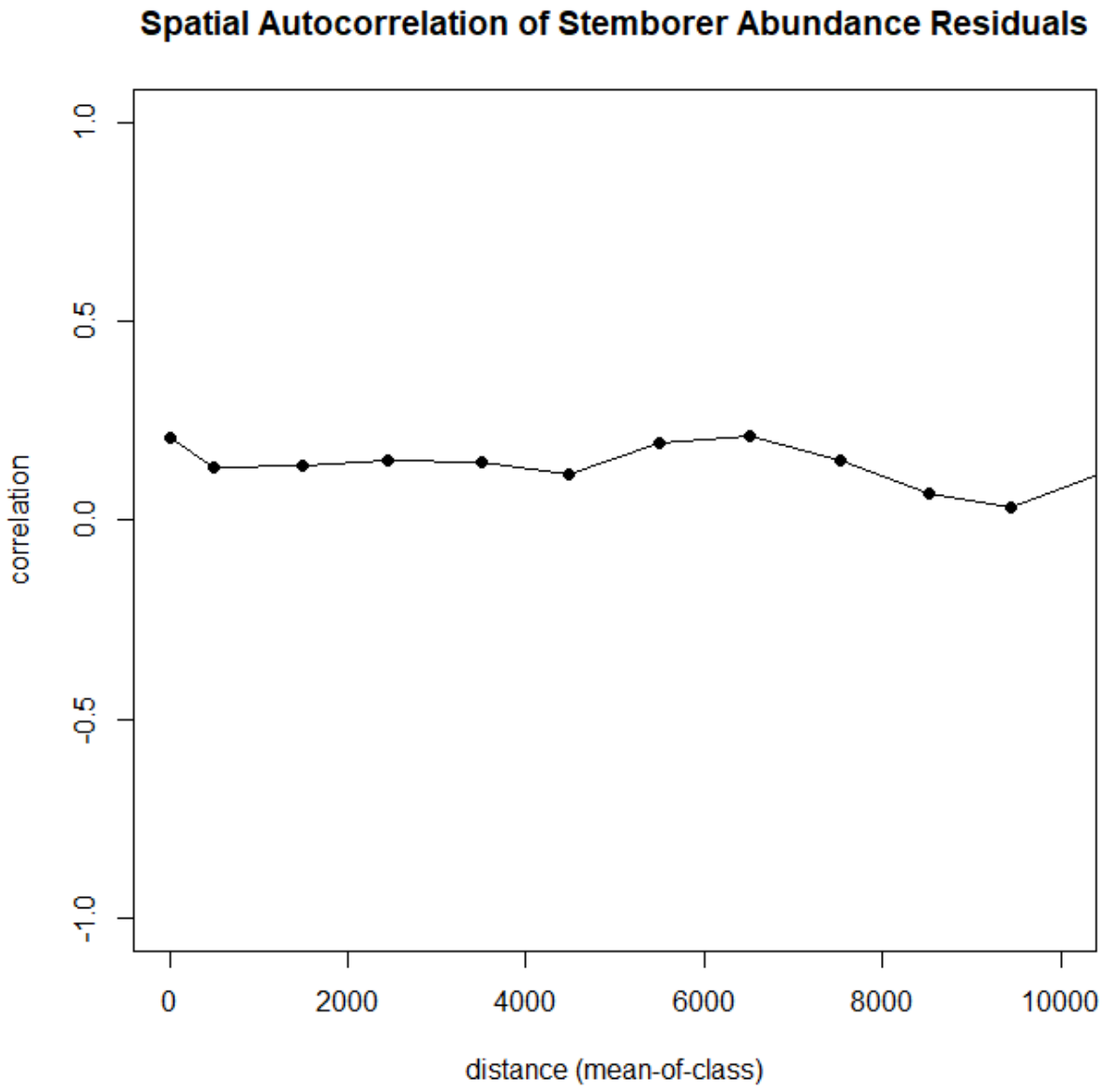
Appendix A – analyses of spatial autocorrelation

To determine whether spatial autocorrelation is present in our results, we calculated Moran's I for a set of distance classes and constructed empirical correlograms to visualize spatial autocorrelation across the model results. When interpreting a correlogram, the presence of a distinct trend in the calculated Moran's I indicates the presence of spatial autocorrelation. If there is no strong trend seen in the correlogram, we can assume that there is no strong spatial autocorrelation effect present within the data (Legendre and Fortin, 1989). We constructed empirical correlograms using 1000 permutations for the residuals of the model for each of our dependent variables (stemborer abundance, striga abundance, yield, stemborer suppression, striga suppression, and yield efficacy). To avoid spurious correlations between nearby sites in different seasons, we created a false northing variable for each time point, effectively "moving" the data points north by 350km each growing season after season 0 (Long Rains 2005). This ensured that each correlogram was only calculating any effects of spatial correlation between points collected in the same season. We found that there was weak or no spatial autocorrelation present. Given the large number of points across both space and a time, and the fact that even the strongest evidence for spatial autocorrelation was quite weak, we are not concerned that spatial autocorrelation is affecting the results of our main analysis.


Spatial Autocorrelation of Stemborer Abundance Residuals
correlation
1.0
0.5
0.0
-0.5
-1.0
0
2000
4000
6000
8000
10000
distance (mean-of-class)

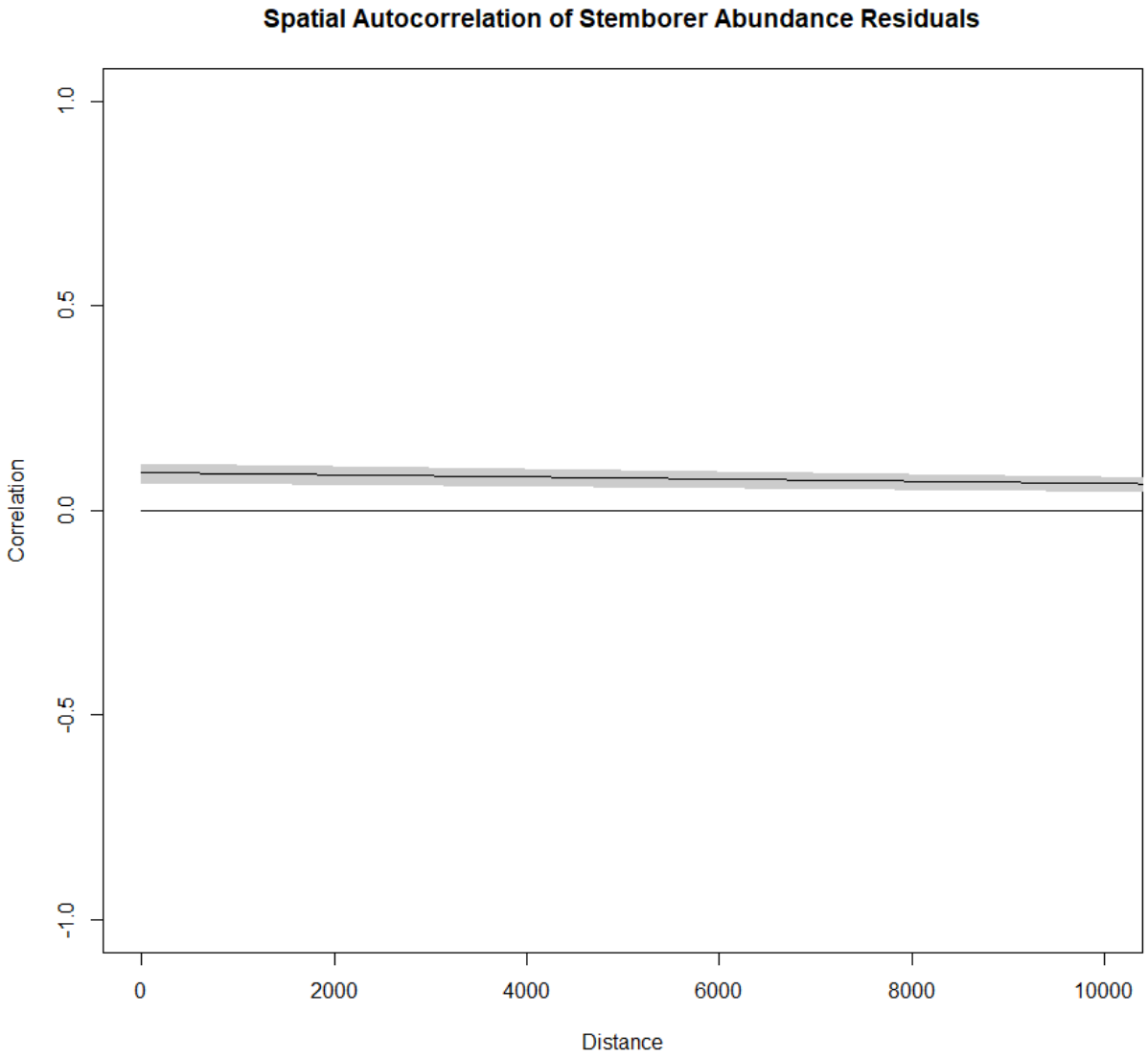
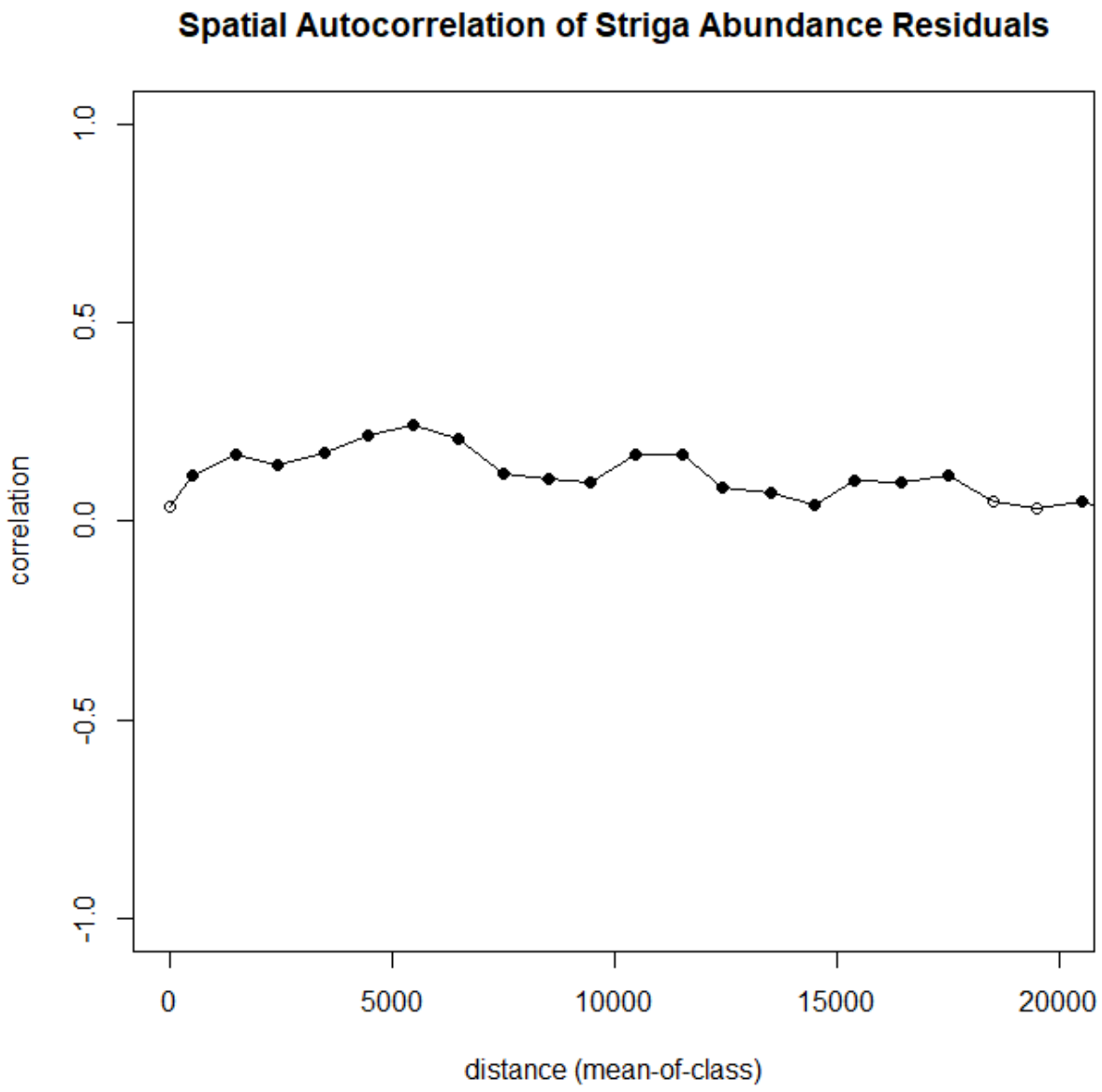


Fig A.1. Moran's I empirical correlelogram for residuals of the model for stemborer abundance shows a weak pattern of spatial autocorrelation (Moran's I $\leq$ 0.25 at all spatial scales).


Spatial Autocorrelation of Striga Abundance Residuals
correlation
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0.0
-0.5
-1.0
0
5000
10000
15000
20000
distance (mean-of-class)

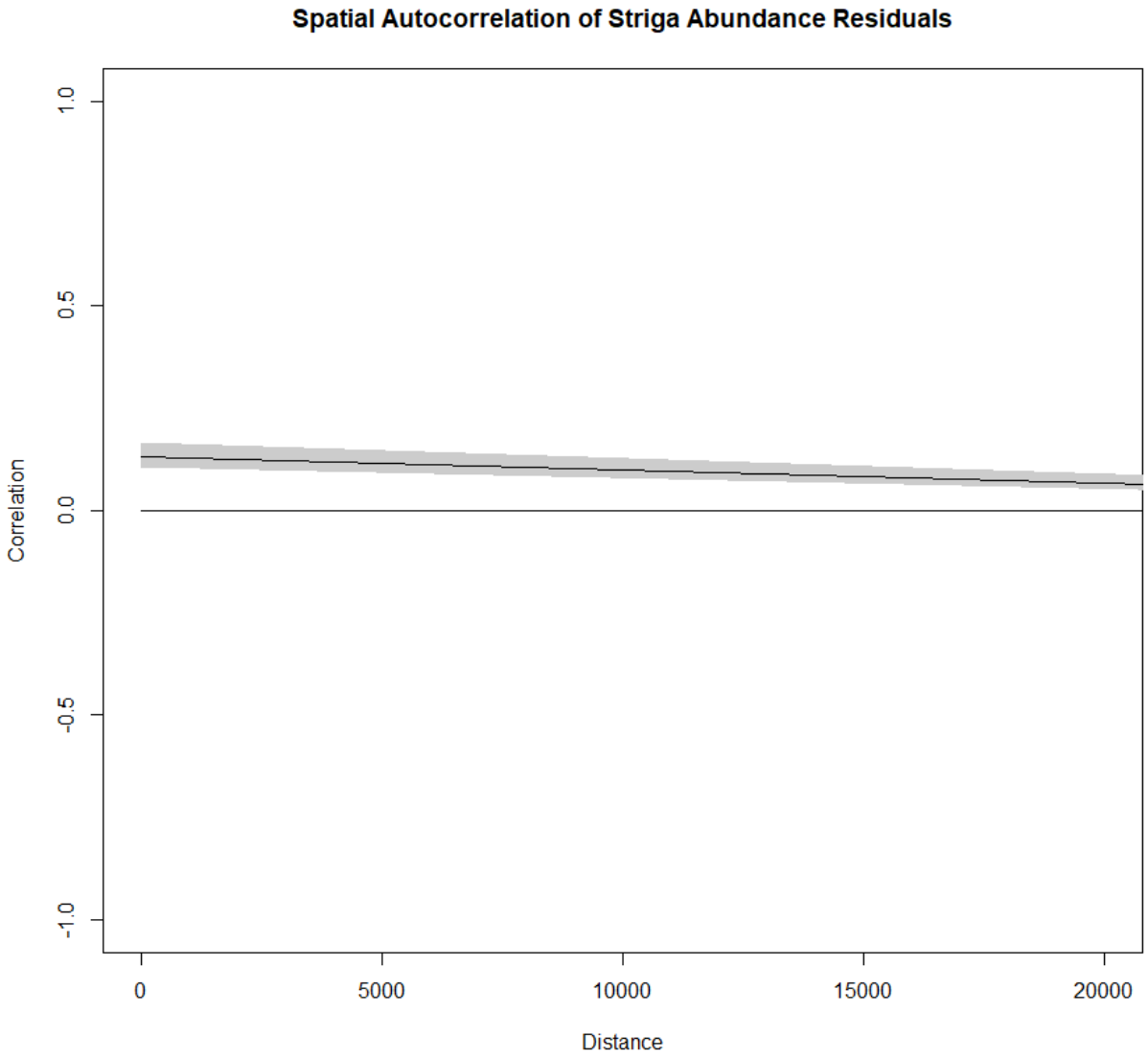
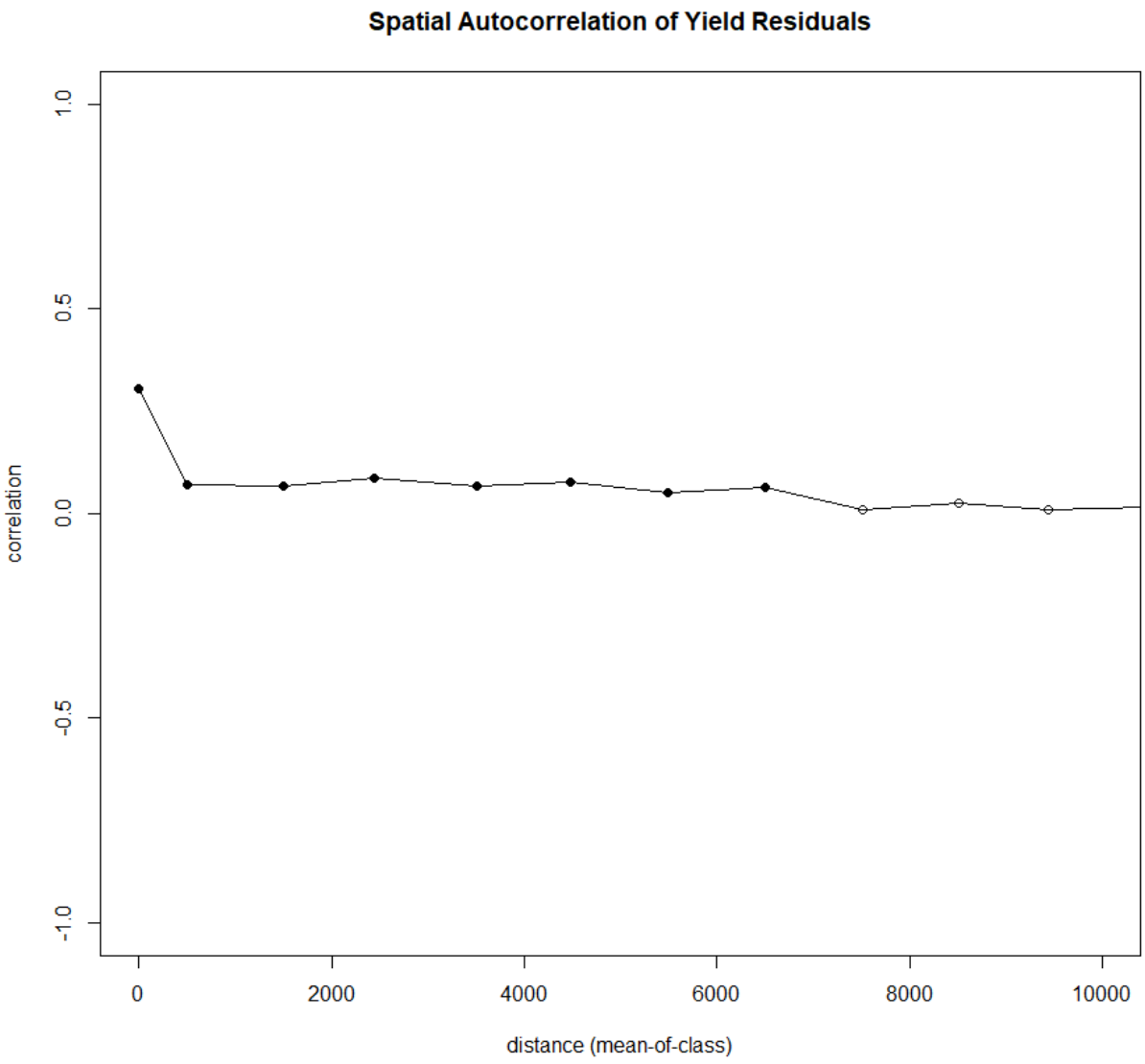


Fig A.2. Moran's I empirical correlelogram for residuals of the model for striga abundance shows a weak pattern of spatial autocorrelation (Moran's I ≤ 0.25 at all spatial scales, and with an inconsistent pattern with increasing distance).


Spatial Autocorrelation of Yield Residuals
correlation
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0.0
-0.5
-1.0
0
2000
4000
6000
8000
10000
distance (mean-of-class)

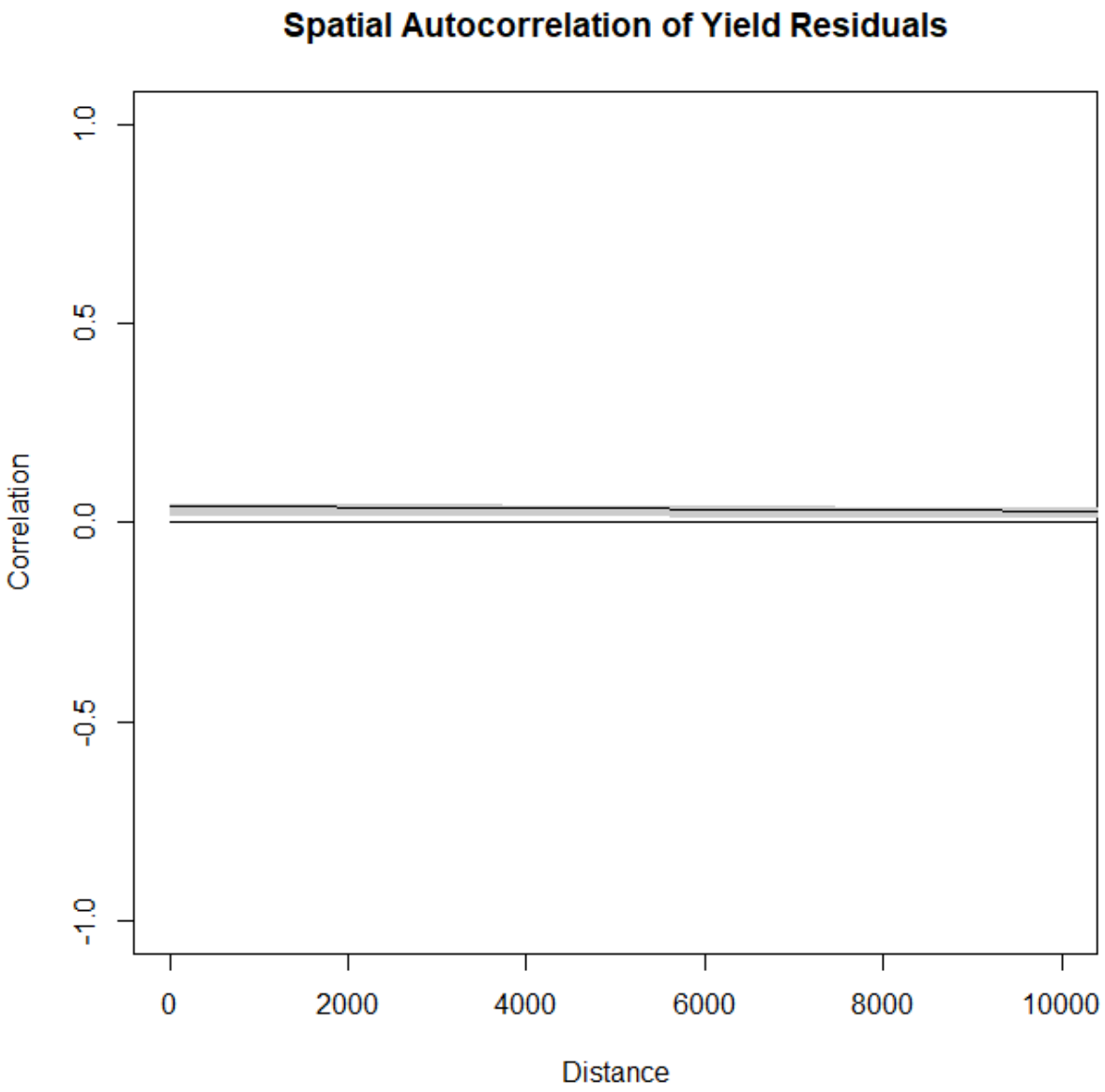

Fig A.3. Moran's I empirical correlelogram for residuals of the model for yield shows a small effect of spatial autocorrelation (Moran's I = 0.4) for farms within 1km of each other, with no spatial autocorrelation at larger spatial scales.

Appendix B – analyses of time point (calendar season/year), independent from time since establishment

We visually examined the relationship between each of our dependent variables (stemborer abundance, striga abundance, yield, stemborer suppression, striga suppression, and yield efficacy) and time point (chronological season-year, e.g. Long Rains 2010). While stemborer and striga abundance may have some cyclical patterns (a longer time series would be needed to analyze this), and the highest maximum yields were observed after 2011, we see no linear patterns for any of our variables. Indeed, the two *lowest* maximum yields were also observed after 2011. Given this variation season to season, we used time point as a random factor in all of our models. Furthermore, we believe that the lack of linear patterns relating to time point reinforces that our results are truly the effect of time since push-pull establishment, and not simply changes in our variables over time.

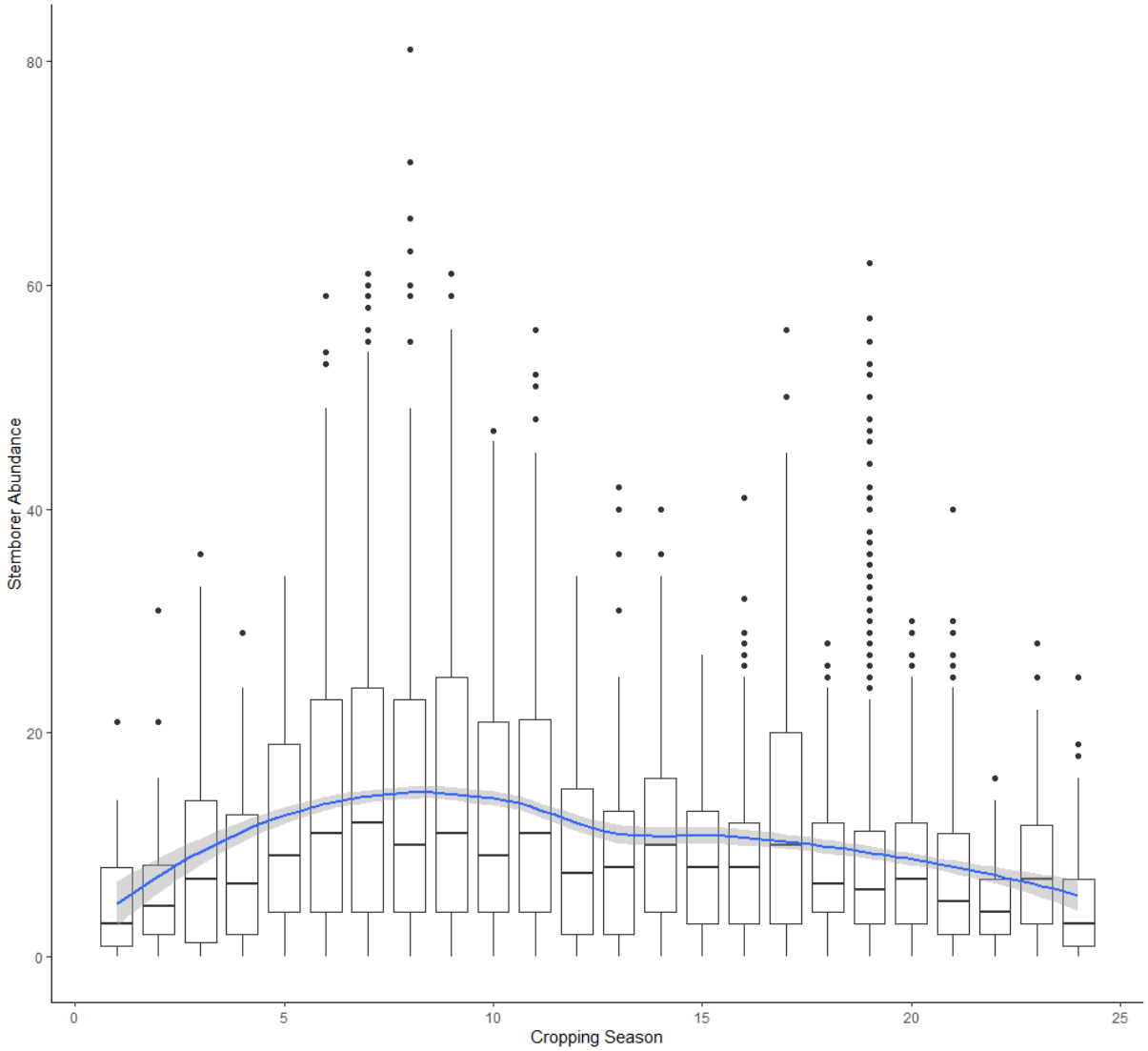

Figure B.1. Stemborer abundance over different cropping seasons, showing the smoothed curve over time (Long Rains 2005 through Short Rains 2016).

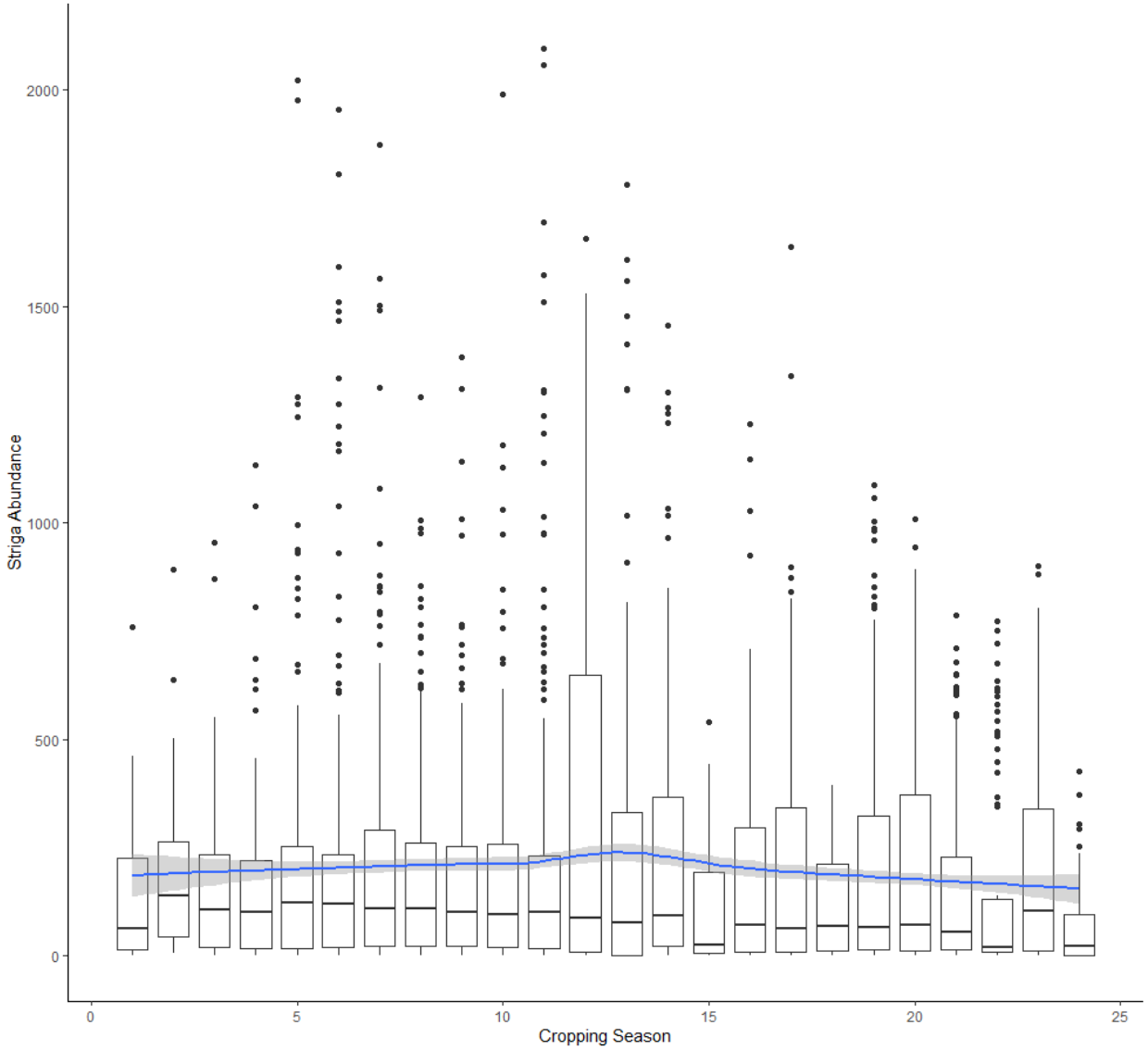

Figure B.2. Striga abundance over different cropping seasons (Long Rains 2005 through Short Rains 2016). There does not appear to be a linear pattern.

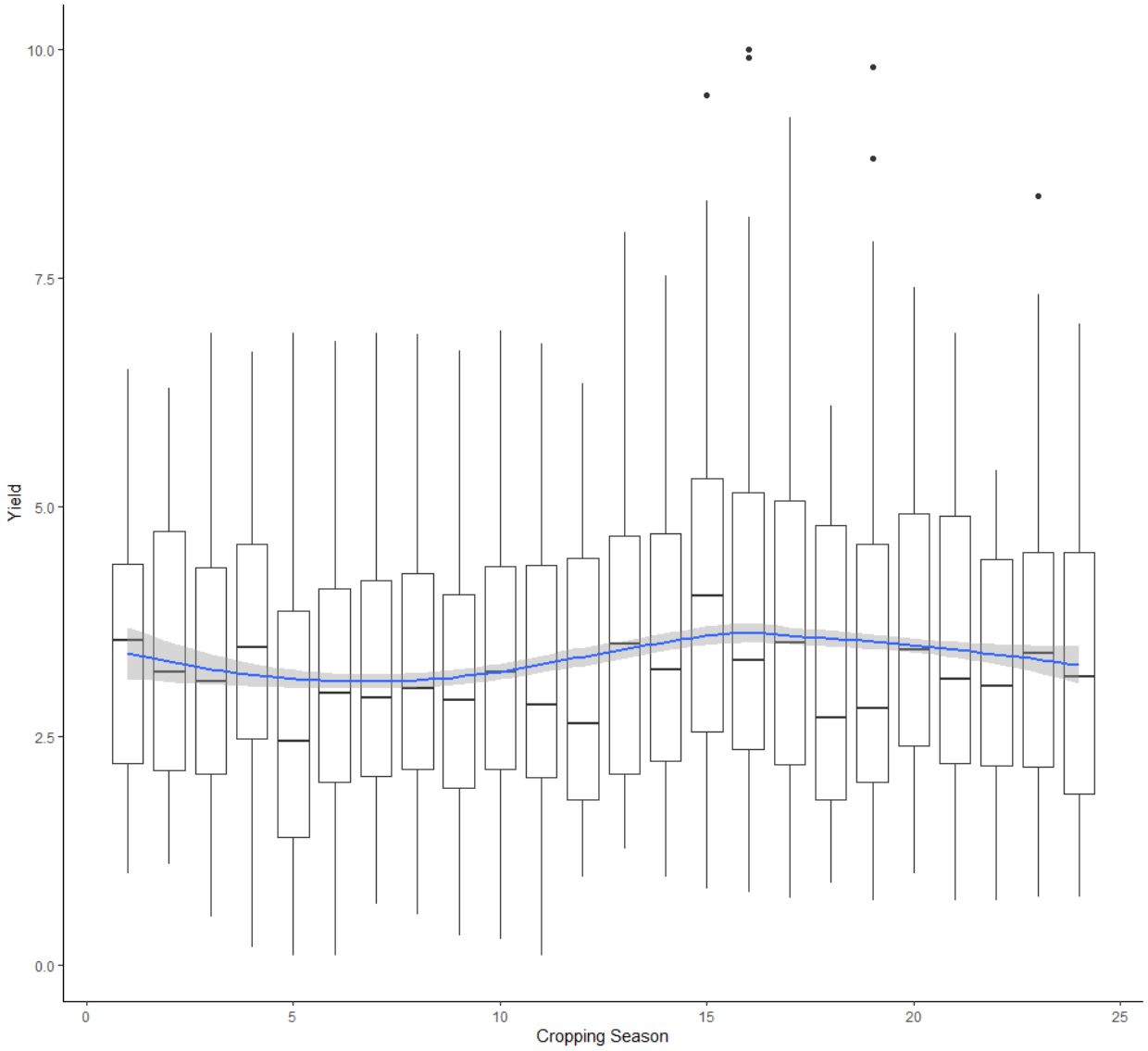

Figure B.3. Yield over different cropping seasons (Long Rains 2005 through Short Rains 2016). While some seasons do have higher maximum yields, there is no clear pattern in mean yield over time.

Appendix C – All Farmers in Long-Term Dataset

I would like to sincerely thank all of the farmers whose data contributed to this dissertation, including the many farmers who allowed their fields to be sampled for the long-term dataset used in the first and second chapter. This appendix contains the names of all farmers in the long-term dataset as well as the region they live in – any errors or accidental omissions are my own.

Thank you:

Abdalla Aseka, Butere
Abigael Anyango, Butere
Abisage Adede, Bondo
Adda Omulo, Vihiga
Aggrey Amukhungu, Butere
Aggrey Angoya, Butere
Aggrey Azere, Migori
Aggrey Okutu, Vihiga
Agnes Ambubi, Vihiga
Agnes Nyakwaka, Suba
Agneta Aoko, Rachuonyo
Agneta Ogutu, Siaya
Ainea Angose, Vihiga
Albert Shikuku, Butere
Alex Angoya, Butere
Alfred Otieno, Homa Bay
Alice Adhiambo, Rachuonyo
Alice Adhiambo, Siaya
Alice Asahala, Butere
Alice Atero, Vihiga
Alice Jaba, Siaya
Alice Jura, Suba
Alice Odima, Siaya
Alice Oduol, Siaya
Alice Onam, Bondo
Alice Ongi'njo, Siaya
Allan Mugasu, Migori
Alphuse Onyango, Migori
Amiano Rabilo, Suba
Amina Otengo, Butere
Amkoa Benson, Vihiga
Amos Afwambo, Vihiga
Andrew Ouma, Bondo
Anjeline Mkoto, Rachuonyo
Anjeline Olwande, Siaya
Anjeline Ombul, Siaya
Anjeline Owino, Siaya
Ann Adhiambo, Butere
Ann Kataka, Butere
Anna Auma, Rachuonyo
Annah Amollo, Bondo
Anne Angatia, Vihiga
Anne Okatch, Suba
Anton Mwayi, Homa Bay
Antonina Achieng, Vihiga
Antonina Mwayi, Homa Bay
Arnold Agaromba, Migori
Aska Adhiambo, Rachuonyo
Banta Atieno, Bondo
Beatrice Ameyo, Vihiga
Beatrice Anyango, Suba
Beatrice Odhiambo, Butere
Beatrice Okila, Vihiga
Beatrice Otweche, Vihiga
Beatrice Otwera, Siaya
Belinda Atieno, Bondo
Belinder Samuel, Suba
Belita Otinga, Butere
Benson Ogutu Simba, Migori
Benson Omukuba, Butere
Benta Adhiambo, Rachuonyo
Benta Otieno, Bondo
Benter Atieno Omollo, Migori
Benter Odiyo, Suba
Bernard Gor, Bondo
Bernard Odhiambo, Siaya
Bernard Oracha, Homa Bay
Beryl Abayo, Homa Bay
Beryl Atieno, Vihiga
Brigit Rapenda, Siaya
Brigita Pesa, Siaya
Caleb Ojuok, Suba
Caren Amanya, Butere
Caren Odero, Suba
Caroline Adhiambo, Suba
Caroline Adhiambo, Rachuonyo
Caroline Anyango, Siaya
Caroline Mirasi, Bondo
Caroline Okeyo, Rachuonyo
Carolyne Achieng Okonda, Vihiga
Cassidy Omutinyu, Butere
Catherine Mbone, Butere
Catherine Odera, Butere
Catherine Oloo, Rachuonyo
Cefa Mboya, Suba
Celestine Okode, Bondo
Charles Anjere, Butere
Charles Aol, Siaya
Charles Obunga, Homa Bay
Charles Obuya, Homa Bay
Charles Ochola, Homa Bay
Charles Odhiambo, Siaya
Charles Odira, Homa Bay
Charles Onyango, Homa Bay
Charles Otee Ochieng, Rachuonyo
Charles Otieno, Migori
Charles Owuor, Homa Bay
Chistine Omwaka, Butere
Choleta Odek, Suba
Choleta Ouma, Suba
Christine Akoth, Rachuonyo
Christine Auma Agwa, Rachuonyo

Christine Kutayi, Vihiga
Christine Odek, Bondo
Christopher Abok, Homa Bay
Christopher Eshikumo, Vihiga
Claris Ochungi, Siaya
Claris Otieno, Migori
Clement Odongo, Bondo
Clement Ogalo, Homa Bay
Clementina Juma, Siaya
Cleopa Mukuna, Vihiga
Coleta Atieno, Bondo
Colleta Auma, Suba
Conslata Dianga, Bondo
Conslata James, Vihiga
Conslata Khaoya, Butere
Cornellia Akinyi, Homa Bay
Damar Oyoo, Rachuonyo
Damson Wasonga, Migori
Daniel Odoyo, Suba
Daniel Otieno, Vihiga
Daudi Riwi, Homa Bay
David Anyang, Bondo
David Mbalo, Butere
David Odhiambo, Homa Bay
David Omondi, Bondo
David Omurumba, Butere
David Ouma, Homa Bay
David Waga, Migori
Dawson Sande, Butere
Deaf School, Suba
Debora Oguta, Suba
Deborah Odhiambo, Suba
Deborah Sande, Vihiga
Dennis Odongo, Migori
Diana A. Opunde, Vihiga
Dina Savai, Migori
Dinah Obunga, Rachuonyo
Dishon Ameyo, Vihiga
Dishon Msukhani, Migori
Dolly Rajuai, Migori
Domnic Ombok, Homa Bay
Domnicus Odhiambo, Butere
Donald Alwalo, Migori
Donatus Opiyo, Bondo
Dorcas Afuyo, Vihiga
Dorcas Twoma, Butere
Dorine Akinyi, Homa Bay
Doris Oguta, Suba
Dulo Ezron, Suba
Edward Owinyo, Migori
Edward Rajoro, Suba
Edward Siku, Vihiga
Edwin Otieno Olweny, Bondo
Elaly Nyawanda, Homa Bay
Elfa Onyango, Homa Bay
Eliakim Auko, Rachuonyo
Eliakim Okeyo, Rachuonyo
Eliakim Otieno, Homa Bay
Elija Omuga, Rachuonyo
Elisha Onyango, Rachuonyo
Elizabeth Akinyi Omondi, Rachuonyo
Elizabeth Atieno, Butere
Elizabeth O. Ong'injo, Siaya
Elizabeth Obiero, Siaya
Elizabeth Ochieng, Bondo
Elizabeth Ogombo, Siaya
Elly Onjure, Suba
Elmina Omollo, Siaya
Elphas Ameyo, Vihiga
Elsa Akeyo, Homa Bay
Emilly Auma, Bondo
Emilly Nandi Awori, Butere
Emily Atieno Ongou, Rachuonyo
Emily Atieno Onuonga, Rachuonyo
Emily Auma, Migori
Emma Achieng, Homa Bay
Enock Seda, Suba
Enos Onduru, Bondo
Epines Egosangwa, Migori
Erick Otieno, Suba
Ernest Okusi, Vihiga
Esborn Onyango, Suba
Ester Atieno, Suba
Esther Adhiambo, Rachuonyo
Esther John, Vihiga
Esther Ongare, Migori
Eunice A. Gogo, Suba
Eunice Atieno, Rachuonyo
Eunice Obiero, Siaya
Eunice Omondi, Siaya
Eunice Osiare, Rachuonyo
Euphresia Mwandu, Rachuonyo
Evaline Akinyi Ouma, Rachuonyo
Evaline Otunga, Rachuonyo
Everlyne Onyango, Vihiga
Ezekiel Mayodi, Vihiga
Ezra Amoche, Vihiga
Ezra Wambura, Rachuonyo
Fanice Asluanga, Butere
Fanuel Obisa, Butere
Felgona Eshiunwa, Butere
Femina Mwigamani, Migori
Fena Maramba, Butere
Festus Oguna, Siaya
Festus Otiang-a, Vihiga
Fidel Odhiambo, Suba
Filgona Okello, Homa Bay
Flora Abuti, Butere
Florence Agutu, Migori
Florence Boyani, Migori
Florence Keya, Suba
Florence Kiche, Homa Bay
Florence Kissaka, Migori
Florence Onduru, Bondo
Flourence Agutu, Migori
Floyce Adoyo, Vihiga
Floyce Mandela, Butere
FR. Ernest Wafula, Butere
Francis Makanga, Vihiga
Francis Ochieng, Bondo
Francis Okaalo, Butere
Francis Okato, Butere
Francis Otweche, Vihiga
Francisca Ouma, Siaya
Frank Atieli, Vihiga
Fred Nagide, Migori
Fridah Andayi, Vihiga

Gabriel Onyango, Bondo
Geff Apiyo, Homa Bay
George Awuor, Suba
George Dietto, Migori
George Kegode, Vihiga
George Ochieng, Suba
George Odari, Migori
George Onyango Obewa, Migori
George Otieno, Bondo
Gershom Sindani, Migori
Gershon Sidendi, Migori
Getray Ndude, Butere
Getrude Ouma, Suba
Gilbert Ombok, Migori
Gilbert Omukunda, Butere
Gilbert Onjiko, Homa Bay
Gladys Muhonja, Vihiga
Gladys Nandwa, Vihiga
Gladys Owenga, Siaya
Grace A. George, Suba
Grace Adhiambo, Suba
Grace Adhola, Bondo
Grace Anyango, Migori
Grace Auma, Homa Bay
Grace Ogwari, Bondo
Grace Orot, Bondo
Grace Otieno, Siaya
Grace Oyiengo, Suba
Haggai Otieno, Siaya
Harrison Abong'o, Rachuonyo
Hebon Musera, Migori
Hellen Kabasa, Rachuonyo
Hellen Ndede, Rachuonyo
Hellen Odhiambo, Siaya
Hellen Okeyo, Migori
Hellen Ondigo, Rachuonyo
Hellen Onyango, Siaya
Hellen Onyango, Suba
Hellen Owate, Migori
Hellen Owino, Rachuonyo
Hellen Stela Onyango, Migori
Heman Ndiegu, Migori
Henry Mwalimu, Migori
Herina Anyago, Bondo
Herine Odera, Suba
Herman Ochieng, Rachuonyo
Hezekiah Mbiru, Vihiga
Hezekiah Omukuba, Butere
Hezron Dulo, Suba
Hezron Opar, Migori
Hilder Adhiambo, Suba
Hosea Ndakala, Butere
Hudson Mulonga, Vihiga
Ibrahim Ingutia, Butere
Isaac Ambani, Butere
Isaac Ochola, Migori
Isaac Otieno, Migori
Isack Ochieng, Suba
Isack Oguta, Suba
Isaiah Soroh, Rachuonyo
Issa Nemali, Vihiga
Jack Ochieng', Migori
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Jacktone Ndong, Homa Bay
Jacob Otieno, Migori
Jael Akali, Butere
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Janet Makutwa, Vihiga
Janet Odiyo, Suba
Janet Osio, Suba
Japheth Omkato, Vihiga
Jared Adit, Siaya
Jared Odondo, Migori
Jared Omusala, Butere
Jason Akala, Butere
Jenifer Akinyi, Migori
Jenifer Nyadaa, Bondo
Jenipher Achieng Ongou, Rachuonyo
Joan Achola, Siaya
Joan Odhiambo, Siaya
Joanes Alwanga, Butere
Joel Amukhungu, Butere
John Amore, Butere
John Amuom, Suba
John Ashioya, Vihiga
John Buong, Bondo
John Bwana, Rachuonyo
John Dinga, Homa Bay
John Munala, Vihiga
John Odhiambo, Rachuonyo
John Ogongo, Bondo
John Omulo, Migori
John Oyatsi, Vihiga

Johnson Ngige, Suba
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Joice Tumbo, Bondo
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Joseph Angoya, Butere
Joseph Deya, Homa Bay
Joseph Litunya, Butere
Joseph Odek, Suba
Joseph Oduogo, Vihiga
Joseph Ogutu, Homa Bay
Joseph Opundo, Homa Bay
Joseph Osir Nyambega, Vihiga
Joseph Ouma, Homa Bay
Joseph Saka, Homa Bay
Josephine Adhiambo, Suba
Josephine Ogot, Siaya
Joshua Indiori, Migori
Joshua Ouma, Rachuonyo
Joshua Simidi, Migori
Josiah Okonda, Vihiga
Josphat Amadi, Migori
Josphine Onyango, Bondo
Joyce Tumbo, Bondo
Judith Aoko, Siaya
Judith Awuor, Siaya
Judith Okello, Suba
Judith Onginjo, Suba
Judith Sogoro, Butere
Julia Auko, Rachuonyo
Julia Mukuna, Vihiga
Julia Were, Butere
Julias Gwada, Siaya
Julita Smath, Migori
Julius Agengo, Vihiga
Karen Atieno, Siaya
Kefa Ongi'njo, Siaya
Kennedy Odhiambop, Suba
Kennedy Ongere, Suba
Kenson Khamala, Butere
Kerina Ngala, Migori
Kerina Oongo, Rachuonyo
Lawrence Ndenga, Migori
Lawrence Odek, Suba
Lawrence Opiyo, Homa Bay
Leah Adhiambo Onguru, Rachuonyo
Leah Omedo, Suba
Leodon Musuta, Vihiga
Leonard Okumu, Siaya
Leonida Aura, Butere
Lilian Anyango Kefa, Homa Bay
Lillian Amwayi, Butere
Linus Ochido, Suba
Loice Andiba, Vihiga
Loice Anyango, Homa Bay
Loice Awiti, Bondo
Loise Migusa, Suba
Lucas Ochich, Rachuonyo
Luke Shiroya, Butere
Madam Atieno, Vihiga
Magret Anyango, Rachuonyo
Magret Asava, Migori
Magret Awuor, Suba
Manase Wasonga, Suba
Margaret A. Odongo, Bondo
Margaret Mwigamani, Migori
Margaret Ochiel, Siaya
Margaret Okuma, Rachuonyo
Margaret Ombul, Siaya
Margaret Ongole, Vihiga
Margaret Ongowo, Bondo
Margret Okeyo, Rachuonyo
Mariko Mayende, Vihiga
Mark Odede, Rachuonyo
Martha Akinyi, Migori
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Martha Mnayi, Vihiga
Martha Sibo, Vihiga
Martin Kabasa, Rachuonyo
Martin Mitende, Migori
Martin Omukube, Butere
Mary Achieng, Bondo
Mary Adhiambo, Rachuonyo
Mary Adhiambo, Suba
Mary Anyama, Suba
Mary Anyango, Butere
Mary Atemo, Vihiga
Mary Atieno, Bondo
Mary Awiti, Rachuonyo
Mary Bolimo, Migori
Mary Chilo, Siaya
Mary Haya, Bondo
Mary Kaghera, Homa Bay
Mary Ndeeta, Butere
Mary Ochieng, Suba
Mary Odhiambo, Migori
Mary Odiwuor, Suba
Mary Odongo, Bondo
Mary Oguda, Migori
Mary Okongo, Bondo
Mary Omondi, Siaya
Mary Ongou Atieno, Rachuonyo
Mary Ongowo, Bondo
Mary Onyango, Migori
Mary Opel, Bondo
Mary Otiende, Bondo
Mary Otieno, Siaya
Mary Otundo, Butere
Mary Otuoma, Bondo
Mary Polo, Suba
Mary Rabilo, Suba
Maryloice Auma, Rachuonyo
Maseno Depo Disabled Gr., Vihiga
Mathew Migori, Migori
Maureen Ambubi, Vihiga
Maurice Adhere, Migori
Maurice Okoth, Siaya
Maurice Ouma, Migori
Medira Omukatu, Vihiga
Melisa Otieno, Bondo
Melsa Ashindu, Butere
Merab Atieno, Suba
Merab Ouko, Bondo
Mercel Olela, Migori
Mercy Olela, Migori
Mercy Onyango, Bondo

Michael Ayaro, Suba
Michael Ingutia, Butere
Michael Manga, Rachuonyo
Michael Ogenda, Rachuonyo
Michael Omondi, Bondo
Michael Ouma, Rachuonyo
Mildred Kowa, Siaya
Milka OBondo, Migori
Millicent Ayola, Suba
Millicent Ongou, Rachuonyo
Millicent Were, Suba
Miriam Mudumba, Butere
Monica Akoth, Rachuonyo
Monica Okumu, Siaya
Moses Aluchio, Butere
Moses Odhiambo, Suba
Mustafa Otieno, Bondo
Nactical Kutayi, Vihiga
Nancy Awino, Homa Bay
Nancy Awuor, Homa Bay
Nancy Ouru, Homa Bay
Naomi Adhiambo, Migori
Nelson Oyoko, Vihiga
Nicholas Otieno, Homa Bay
Nicholas Ouma, Vihiga
Nicholus Aura, Butere
Nimrod Maleya, Migori
Noah Okeyo, Rachuonyo
Norah Omach, Bondo
Obadia Osiolo, Vihiga
Ochieng Alaro, Homa Bay
Odera Amayo, Suba
Oketch Odidi, Suba
Okutu, Vihiga
Opicha Malachi, Butere
Pacific Adhiambo Akuno, Rachuonyo
Pamela Adhiambo, Migori
Pamela Atieno, Rachuonyo
Pamela Mwaga, Rachuonyo
Pamela Obuogo, Migori
Pamela Ochieng, Homa Bay
Pamela Okumu, Rachuonyo
Pamela Olunga, Homa Bay
Pamela Otieno, Homa Bay
Pamela Otieno, Suba
Paskalia Shikuku, Siaya
Patricia Anyango, Butere
Patricia Orido, Siaya
Patricia Umala, Siaya
Patrick Alube, Butere
Patrick Ndong, Homa Bay
Patrick Odhiambo, Vihiga
Patrick Oyier, Bondo
Paul Leteban, Butere
Paul Musumba, Butere
Paul Ogango, Suba
Paul Omuga, Homa Bay
Pauline Molo, Siaya
Pauline Odongi, Rachuonyo
Pauline Otieno, Homa Bay
Penina Atieno, Bondo
Penina Omogo, Bondo
Peres Mwanda, Siaya
Peres Ocharo, Rachuonyo
Peres Odiyo, Rachuonyo
Peres Omondi, Siaya
Peres Orido, Siaya
Perpetua Olando, Suba
Pesila Okeno, Bondo
Peter Amimo, Suba
Peter Lugutsa, Vihiga
Peter Nyaguti, Homa Bay
Peter Odhiambo, Siaya
Peter Ogutu, Vihiga
Peter Onyango, Bondo
Peter Ouso, Suba
Peter Oyatsi, Vihiga
Peter Wasonga, Butere
Peter Wasonga, Siaya
Philemon Onyango, Rachuonyo
Philgone Adhiambo Omondi, Migori
Philgone Dieto, Migori
Philimon Ochieng, Suba
Philip Angula, Rachuonyo
Philip Mbera, Migori
Philip Muma, Rachuonyo
Philip Odero, Suba
Philip Odindo, Bondo
Philis Odindo, Bondo
Philister Awino, Rachuonyo
Phoebe Ayiera, Butere
Phoebe Ndenga, Migori
Phoebe Otieno, Siaya
Pius Abonyo, Bondo
Pius Magudha, Vihiga
Polivent Achieng, Suba
Polivent Atieno, Suba
Pollyne Omuya, Vihiga
Priscilla Otieno, Migori
Quinter Onditi, Rachuonyo
Rachael Nanjala, Butere
Rael Anyango Abongo, Rachuonyo
Raphael Odero, Bondo
Raphael Oduto, Rachuonyo
Raphael Otieno, Rachuonyo
Rasto Ambudo, Butere
Rebeca Miyuka, Homa Bay
Rebecca Atieno, Bondo
Rebecca Ochieng, Bondo
Redemta Nafula, Vihiga
Refa Imbuye, Butere
Regan Ambembe, Butere
Regina Olweya, Suba
Regina Wandaye, Suba
Reuben Onyango, Homa Bay
Rhoda Adhiambo, Rachuonyo
Riadon Musuta, Vihiga
Richard Amollo, Bondo
Richard Odero, Migori
Richard Ogwang, Homa Bay
Richard Omari, Homa Bay
Richard Omolo, Vihiga
Rispa Ouso, Suba
Risper Oletsi, Vihiga
Risper Onyoyo, Vihiga
Risper Oreje, Homa Bay

Risper Otuoma, Butere
Rita Anyangu, Butere
Roda Apiyo, Homa Bay
Rogan Ambembe, Butere
Rogan Nagabo, Butere
Romanos Akwenda, Butere
Romona Mayoka, Vihiga
Romona Mulembo, Vihiga
Rose Atieno Ogweno, Suba
Rose Bala, Siaya
Rose Maloba, Butere
Rose Obondi, Suba
Rose Ogello, Suba
Rose Ogutu, Migori
Rose Olwenyi, Vihiga
Rose Onduru, Bondo
Rose Ouma, Migori
Rose Sana, Suba
Rose Wasonga, Suba
Rosebella Omukatu, Vihiga
Roselida Juma, Siaya
Rosemary Achieng, Siaya
Rosemary Odhiambo, Siaya
Rosemary Okinyo, Siaya
Rukia Omar, Homa Bay
Rumona Muteba, Vihiga
Ruth Atinga, Siaya
Ruth Obiero, Bondo
Ruth Okutoyi, Butere
Ruth Oluoch, Vihiga
Ruth Owegi, Bondo
Salim Oindo, Siaya
Saline Ombok, Bondo
Salome Awino, Rachuonyo
Salome Otieno, Bondo
Salome Owiyo, Homa Bay
Salome Vusaka, Migori
Samsom Amboro, Bondo
Samson Vidija, Migori
Samson Wasonga, Migori
Samuel Angira, Migori
Samuel Anyach, Homa Bay
Samuel Lubanga, Migori
Samuel Mnangwe, Migori
Samuel Ochieng, Rachuonyo
Samuel Odhiambo, Homa Bay
Samuel Ongalo, Bondo
Samuel Osao, Homa Bay
Samuel Ouma, Migori
Samuel Sana, Suba
Samwel Otieno, Butere
Sarah Dianag'a, Butere
Sarah Sande, Vihiga
Saul Ekhonya, Butere
Sefa Ayub, Vihiga
Sella Amukhoya, Vihiga
Sella Hamisi, Vihiga
Sellah Omakwe, Vihiga
Shaban Okoth, Rachuonyo
Shadrack Oile, Siaya
Shem Ondego, Migori
Silas Abayo, Homa Bay
Silermina Atieno, Homa Bay
Silfano Orew, Siaya
Silvia Otieno, Migori
Simeon Nyakwaka, Suba
Simion Rabilo, Suba
Simon Obara, Bondo
Sipora Atako, Butere
Sofas Jairo, Vihiga
Solmena Wasonga, Homa Bay
Solomon Atanga, Suba
Sospeter Odongo, Suba
Stephen Amkhono, Vihiga
Stephen Ataaba, Butere
Stephen Odongo, Migori
Stephen Oketch, Homa Bay
Stephen Omurakaya, Butere
Stephen Otaba, Butere
Stephen Otieno, Homa Bay
Sucilia Oywer, Migori
Susan Atieno, Rachuonyo
Susan Nyamwanga, Siaya
Susan Wagesa, Suba
Sylvance Abayo, Homa Bay
Syprose Apodo, Siaya
Syprose Atieno, Homa Bay
Syprose Deya, Homa Bay
Tereza Were, Butere
Thadayo Asere, Migori
Thadeus Oketch, Rachuonyo
Theodora Olela, Rachuonyo
Thomas Angatia, Vihiga
Thomas Joseph, Vihiga
Timothy Chalamba, Vihiga
Titus Adede, Suba
Tobias Omolo, Homa Bay
Tobias Onyango, Homa Bay
Tobias Onyango - Mig, Migori
Tom Awana, Bondo
Tom Awuor, Suba
Tom Kajulu, Bondo
Tom Mboya, Vihiga
Tom Ochieng, Suba
Tom Olweny, Vihiga
Triza Auma, Rachuonyo
Turfosa Kabaka, Vihiga
Victoria Ashioya, Butere
Victoria Owino, Siaya
Vincent Aliwa, Bondo
Vincent Aswani, Butere
Violet Midesi, Migori
Vitalis Ogude, Bondo
Wilboria Okello, Suba
Wilfrida Atieno, Rachuonyo
Wilfrida Ramba, Bondo
Wilis Okelo, Homa Bay
Wilkista Oludhe, Siaya
William Okwaro, Vihiga
Willis Otieno, Bondo
Wilson Oloo, Butere
Wilson Onduru, Migori
Wilson Onyango, Butere
Winny Ochieng, Suba
Wyclife Osale, Butere
Wycliffe Sichenji, Vihiga
Yuanita Wera, Bondo