Hide and seek: management and landscape factors affecting maize stemborers *Busseola fusca* (Fuller) infestation levels in Ethiopia

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Chapter 1

General Introduction

1. Background

Human beings are altering Earth's land surface at a fast pace and on a large scale (Foley *et al.*, 2005). These alterations include changes in land cover (the biophysical attributes of the earth's surface, such as forest, river) and land use (the way humans use the land) (Lambin *et al.*, 2003). Land cover and land use changes are influenced by complex socio-economic and political drivers as well as the biotic context, and are directly affecting local and global biological processes. As such, these drivers have an effect on biotic diversity worldwide (Newbold *et al.*, 2015), contribute to local and regional climate change (Schmitz and Barton, 2014) and are the primary cause of soil degradation (Wagner *et al.*, 2015). The on-going changes in land cover/land use are also reshaping agricultural landscapes and their potential to support, provide and regulate ecosystem services, which are essential to meet current and future human needs. Therefore, assessment of land cover and land use changes is crucial for informing land use policies aiming at designing biodiversity-based land management practices (Kremen and Merenlender, 2018) that can reduce agro-biodiversity losses and environmental degradation (e.g. soil fertility loss, erosion, loss of habitat). Assessing land cover/land use changes is particularly important for sub-Saharan Africa, which is experiencing rapid transformation in rural and urban areas as a consequence of urbanisation and population growth. Ethiopia serves as a good case for studying the impact of these changes since it is now the second most populated country in Africa with more than 100 million people and a population growth rate of 3.0% per year (World Bank 2018).

2. Landscape ecology for multifunctional agro-ecosystems

Agro-ecosystems are of major importance to humans since they provide food, feed and energy, while supporting a significant amount of biodiversity. Intensive conventional agriculture as promoted in the Green Revolution since the 1970s increased agricultural productivity through mechanization and extensive use of chemical fertilisers and pesticides (De Nooy van Tol, 2016). However, this has also led to considerable homogenisation of agricultural landscapes, loss of biodiversity and a deterioration of regulatory functions, such as the maintenance of soil fertility or the regulation of pests (Chapin Iii *et al.*, 2000; Baudron and Giller, 2014; Brose and Hillebrand, 2016). Today, there is growing consensus on the need for alternative agricultural practices that conserve biodiversity and natural regulatory processes in order to meet global food demand and dietary diversity, mitigate climate change and restore degraded landscapes (Kremen and Merenlender, 2018). Plant pests cause significant crop losses worldwide and constitute one of the barriers to the achievement of global food security. The use of pesticides has been demonstrated to have a detrimental impact on pest resistance, human health, natural enemies and the overall sustainability of agro-ecosystems (Pretty and Bharucha, 2015). Finding alternative agricultural practices that minimise or eliminate pesticide use, restore and/or conserve soil fertility and natural regulation while maintaining or improving production capacity is crucial (Chappell and LaValle, 2011). Designing sustainable agro-ecosystems in particular for multifunctional subsistence agriculture requires an understanding of the functioning of crop pest populations within agricultural landscapes (Wood et al., 2015).

3. Effect of landscape composition and structure on arthropod populations

The natural control of pests by their natural enemies is an important regulatory ecosystem service, the value of which has been estimated as 4.5 billion US$ in the USA alone (Losey and Vaughan, 2006). Natural pest control is the ecological process by which naturally occurring predators and parasitoids suppress the population of pests. Agricultural landscapes are often a matrix of cropped and non-cropped habitat with varying complexity (for instance in term of diversity, homogeneity and connectivity) that can influence the distribution and abundance of species across different spatial scales (Rusch *et al.*, 2016). While cropped fields are ephemeral and often disturbed, non-crop habitats are more stable and, depending on the vegetation composition, may provide resources (e.g. pollen, nectar), a moderate microclimate and refuge for natural enemies of stemborers. Non-crop habitats may also cause an increase in natural enemy densities within the crop fields due to movement facilitation of insect populations (Kruess and Tscharntke, 1994; Thomson and Hoffmann, 2013). In agricultural landscapes, two features that influence the spatial and temporal dynamics of arthropod species are (i) cropping systems (e.g. rotation, intercropping, ratio annual/perennial crops) and practices (tillage, use of pesticides, harvesting), and (ii) the availability of non-cropped habitats within the matrix of crop fields (Woltz *et al.*, 2012; Bianchi *et al.*, 2013; Chateil and Porcher, 2015). When crops senesce or are harvested, most herbivore and predatory arthropods move to surrounding semi-natural habitats for diapause or to find suitable resources (Zhao *et al.*, 2016). Accordingly, landscapes composed of a mixture of semi-natural habitats and perennial crops may provide more resources and sustain larger natural enemy populations than simple landscapes (Chateil and Porcher, 2015; Geertsema *et al.*, 2016). Despite the speed of change in land cover and land use, and negative impacts on both functional (Northfield *et al.*, 2014) and overall diversity (Crowder and Harwood, 2014), the effects of land cover and land use changes on biodiversity and ecological processes remain poorly quantified and understood (Bennett *et al.*, 2015). This is particularly the case for Africa where research investments are typically low (Lemessa *et al.*, 2015; Zhang *et al.*, 2018). This dissertation aims at contributing to fill this knowledge gap by analysing how changes in agricultural landscapes and farming practices are influencing the incidence of maize stemborers, *Busseola fusca* (Fuller), in Ethiopia in order to identify stemborer management strategies at the field, farm and landscape levels for a sustainable intensification of maize-based production systems. This research aims at answering the following questions (Fig. 1): (i) What is the trajectory of change of farming systems in Southern Ethiopia, what are the drivers of these changes, and how are these changes affecting the dynamic of agricultural landscapes? (ii) how do current agricultural landscape elements, in particular perennial crops and semi-natural habitats like hedgerows, influence the abundance of stemborer natural enemies? (iii) how does the landscape composition and its associated management practices impact maize stemborer infestation levels and maize productivity? (iv) how does landscape composition influence the performance of the push-pull system in terms of maize stemborer infestation level, abundance of natural enemies and maize productivity? By bringing some elements of answers to these question, this research aim to identify and inform future management practices at the field, farm and landscape levels for a sustainable intensification of maize-based production.

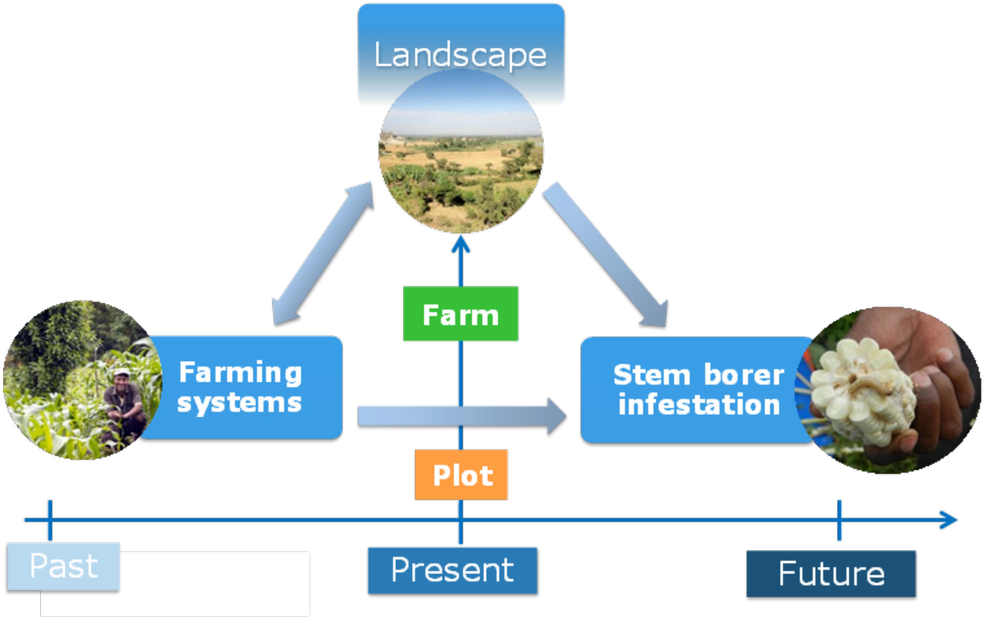


Figure 1: Conceptual framework of the study, showing the relationship between maize stemborers, landscape patterns and farming systems. Adapted from Benoît *et al.* (2012).

4. African cereal stemborers: life cycle, biology and ecology

Stemborers can be major pests of maize and other grain crops, such as sorghum, millet and sugarcane, throughout Africa, causing yield losses from 20-50% in maize and sorghum (Getu *et al.*, 2001b). However, yield losses due to stemborers vary widely by country, season, crop type and management (Khan *et al.*, 2007b). The two important stemborers species attacking maize and sorghum in Ethiopia are the exotic *Chilo partellus* (Swinhoe) (Lepidoptera: Crambidae) and the indigenous *Busseola fusca* Fuller (Lepidoptera: Noctuidae) (Le Rü *et al.*, 2006). Temperature, relative humidity, rainfall and elevation are the most important physical factors affecting the distribution, abundance and species composition of stemborers (Polaszek *et al.*, 1998; Getu *et al.*, 2001a; Asmare *et al.*, 2014). In the Eastern and Southern parts of Africa, *B. fusca* is dominant in mid to high altitude areas between 600 m and 1800 m above sea level (Getu *et al.*, 2001a; Guofa *et al.*, 2001; Calatayud *et al.*, 2014). Stemborer infestations can increase after short rainy periods and be problematic in crops grown on soils with low fertility (Ong'amo *et al.*, 2006).

Life cycle

B. fusca is a nocturnal moth. Its life cycle takes about two months in Hawassa, Ethiopia, and includes a complete metamorphosis, including egg, larval, pupal and adult stages (Fig. 2). Eggs of stemborers are flat and oval with a creamy-white colour, are about 0,8 mm long and are laid in overlapping batches of 10-80 eggs on the upper and underside leaf surface, mainly near the midribs (Azerefegne and Gebre-Amlak, 1994). *B. fusca* females usually lays eggs between the stem and leaf sheets. The oviposition of *B. fusca* starts quickly after mating, peaks during the second day after mating and gradually decreases until the fifth day (Calatayud *et al.*, 2014). The development time of eggs depends on the temperature and ranges between 4-8 days (Khadioli *et al.*, 2014).

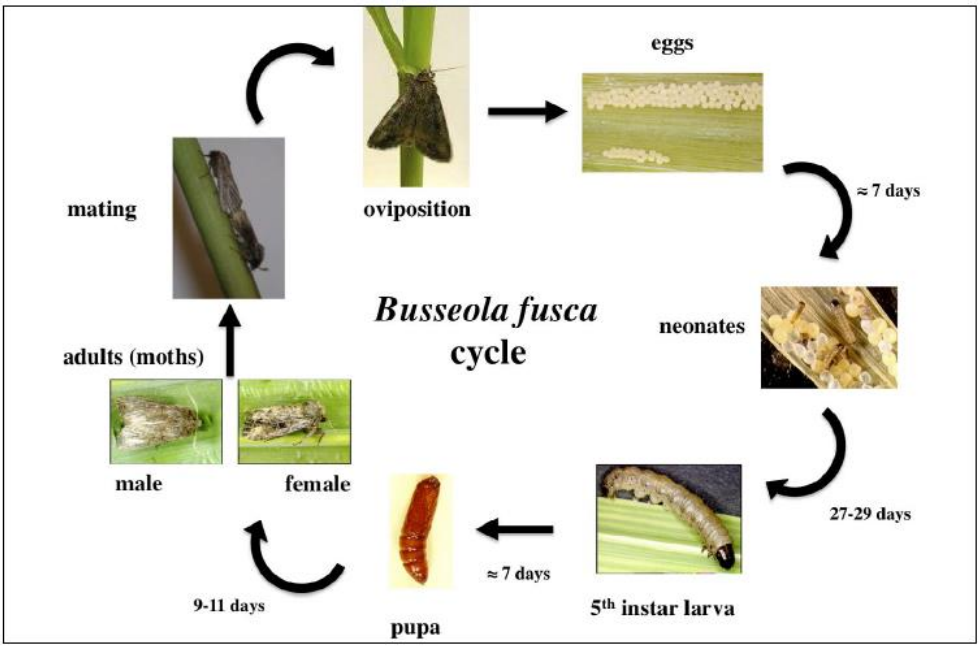


Figure 2: Life cycle of *Busseola fusca* (Calatayud *et al.*, 2014).

B. fusca has five larval stages, during which it can cause crop injury. Early instar larvae feed on the growing points of plants and young maize leaves, and later larval stages bore inside maize stems. Damage on leaves can be identified by so-called "dead-heart" when the youngest partially unfurled leaf of the plant begins to whiter, while infested stems can be recognised by entry or exit holes on the top of the stem or tunnels within the stem. The larvae feed and grow within the maize stem during 2-4 weeks. The pupal stage in the stem lasts for 9-11 days and is terminated by the emergence of the adult moth (Calatayud et al., 2014). Fifth instar larvae may enter diapause during the dry season and at high altitudes, which can last up to 6 months. The larvae pupate and emerge as moths under favourable conditions during the following growing season (Kfir et al., 2002b).

Figure 3: Damage of the stemborer *Busseola fusca* on the leaves (A), in the stem (B) and on the cob of maize (C) (Pictures credit: Y. Kebede).

Busseola fusca phenology in the Hawassa area

In Hawassa, *B. fusca* can have up to three generations (Gebre-Amlak *et al*., 1989), and the first two can cause damage to maize fields (Fig.4). The first generation of eggs are laid from early April until the end of May, peaking around the end of April. The first generation larvae pupate from early June until late August. The eggs of the second generation are laid between the first week of July and early September. The majority of second generation larvae go into diapause and remain dormant from September to February, while a small proportion may pupate in September or October and give rise to a third generation. The diapausing larvae pupate in April. The first larval generation feeds on maize planted in March, whereas the more abundant second generation, may inflict serious crop injury in maize planted later than April. The third larval generation, which appears in September-October, does typically not cause damage in maize that has been planted in April or May because the crop is reaching maturity and is no longer a high-quality host plant (Gebre-Amlak *et al*., 1989).

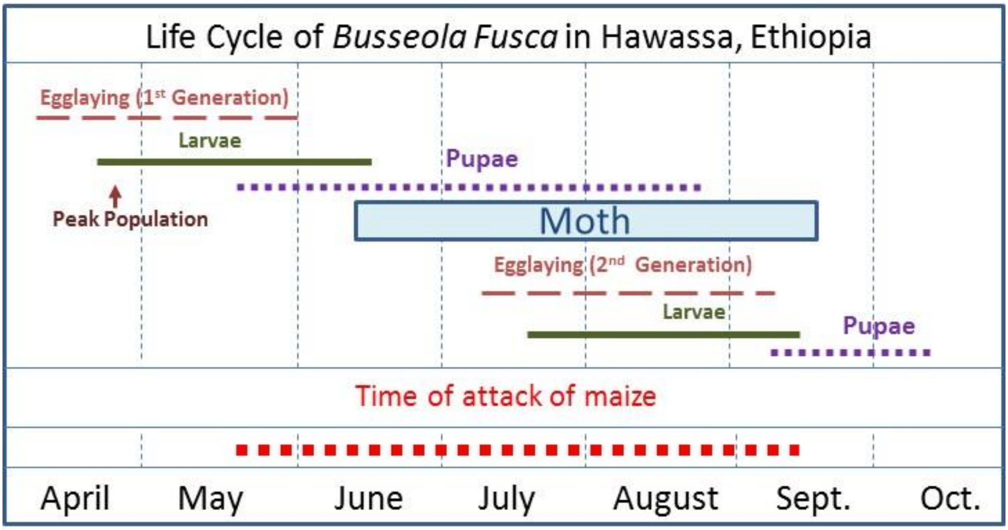


Figure 4: Life cycle and generations of *Busseola fusca* in the Hawassa area, Southern Ethiopia.

Mobility and dispersal

Newly hatched larvae crawl away from the hatching site, and movement is stimulated by light, gravity, plant architecture and plant semiochemichals (Van Rensburg et al., 1988). In this phase, larvae do not stay on the oviposition plant, but spin off on a silken thread and, supported by wind, travel to other plants (Polaszek et al., 1998). As soon as larvae find their new host plant, the feeding process starts (Berger, 1992). The larvae leave the whorl in the direction of the plant internodes where they start tunnelling into the stem, and when the feeding conditions deteriorate, larvae migrate to another plant (Berger, 1992). Adult moths live for about 2-5 days and do not generally disperse far from emergence sites (Calatayud et al., 2008). However, the dispersal capacity and range expansion of *B. fusca* has been poorly documented, and therefore reliable estimations are lacking.

Host plant range and natural enemies

Stemborers larvea have been recorded to feed on maize (*Zea mays*), sorghum (*Sorghum verticilliflorum*), rice (*Oryza sativa*, Asian rice) or *Oryza glaberrima* (African rice), and sugarcane (*Saccharum officinarum*). Stemborer larvae also feed on wild grasses in the three main families Cyperaceae, Gramineae, Typhaceae (Polaszek et al., 1998; Khan et al., 2007a). A recent surveys on 197 plants in 15 African countries, Calatayud et al. (2014) reported *B. fusca* to occur on only seven wild plants species: *Sorghum arundinaceum*, *Setaria megaphylla*, *Pennisetum purpureum*, *Panicum maximum*, *Cymbopogon nardus*, *Cymbopogon giganteus*, and *Arundo donax*. Although these wild plants species can serve as alternative oviposition sites for *B.fusca*, they have been reported of being poor host with low carrying capacity (Van den Berg, 2017). However, the presence of wild plants can serve as refuge for stemborers natural enemies, which may colonise maize fields later on (Getu et al., 2002).

A survey on natural enemies in Ethiopia indicated that there were, 21 parasitoids, 14 predators and seven pathogens that may affect stemborers. All the natural enemies were recorded on eggs, larvae and pupae of stemborers (Getu et al., 2001a). The most widely distributed and abundant parasitoid of stemborers in Ethiopia is *Cotesia flavipes* Cameron (Hymenoptera:Braconidae), which is a larval endoparasitoid that originates from Asia. This parasitoid has spread from Kenya to Ethiopia (Getu et al., 2003) where it was released as a biocontrol agent of stemborers. Parasitism of stemborers is generally lower in crop fields (typically lower than 10%) than in wild host plants (Kankonda et al., 2017) and peaks during the non-cropping season in non-crop habitats (Mailafiya et al., 2011). Predators, such as ants, spiders and earwigs, can cause high mortality of eggs and young larvae (Bonhof et al., 1997).

5. Current pest management strategies of stemborers at field scale

Stemborer pest management may involve chemical, mechanical and ecological methods. Chemical control of stemborers is limited because of the cryptic behaviour of the larvae in the stems (Lawani, 1982), and insecticides are often too expensive for smallholder farmers of Ethiopia. Indigenous predators are often not able to keep stemborer populations below economic injury levels (Kfir et al., 2002a). Cultural farmers' practices to control stemborers damage include: appropriate residue disposal, planting date manipulation, and destruction of volunteer and alternative host plants. Planting date influence infestation levels and yield loss caused by maize stemborers (Gebre-Amlak et al., 1989; Ebenebe et al., 1999). Manipulation of the sowing date ensures that the most susceptible stage in maize growth does not coincide with peak stemborer activity. Soil tillage practices can significantly reduce insect populations through mechanical damage by burying maize roots or by bringing them the roots to the surface where they may be killed by weather factors, birds or other natural enemies. Tillage at off season will destroy volunteer plants, stubble and weeds that may provide food and breeding sites for stemborers (Kfir et al., 2002a). Although burning or partial burning of maize stems decreases the population of stemborers by 95%, this cannot be considered as a sustainable solution given that crop residues are usually the only organic matter supply to maintain soil fertility for smallholder farmers (Kfir et al. 2002). In addition, maize crop residues are also an important source of fuel for smallholder farmers. Therefore, there is high competition for the use of maize residues as mulch and feed for livestock (Valbuena 2012), which represent a major livelihood asset for smallholder farmers.

Functional diversity may contribute to the reduction of crop losses by repelling pests via plant-mediated semiochemicals (Khan et al., 2010; Farooq et al., 2011), or by increasing mortality due to top-down control by natural enemies (Mailafiya et al., 2011). This principle is applied in the push-pull system, which involves the intercropping of a pest repelling crop within maize (i.e. push; *Desmodium spp*. or Molasses grass, *Melinis minutiflora*) and planting a trap crop in the border (i.e. pull; Napier grass, *Pennisetum purpureum* or Brachiaria) (Khan et al, 2010). The push-pull system is a promising farming strategy for African multifunctional subsistence agriculture. However, its adoption by farmers has been limited in Kenya (Fischler, 2010), possibly due to farmers' reluctance to replace food crops, such as common bean, by a fodder crop, and the reluctance to reduce maize production area in favour of companion trap crops in an already land-constrained situation. The adoption of the push-pull system may be further stimulated by replacing the *Desmodium spp*., which can only be used for feed, by a multipurpose grain legume such as common bean, which is an important source of protein in local diets (Fischler, 2010). Beyond their ability to fix nitrogen, legume crops produce secondary metabolites as defence compounds against herbivores (Wink, 2013). Indeed, traditional maize/bean or maize/cowpea intercropping systems are less prone to stemborer infestations than sole maize (Amoako-Atta et al., 1983; Chabi-Olaye et al., 2002; Chabi-Olaye et al., 2005; Belay et al., 2008), and tend to provide higher maize yield (Songa et al., 2007; Seran and Brintha, 2010). However, the push-pull system has often been assessed as a package and the contribution of each component is not clear (Eigenbrode et al., 2016). In addition, the performance of the push-pull system based on *Desmodium spp*. and other legume crops in different landscape contexts is not well known (Midega et al., 2014).

Rational and objectives of this research

Natural resources are being degraded and finite resources depleted by current land-use practices, and smallholder producers are confronted with seasonal food self-insufficiency. At the same time, there is an increasing societal concern to feed a growing global population with larger nutritional needs. The ATTIC project (Trajectories and Trade-offs for Intensification of Cereal-based systems), part of the MAIZE Strategic Initiative of the Consultative Group for International Agricultural Research (CGIAR), aims to provide and implement a generic analytical framework to inform the design of more sustainable cereal-based agro-ecosystems by contextualising and assessing the potential impact of institutional changes and technological innovations along sustainable intensification trajectories and across scales. This research contributes to this project, taking the Hawassa area in Southern Ethiopia as a case study with a system-level baseline description of agro-ecosystems, and assesses the trajectories of smallholder households engaged in maize-based farming systems.

There is an on-going transformation of farming systems in the Hawassa area, and these changes are influenced by institutional and socio-economic drivers, such as land tenure regulation, market access and population growth. It is unclear how these drivers influence the dynamics of farming systems and ultimately the resulting composition and structure of agricultural landscapes. Although agricultural management decisions are mainly taken at the field and farm levels, the dynamics of stemborers and their natural enemies are likely to be best explained at the landscape level because of their potential mobility (Ndjomatchoua et al., 2016). The landscape context can influence pest-natural enemy interactions by providing food resources and shelter for pests and natural enemies (Tsafack et al., 2013; Schellhorn et al., 2014). Biodiversity at the landscape level is also important for the long-term sustainability of ecosystems and the wider ecosystem services they provide (Tscharntke et al., 2012; Werling et al., 2014; Wood et al., 2015; Brose and Hillebrand, 2016).

The ultimate goal of this PhD project is to identify management practices at the field, farm and landscape levels for a sustainable intensification of maize-based production systems that (i) reduce stemborer infestations, (ii) maintain or improve soil fertility, and (iii) improve fodder production for livestock. The study included the quantification of historic changes in land cover and land use, a participatory approach with farmers and farm household surveys, an assessment of stemborer and natural enemy abundance and diversity in farmer's fields, and on-farm experiments to assess the relationship between stemborer abundance and management practices at the field (e.g. maize-legume intercropping, push-pull system), farm (e.g. crop diversification) and landscape level (e.g. proportion maize in the landscape, landscape diversity).

The general objective of this thesis is to identify pest management strategies at the field, farm and landscape levels for a more sustainable intensification of maize-based production systems. The main hypothesis of this research is that the concentration of host plants for stemborers *B. fusca* in the landscape and the reduction of habitats for their natural enemies can lead to increased infestation levels. We expect that landscapes with high density of maize generate a higher population of stemborers as compared to low density maize landscapes, and therefore experience higher pest pressure.

Specific objectives

1- To describe the changes in land cover and land use in the region of Hawassa over the last four decades and the consequences for farmers' livelihood strategies and current landscape composition (Chapter 2).

2- To assess how the changes in farming systems that shaped the current landscape composition and structure influence the abundance and diversity of stemborer natural enemies (Chapter 3)

3- To understand the factors at field, farm and landscape scales that influence stemborer infestation levels and maize productivity (Chapter 4)

4- To assess the performance of the push-pull system with varying companion crops on stemborer infestation level, predators abundance and maize productivity in contrasting complexity landscapes: simple, intermediate and complex landscapes (Chapter 5).

Outline of this thesis

Chapter 2 aims at understanding the drivers of change in land cover and land use as a result of changes in farming systems and how these changes shaped current agricultural landscapes.

Chapter 3 investigates the implications of the changes in land cover and landscape structure for the biocontrol potential of maize stemborers. By assessing the abundance of the natural enemies of stemborer in maize fields bordering perennial crops and simple and complex hedgerows, we found that the historical changes in land cover and landscape structure may have had a positive impact when maize fields are bordered by enset (*Ensete Ventricosum*) or dense hedgerows for the biocontrol potential of stemborers in the landscape of the Hawassa region.

Chapter 4 explores the landscape and management factors at field, farm and landscape levels influencing maize stemborer infestation and maize productivity in farmers' fields. Thirty-three farms were monitored during three years and stemborer infestation levels, crop management and maize production were assessed.

In **Chapter 5**, the performance of the push-pull system in repelling stemborers is investigated in a gradient of landscape complexity from maize dominated to perennial dominated, as well as the abundance of natural enemies, egg parasitism and maize productivity. The traditional push-pull system (maize, *Desmodium* and Napier grass) is compared with an alternative system composed of maize, Napier and common bean, which has the additional benefit of providing food.

In **Chapter 6**, the different findings of this thesis are integrated. The need for integrated management strategies at field, farm and landscape levels for effective control of maize stemborers is discussed. Trade-offs and opportunities for sustainable pest management strategies against stemborers, conserving soil fertility and increasing maize production are discussed.

Chapter 2

Drivers, farmers' responses, and landscape consequences of smallholder farming systems changes in Southern Ethiopia

Chapter submitted as: Kebede, Y., Baudron, F, Bianchi, F.J.J.A., Tittonell, P., 2018. Drivers, farmers' responses, and landscape consequences of smallholder farming systems changes in Southern Ethiopia, International journal of agricultural sustainability.

Abstract

Agricultural landscapes in sub-Saharan Africa are dynamic and are shaped by farmers' land use decisions and livelihood strategies over time. Farmers' decisions are influenced by the opportunities and constraints emanating from different socio-economic, biophysical, and political drivers. Ethiopia is now the second most populated country in Africa with more than 100 million people and an annual population growth rate of 3%. Here, we assess how the on-going expansion of arable land and urban areas is affecting the availability of common resources, such as forest and grazing land, and the availability of biomass for food, feed, and energy. Taking the Hawassa area in the Rift Valley of Ethiopia as a study case, this study aims at analysing the drivers of change of farming systems, assessing farmers' responses to these drivers and appreciating the consequences for the agricultural landscapes' composition. The methodological approach integrates farm household surveys, focus group discussions with farmers, statistical typology of trajectories of change in farming systems, remote sensing and secondary data analysis. We found that (i) national level policies, climate and soil fertility changes, population increase, and urban expansion were major drivers of farming systems change in the Hawassa area, (ii) forests and grasslands have been progressively replaced by cropland and urban areas, and (iii) these changes resulted in fragmentation and diversification of local agricultural landscapes with potential consequences for ecosystem service provision. Farmers responded with the following three main livelihood strategies: consolidation (maintaining food crops and livestock), diversification (a combination of agricultural and off-farm activities) and specialisation (an increase in cash crop production). These changes led to more diverse and fragmented agricultural landscapes. These findings suggest that farmers were able to compensate the decrease in farm size by a diversification of their food and income sources, a specialisation in cash crops, off-farm activities, and transhumance. This research contributes to the ongoing debate of the viability of small farms. In addition, the social-ecological changes associated with livelihood strategies and household trajectories resulted in changes in landscape structure and composition, specifically in fragmentation and diversification, which may have implications for the future provision of ecosystem services, including food provisioning.

1. Introduction

Farming systems are dynamic, complex socio-ecological systems that provide food, feed, and cash and result from past farmers' livelihood strategies and land use decisions. Farming system trajectories are the succession of chronological steps leading to structural or organisational changes in a population of individual farms sharing similar opportunities and constraints (Rueff and Gibon, 2010). Consequently, farming system changes and their drivers are heterogeneous and complex, varying between households, locations, and time (Carswell, 2000; Tittonell *et al.*, 2011). Two main drivers, availability of farmland and access to market, are considered to have major effects on farmers' decision making in terms of production orientation, land allocation, livestock densities, and involvement in off/non-farm activities (Mellor, 2014; Muyanga and Jayne, 2014). However, the dynamics of these drivers, their link to regional and national level socio-economic context, and the response of farmers over time are poorly understood.

Farm sizes across sub-Saharan Africa have gradually declined over the past 50 years (Jayne & Muyanga, 2013). The reduction in cropland is leading to expansion into forested areas and cultivation of steep slopes. Continuous cropping without adequate crop nutrition is also causing erosion, soil nutrient mining, and increasing risk of pests and disease outbreaks due to lack of crop rotations (Van Huis and Meerman, 1997; Tittonell *et al.*, 2010; Zhang *et al.*, 2018). The projected population increase is likely to lead to further structural and organisational changes in farming systems, and can redirect trajectories with uncertain future outcomes in terms of food provision and income generation. While many studies analysed typologies of static farming systems at a certain point in time (Pacini *et al.*, 2013; Tittonell, 2014), researchers often fail to understand how farming systems evolve in different directions by responding to historical and current drivers of change and how these changes shape the composition of landscapes in which farms are embedded (Carmona *et al.*, 2010). The lack of comparable information across intervals of time makes it difficult to assess whether rural livelihoods are diversifying or becoming more self-sufficient. Therefore, building more sustainable agricultural systems requires an understanding of the historical socio-ecological dynamics of farming systems, the drivers of change, and the direction of these changes (Valbuena *et al.*, 2015).

Analysing trajectories of change of farming systems is particularly important for sub-Saharan Africa, which is experiencing fast changes in land cover/land use as a consequence of urbanisation and population growth. Ethiopia is a good case to study the impact of these changes, as it is now the second most populated country in Africa with more than 100 million people and a population growth rate of 3% per year (World Bank 2018). The ongoing expansion of arable land and urban areas is leading to increasing pressure on common resources, such as forests and grazing lands, and increasing biomass competition for food, feed, and energy (Kindu *et al.*, 2013; Assefa and Bork, 2014). These changes have a direct effect on the composition and structure of agricultural landscapes and may affect current and future biodiversity and the ecological processes it supports. We analyse the ways in which socio-economic, political, and biophysical drivers from national to local scales influenced farmers' livelihood strategies. More specifically, the aims of this study were (i) to describe the drivers of farming systems changes in the Hawassa area, (ii) to analyse how farmers responded to these changes and the resulting trajectories of farming systems, and (iii) to explain how these changes shaped current agricultural landscapes and the possible ecological consequences this may have for agricultural production and ecosystem services.

2. Materials and methods

Data were collected in five steps (Table 1). A farm household survey with 173 respondents was conducted in 2013, followed by focus group discussions which consisted of three activities: the assessment of perceived drivers of change, land cover/land use changes, and participatory typology of current farming systems. Based on the participatory typology, a subsample of 15 farms per type were selected among the 173 respondents for a statistical typology of farming system trajectories. A quantitative satellite image analysis complemented the farmers' perceived land cover/land use changes. Population and climate information were gathered from national statistical data and other secondary data.

Table 1: Data collection approach

Step	Data source	Period covered or Year	Analysis or Outcome
1	**Household survey** (173 respondents)	2013	Descriptive statistics of current farming systems
2	**Focus group discussions** (20 participants per district)	1965 to 2015	Drivers of change and land cover and land use changes as per farmers' perception Participatory typology of current farm types
3	**Household survey** (15 respondents per current farm type (n=60))	Between the year of farm settlement and 2015	Statistical typology of trajectories of change of farming systems
4	**Landsat satellite images classification**	1984 to 1998 and 1998 to 2014	Quantitative land cover/land use change analysis (area change)
5	**Secondary data**	1980 to 2018	Drivers of change (socio-economic national statistical data) Weather (rainfall and temperature) Literature

2.1 Study area

The study was conducted in the Hawassa area in the Sidama zone, which belongs to the 'Southern Nations, Nationalities, and Peoples' (SNNPR) province in the Ethiopian Rift Valley (7°03'11" to 7°08'4" N latitude and 38°15'17" to 38°38'47"E longitude; Fig. 1). The study area is located within one of the most densely populated areas of Ethiopia. Hawassa town has been experiencing continuous population growth from 10,000 in 1978 to more than 300,000 in 2015 (Dessie, 2007). The area is characterised by moist to sub-humid, warm subtropical climate with an average temperature of 15 to 20°C. Annual precipitation ranges from 1000 to 1800 mm in a bimodal distribution pattern, expected in March to April and June to August (Dessie, 2007). Historical rainfall patterns show a high variability, with lowest annual precipitation reaching 700 mm in some years. Three districts were selected: Wondo Genet, Tula, and Hawassa Zuria.

Each district is characterised by contrasting farming systems, as illustrated by differences in area of perennial and annual crops, field sizes and livelihoods (Table 2). The three districts are dominated by mixed crop-livestock farming systems with a variable level of integration between the crop and the livestock sub-components.

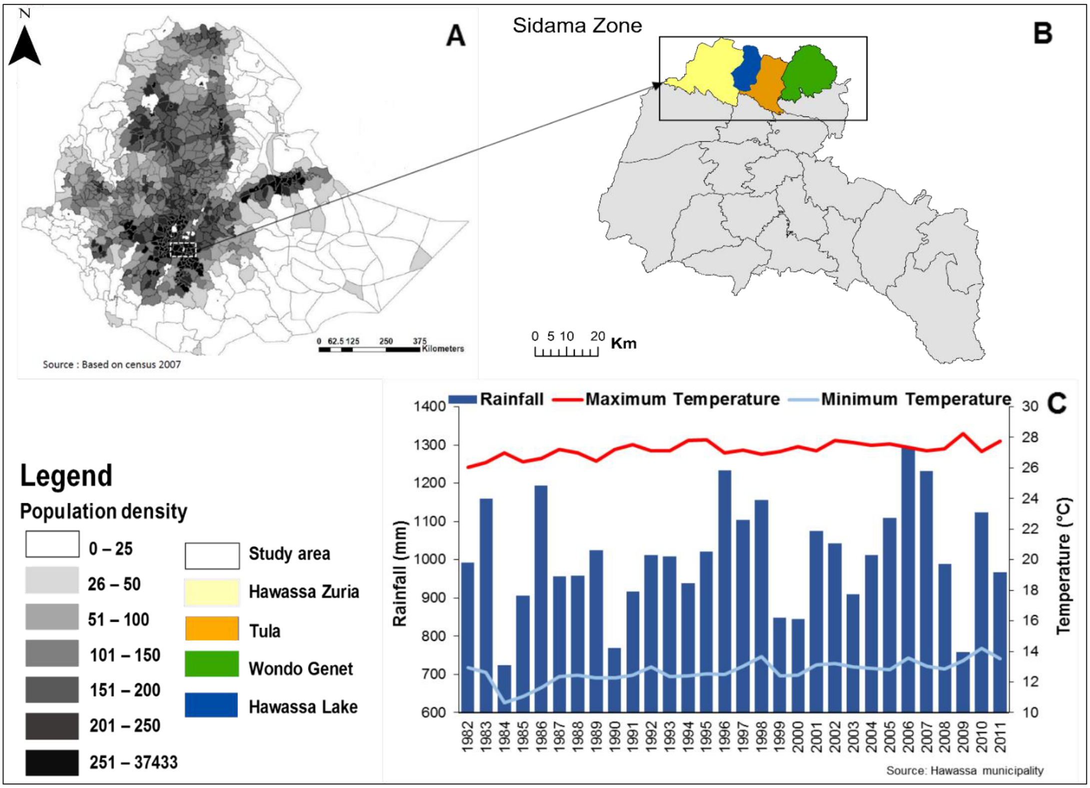


Figure 1: Population density in Ethiopia based on 2007 census (A), location of the study area and the selected three districts: Hawassa Zuria, Tula, Wondo Genet (B), annual mean rainfall, minimum and maximum temperature in the Hawassa area (C).

2.2 Household survey

In 2013, a structured farm household survey was conducted in the three districts to assess current farming system changes. Households were randomly selected along three transects from the lake Hawassa to the inland in each district (i.e. 9 transects in total). A total of 173 households were interviewed (55 in Hawassa Zuria, 64 in Tula and 54 in Wondo Genet). The survey captured general information about the respondent, household composition, main constraints in the farming system, area allocated to different crops and total farm size, input use, livestock number, and feed sources. Livestock numbers have been converted into tropical livestock units (TLU) (Jahnke, 1982). This survey provided insight on current farming systems and cash sources (Table 2).

Table 2: Selected variables describing current farming systems by district (mean ± SD)

	Hawassa Zuria	Tula	Wondo Genet
Respondent age	39.45 ± 12.99	47.01 ± 13.82	44.03 ± 13.54
Household size	6.75 ± 2.42	8.01 ± 3.73	7.49 ± 3.00
Respondent education level (number of years of attendance)	2.67 ± 3.20	3.09 ± 3.70	4.48 ± 3.72
Spouse education level	1.54 ± 2.79	1.43 ± 2.78	1.80 ± 2.58
Area of coffee (ha)	0	0.06 ± 0.09	0.05 ± 0.08
Area of enset (ha)	0.13 ± 1.14	0.23 ± 1.15	0.12 ± 0.10
Area of khat (ha)	0.03 ± 0.11	0.14 ± 0.15	0.27 ± 0.25
Area of maize (ha)	0.74 ± 0.50	0.44 ± 0.35	0.26 ± 0.23
Area of common bean(ha)	0.03 ± 0.08	0.004 ± 0.031	0.004 ± 0.034
Area of other crops	0.06 ± 0.09	0.01 ± 0.05	0.04 ± 0.14
Total area (ha)	1 ± 0.62	0.91 ± 0.57	0.78 ± 0.51
Livestock (TLU/household)	2.91 ± 2.34	2.09 ± 1.85	2.04 ± 1.88
Milk production (Litre/cow/day)	0.95 ± 1.31	1.06 ± 1.82	0.94 ± 1.32
Milk consumption (Litre/cow/day)	0.91 ± 1.21	1.01 ± 1.81	0.86 ± 1.26
Manure (kg/ha)	526 ± 1061	597 ± 1110	605 ± 1025
DAP (kg/ha)	74.45 ± 60.16	48.67 ± 125.73	42.62 ± 51.39
Urea (kg/ha)	77.45 ± 60.92	34.08 ± 26.83	47. 16 ± 51.41
Use of pesticide (Litre/ha)	0.49 ± 3.36	0.25 ± 0.72	0.08 ± 0.37
Households having a mobile phone (%)	65	45	68
Households having a radio (%)	25.45	25	38.88
Primary source of cash	Maize (76%)	Khat (41%)	Khat (87%)
Secondary source of cash	Common bean (33%)	Coffee (33%)	Coffee (46%)
Tertiary source of cash	Cattle (16%)	Cattle (14%)	Cattle (26%)

2.3 Focus group discussion

Focus group discussions were conducted with 20 key informants in each district. The discussions led to three outputs: (i) a timeline construction to capture the perception of historical drivers of change and identify key periods and drivers that have influenced farming systems from 1974 until 2015, (ii) participatory mapping and bar graphing to assess the changes in land cover and land use changes, and (iii) a participatory farm typology of current farm types.

2.4 Survey for trajectories of change of farming systems

Based on the participatory typology, a subsample of five farms per type and per district was selected among the 173 respondents surveyed in 2013. A total of 60 farmers (three districts x four types x five farms) were interviewed to assess the trajectories of farming systems. A detailed survey was conducted to assess changes in farm size, crop allocation, production orientation, livestock number, feed sources, off-farming activities, and food purchases during two points in time: the year when the household began farming and 2015. The average starting year was 1984 with a standard deviation ranging from 1969 to 1999.

2.5 Statistical typology of trajectories of change in farming systems

In order to assess the typology of trajectories of change in farming systems resulting from farmer's livelihood strategies, we assessed past and current farm structure and farm assets in two points in time: the first year of farming (or settlement) and 2015. A statistical typology of trajectories of change was constructed based on the sub-sample of 60 farms considering the difference between the variables in the current situation (t_1) and the year of settlement (t_0). To test for correlations between the variables at t0 and t_1, we assessed the Pearson correlation coefficients between the variables resulting from the detailed survey and have reduced the final set of variables to eight (Table 3). To quantify the change in variables, we used data from the year of settlement (t_0) and 2015 (t_1). The rate of change was then calculated as:

$$\Delta \mathrm{V} = (\mathrm{V}t_1 - \mathrm{V}t_0)/(\ t_1 - \ t_0)$$

where ΔV is the annual change of the variable Vi between the time t_0 and the time t_1; Vt_0 is the value of the variable Vi during the year of settlement; Vt_1 is the value of the variable Vi in 2015, and (t_1- t_0) is the difference in years between the time t_1 and the time t_0.

Table 3 – Selected variables for developing the statistical typology of farming system trajectories (mean ± standard deviation).

Variable	Unit	Year of settlement (t_0)	Current situation, 2015 (t1)
Land resources			
Household-level land available per capita (PerCapitaland)	ha	0.38 ± 0.24	0.09 ± 0.06
Cropping orientation			
Area dedicated to food crops (FoodCropArea)	ha	0.62 ± 0.38	0.45 ± 0.32
Area dedicated to cash crops (CashCropArea)	ha	0.07 ± 0.09	0.17 ± 0.15
Livestock management			
Livestock size per household	TLU[a]	6.07 ± 5.24	2.98 ± 4.23
Proportion of feed purchased (FeedPurchased)	%	2.93 ± 9.36	19.48 ± 17.51
Off-farm activities			
Proportion of off-farm income (InOffFarm)	%	5.86 ± 13.51	9.13 ± 14.54
Food purchase dependence			
Proportion of income used for food purchases (RatioExpFood)	%	11.81 ± 4.16	24.32 ± 6.18

[a] One Tropical Livestock Unit corresponds to a value of 250 kg live weight for 1 TLU (Le Houérou and Hoste, 1977). Sheep and goats were assumed to be equivalent to 0.1 TLU, donkeys to 0.5 TLU, horses to 0.8 TLU and all types of cattle to 0.7 TLU (Jahnke, 1982).

Principal component analysis (PCA) was used to examine the rate of change of the selected variables, and the PCA output was used to partition the dataset into clusters (Bidogeza *et al.*, 2009; Tittonell *et al.*, 2010; Cortez-Arriola *et al.*, 2015). The number of principal components (PCs) was selected based on the Kaiser's criterion, i.e., all PCs with an eigenvalue exceeding 1 were retained (Hervé, 2011). The PCA output was further analysed using cluster analysis based on a hierarchical agglomerative clustering algorithm using the Ward's method. This algorithm progressively groups together the observations according to their similarity (measured by a dissimilarity index, Ward's minimum variance criterion), minimizing the augmentation of the total intra-class inertia (Ward Jr, 1963). The resulting clusters were examined in terms of their position in two PCs planes defined by PCA1, PCA2, and PCA3 representing 28.1%, 18.3%, and 15.4% of the variability respectively. Three axes were necessary to explain 61.7% of the variability (Eigen-value = 1.07). The resulting clusters represent broad trajectories of farming systems between t_0 and t_1. All analyses were conducted using R software (version 3.2.1; R Core team, 2015) with the chart.correlation function from the Performance Analytics package for constructing correlation plots (Peterson and Carl, 2018) and the *ade4* package for PCA (Dray et al, 2007).

2.6 Land cover change analysis using satellite images

A quantitative land cover analysis of the Hawassa area was conducted for 1984, 1998, and 2014, using Landsat 8 OLI/TIRS data for 2014 and Landsat 5 TM data for 1984 and 1998. The choice of years of image acquisition allows for a comparison of the current state with the periods preceding and following the Communism period (the Derg), identified by farmers as an important political driver of change. All images had a 30×30 m resolution. Following the procedure described in Kebede *et al.* (2018), an object-based classification was conducted for 1984, 1998 and 2014 in which related pixels were grouped in objects using eCognition (Blaschke, 2010) and cropped and non-cropped areas could be distinguished. Using a phenology-based classification approach, cropland was further subdivided into the following classes: annual, perennial, perennial dominated mixed crops, and annual dominated mixed crops (Wang *et al.*, 2010). Fields were classified as mixed crops when their size was smaller than the resolution of the image (30×30 m) and could not be classified as annual or perennial crops. Changes in land cover were assessed as the difference in the land cover class (in ha and percentage) through pixel-by-pixel comparisons between 1984 and 1998 and between 1998 and 2014 using Erdas software (Lu *et al.*, 2004).

3 Results

3.1 Description of current farming systems

The farm survey indicated that respondents were mostly male (88%) with a mean age between 40 and 50 years, while the average household member ranged between seven and eight members increasing from Hawassa Zuria to Wondo Genet (Table 2). The main food crops were maize (*Zea mays*) and enset (*Ensete ventricosum*), while the main cash crops were khat (*Catha edulis*) and coffee (*Coffea arabica*) with areas varying between the three districts (Table 2). While the district of Hawassa Zuria is oriented toward food crop production (maize, enset, and haricot bean), Tula and Wondo Genet have more cash crops, such as khat and coffee. Households owned between two to three TLU and the sale of livestock constituted the third source of income in the three districts. The average milk production was about one litre/cow/day for the three districts and mostly destined to household consumption.

3.2 Drivers of change as perceived by farmers

The focus group discussions indicated that farmers perceived political regime shifts, climatic conditions, and pest and disease outbreaks as the main drivers of change in their farming systems. Before 1970, livestock diseases exterminated large numbers of cattle. The land use right policy (1974), which marked the end of a feudal system and gave landless people access to land, and the end of the communist regime (Derg) in 1991, were the two major national level political drivers of farming systems changes. Extreme weather conditions (hail, flood, and drought) periodically affected maize productivity. During dry years, locust and maize stemborer were reported as major maize pests. After the year 2000, governmental extension services started a campaign to inform the residents of the study area about improved farming practices and have provided subsidies for agricultural inputs (fertilisers and seeds). Currently, maize (the major staple food) productivity remains very variable and subject to climate hazards and input availability. Average number of members per household has been increasing due to a combined effect of polygamy and improved health access (Fig. 2).

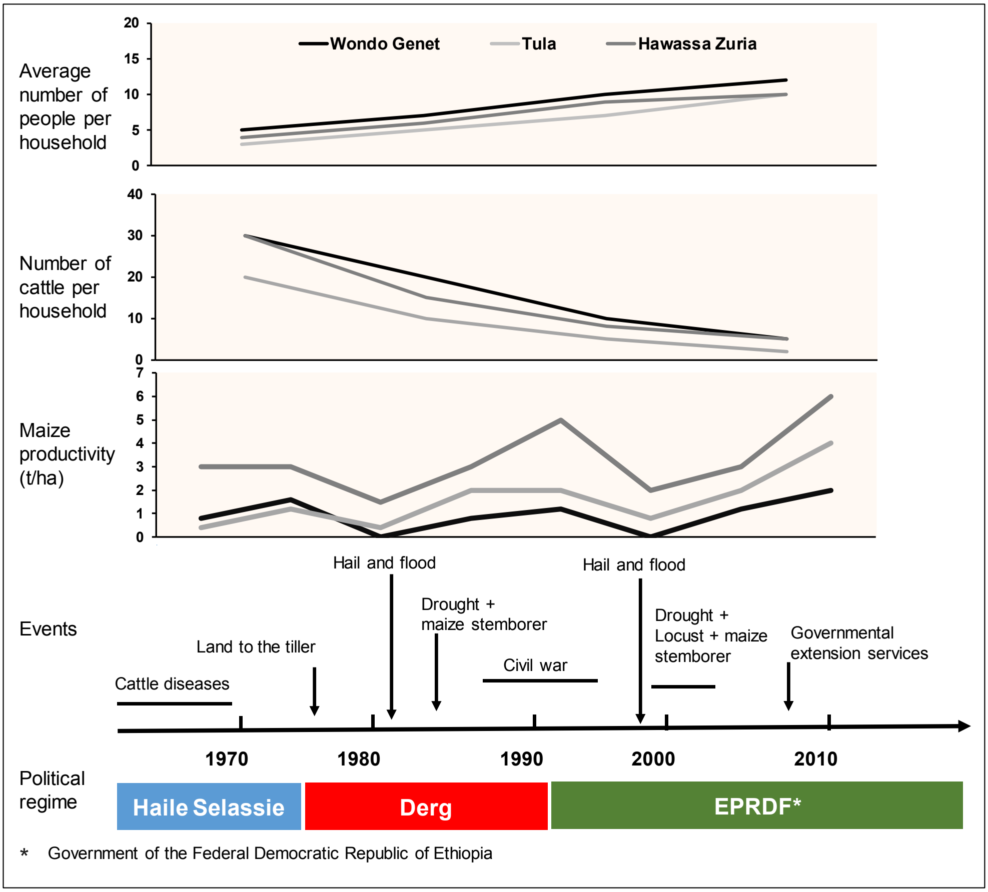


Figure 2: Farmer's perception of historical changes in maize productivity and livestock numbers per household from 1970s to current situation (n = 60).

3.3 Farmers' responses: typology of farming system trajectories

Farmers delineated four farm types based on the farm size, the number of livestock, the variety of crops in the farm, the capacity of the household to send children to school, and the type of housing as criteria for classifying current farming systems and livelihoods (Appendix 1). Generally, three main livelihood strategies with three types of assets or activities contributing to livelihood strategies have been identified. The farmers' strategy consisting of accumulating assets from existing activities for moving into different activities that have higher and/or more stable returns is referred to as specialisation or 'stepping out' strategy (Dorward *et al.*, 2009). Consolidation or 'stepping up' strategy refers to an expansion of existing activities in order to increase production and income. Livelihood diversification is defined as the process by which rural families construct a diverse portfolio of activities and social support capabilities in order to survive and to improve their standards of living (Tittonell, 2014). Based on the cluster analysis, three main trajectories of farming systems change could be distinguished corresponding to three main strategies: ‘consolidation’ (type 1), ‘diversification’ (type 2), and ‘specialisation’ (type 3) (Appendix 2) representing respectively 39, 12, and 9 farmers out of the total of 60. Although these three trajectories differ in current production orientation, some trends in farm structural changes between the two time periods are common to them: (i) a decline in per capita land holding (with highest decrease for the diversification trajectory) and livestock numbers (with highest decrease for the specialisation trajectory), (ii) an increase of cash crop production (with highest increase for the specialisation trajectory) and in the proportion of food purchased by the household, and (iii) a decrease in non-cultivated land with a lesser extent for the consolidation trajectory (Fig. 3, Appendix 3). Under the consolidation trajectory, the proportion of land dedicated to food crop production was maintained or increased, while it has decreased in the two other trajectories (with the highest decrease for the diversification trajectory). While many farmers were self-sufficient in food production at the time they started farming, they are now purchasing up to 70% of their food. The consolidation trajectory was found evenly distributed in the three districts with 15, 13 and 11 farmers out of the 60 in Hawassa Zuria, Tula, and Wondo Genet, respectively. However, the specialisation trajectory was mainly found in Wondo Genet and Tula with respectively 9 and 4 farmers and only 1 farmer in Hawassa Zuria.

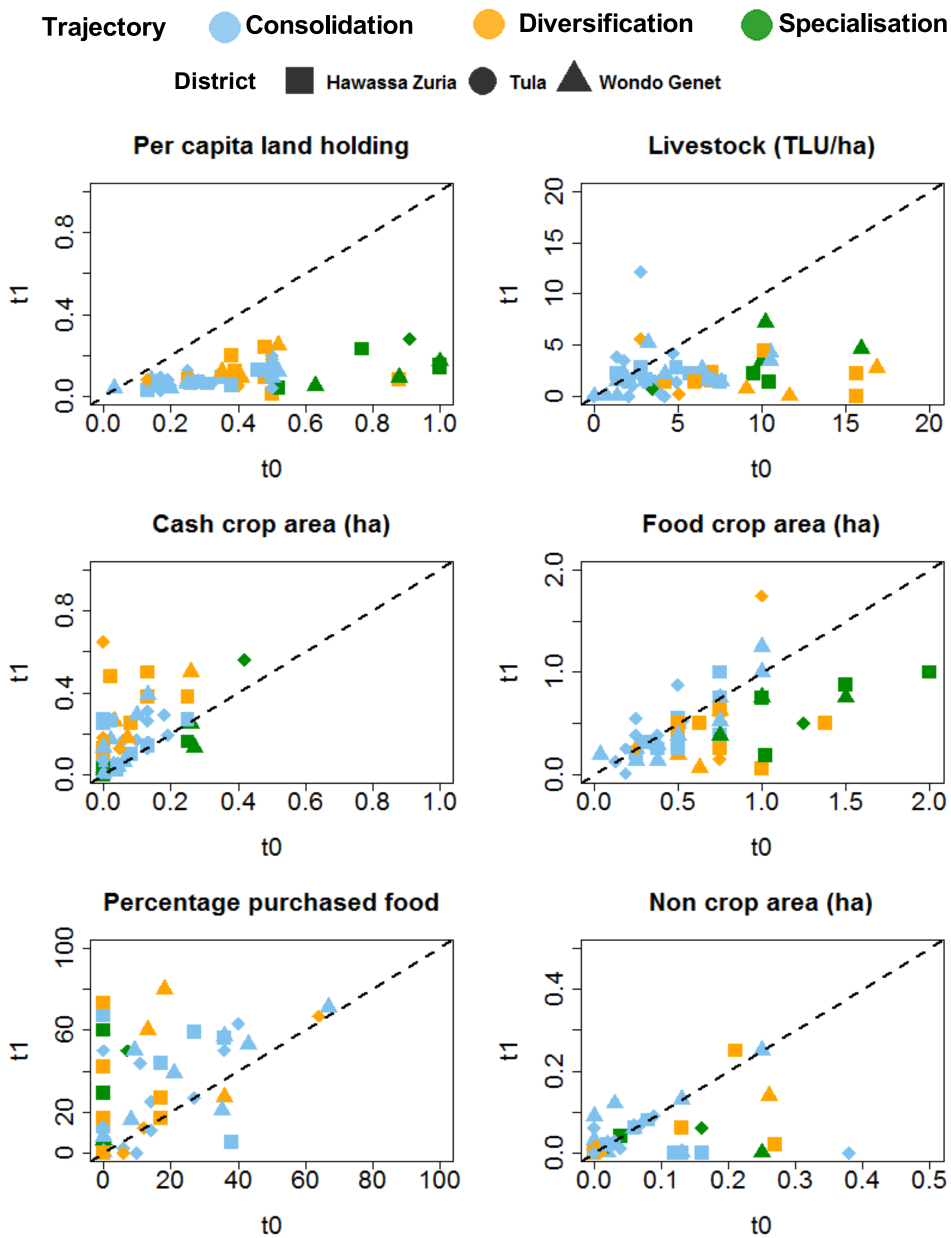


Figure 3: Per capita land holding (A), number of livestock (B), cash crop area (C) and food crop area (D) per farming system trajectory type, percentage of purchased food (E), area of non-cultivated land (F) at two time periods (year of settlement and 2015) per trajectory type (1, 2, 3).

3.4 Current agricultural landscape composition

During the focus group discussion on land cover changes, farmers indicated that the land cover in the three districts was dominated by forest and grassland up to the early 1970's. The principal occupation of farmers was livestock rearing and only a limited area of the land was used for arable crops. From the late seventies to 2015, the area of cropland expanded and has become the main land cover in each district. Maize was the dominant crop in the 1980s covering 90%, 55%, and 65% of the arable land in Hawassa Zuria, Tula, and Wondo Genet, respectively (Fig. 4D, Fig. 4E, and Fig. 4F). After 1990, in Hawassa Zuria, maize was progressively replaced by enset, haricot beans (*Phaseolus vulgaris*) (generally intercropped with maize), and diverse home gardens (Fig. 4D). In Tula, khat increased from less than 5% of the cropland in the 1980's to 30% in 2014, and enset decreased by about 10% along the same period (Fig. 4E). In Wondo Genet, khat was not grown in the 1980's and covered 45% of the arable land in 2014, while enset decreased from 20% to 10% during the same period (Fig. 4F). The land cover change analysis with remote sensing confirmed these changes. The most pronounced changes involved an increase in the area of perennial crops and a decrease in the area of annual crops (mainly maize), grasslands, and bare soil in the whole study area between 1984 and 2014. Mixed croplands, perennial or annual, were relatively stable throughout the study period. The built up area tripled over the same period (Fig. 5B).

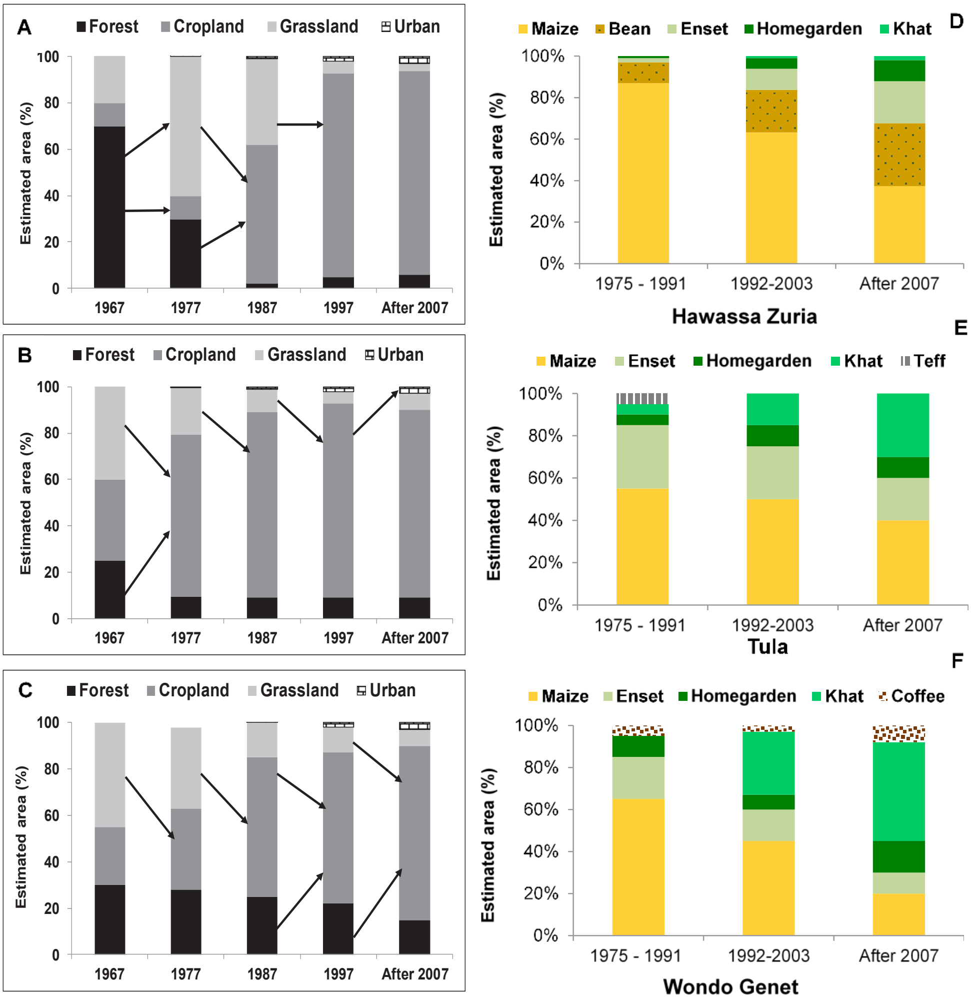


Figure 4: Farmers' perception of historical land cover changes from 1970's to the current situation for the three districts in Hawassa Zuria (A), Tula (B), Wondo Genet (C). Arrows indicate the shift of a land cover class; and farmers' perception of historical land use changes after the land use right reform in 1975 to current situation for the three districts in Hawassa Zuria (D), Tula (E), Wondo Genet (F).

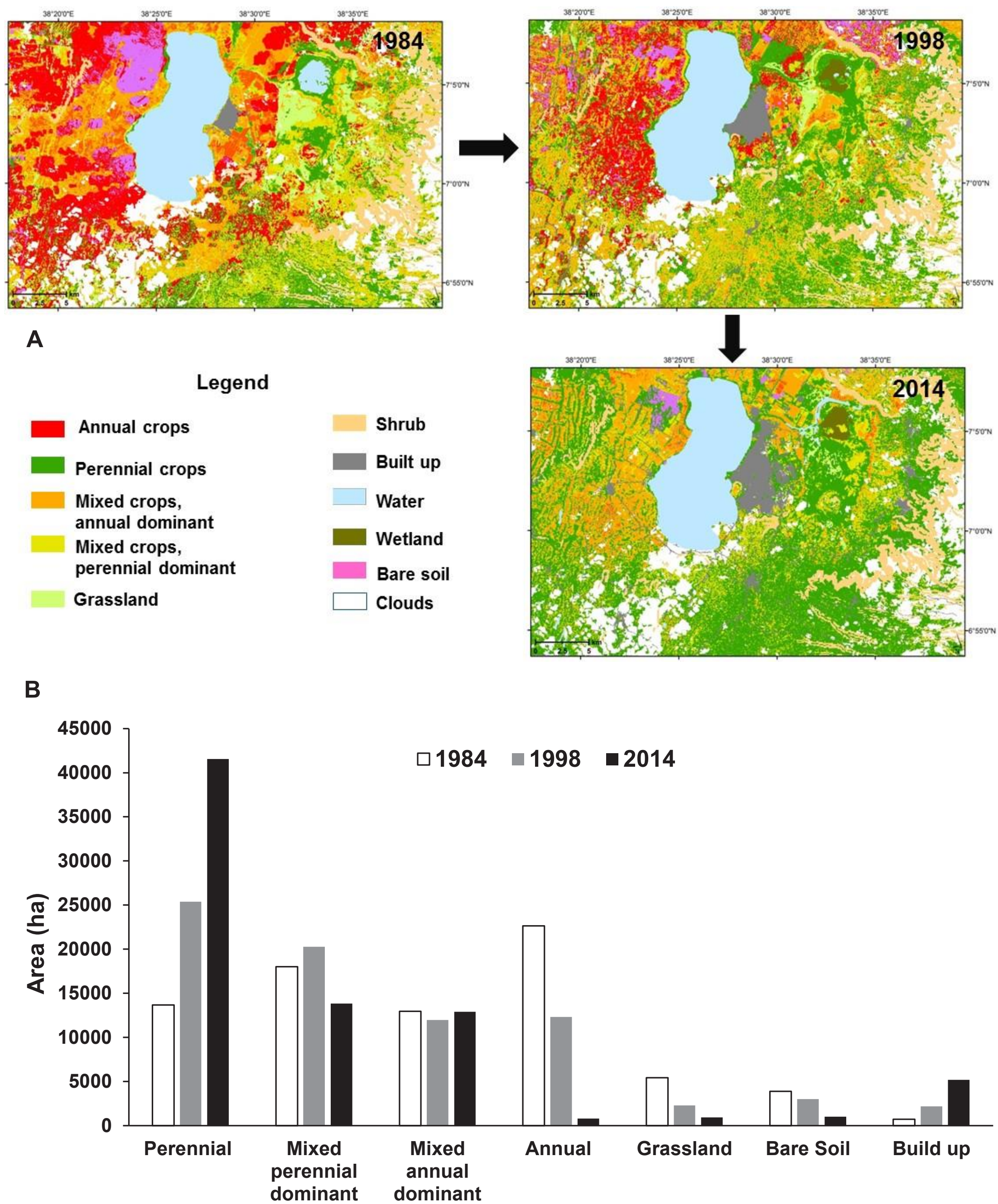


Figure 5: Quantitative analysis of land cover/land use changes using Landsat satellite images for 1984, 1998, and 2014.

4 Discussion

We found that national level policies, extreme climatic events, biotic stress, population increase, and urban expansion were major drivers of farming systems changes in the Hawassa area. At the local level, population growth, the expansion of urban areas, the biophysical conditions found in each district (in particular soil fertility) and the distance to markets influenced land cover/land use changes and farming systems. Per capita land and livestock numbers decreased for the three districts leading to variable responses in farmers' livelihood strategies. Three trajectories of change of farming systems were identified: (1) consolidation and maintenance of farm size for food crop production and number of livestock with a slight increase in off-farm income, (2) diversification, with a slight increase in cash crop area and livestock, and (3) specialisation, with the highest increase in cash crop area combined with reduced livestock numbers. These changes led to a more fragmented (a larger number of small size farms) and diverse landscape, with a more even distribution of crop types. Such fragmentation and diversification of the agricultural landscape has consequences for the provision of ecosystem services of local and global importance (Lambin and Meyfroidt, 2010; Meshesha *et al.*, 2013; Newbold *et al.*, 2015; Kremen and Merenlender, 2018), as discussed in subsequent sections.

4.1 Current farming systems in Hawassa area

Current farming systems in the three districts of the Hawassa area are mixed crop-livestock systems with variable integration levels between the crop and livestock components. Although similar crop types were found in the three districts (enset, khat, maize, and common bean; coffee was only found in Tula and Wondo Genet), the average area allocation for those crops varied between the three districts. Hawassa Zuria remained predominantly oriented towards maize production, building on the historical State farms during the Derg period (cf. Fig. 4D). However, the periodic failure in maize production due to the combined effects of poor rainfall, soil quality decline, and inadequate soil fertility management (Abebe and Feyisa, 2017) led farmers, with the support of local authorities, to reconvert part of their land to enset production. Enset, a drought-resistant crop with high cultural value for Southern Ethiopia, ensures food for more than 15 million people (Abebe *et al.*, 2009) and an essential green feed resource during the dry season. Homegardens in Southern Ethiopia are diverse systems where crop and non-crop plants are found (Abebe *et al.*, 2006; Lemessa and Legesse, 2018). Although small in extent, vegetables such as potatoes, cabbages, tomatoes, sweet potatoes, chilli peppers, and fruit trees (avocado, mango, and banana) were found. These crops were mainly managed by women and play an important role in the dietary diversity of the household and in filling the food gap during the dry season (Calvet-Mir *et al.*, 2016; Gbedomon *et al.*, 2017; Lemessa and Legesse, 2018; Mellisse *et al.*, 2018). In terms of livestock management, next to free ranging, roadside grazing, and/or zero grazing practices, farmers also practise dry-season transhumance to Cheleleka wetlands in the northeast of the Hawassa area where communal grazing lands are available.

4.2 Drivers of change of farming systems

Farmers' perception of drivers of change gave a strong focus on historical political regime changes, abiotic constraints (climate variability and extreme weather events, such as erratic rainfall, hail, and drought episodes), and biotic constraints (animal disease and pest outbreaks). These drivers of land cover/land use change are similar to those reported at national or even international level across Africa (Reid *et al.*, 2000). Farmers reported an increased household size over the studied period, but they did not mention a strong impact on household food security. However, in Tula and Hawassa Zuria some farmers indicated that their production did not allow them to meet the household's need. This is confirmed by the national safety need programme running in those districts (Sharp *et al.* 2006), which provide food in exchange for labour for the community or the municipality. This is a surprising phenomenon since Tula is the closest of the three districts to Hawassa town, an important khat market, implying that off-farm opportunities are high. However, only about 10% of farmers in Tula indicated off-farm activity as their primary source of cash. The proximity to Hawassa town may actually represent a threat for some farmers. Indeed, with an increasing cost of land in Hawassa town and an on-going plan to transform Tula into Hawassa' s sub-city, middle men are approaching farmers to convince them to sell all or part of their land with the intend of purchasing it at an extremely low price compared to the potential (high) value the land would fetch as urban ground (Gebeyehu Admasu, 2015). This is an uncontrolled land market even though land in Ethiopia is state-owned and not meant to be traded. However, once the land is acquired by a middleman, whenever any infrastructure is built on it, it becomes legally more difficult for governmental authorities to reclaim the property. This process is also taking place in the other two districts, thus influencing the land use changes in the overall Hawassa area (Gebeyehu Admasu, 2015).

4.3 Typology of household trajectories

Three trajectories of farmers' adaptation strategies to decreasing land size and livestock numbers were observed: consolidation (65% of households), diversification (15% of households) and specialisation (20% of households). A majority of farmers followed the consolidation trajectory maintaining food crop production and livestock and slightly increasing cash crop area. In the study area, sharing harvest with less-endowed farmers in exchange for labour is a common practice ('shared cropping'), which might benefit the farmers grouped under the diversification trajectory. Indeed, the diversification group has the highest reduction in farmland size with low income from cash crops. Farmers who engaged in the specialisation trajectory (mostly in Wondo Genet and Tula) were able to take this direction due to a combined effect of market proximity (Fig. 6A) and biophysical potential for khat and coffee production (Mellisse *et al.*, 2017). In addition, the production of khat has only been tolerated since the end of the Derg regime (previously not encouraged). The observed shift in favour of this high-profit cash crop has been seen in other regions of Ethiopia that were mostly coffee-oriented (Mellisse *et al.*, 2017). Both coffee and khat are important export commodities for Ethiopia. In the last 15 years, khat gained popularity among smallholders over coffee production due to the high and constant market demand for this stimulant produce. In addition, khat can be harvested two to three times per year, is relatively quick to establish (one to two years) and is less demanding in management or input compared to annual crops. These specificities make khat a very competitive cash crop over coffee production, although traditional subsistence food crops, such as maize and beans, can still be important sources of income (i.e., in Hawassa Zuria, see Table 2). The time to reach the market plays a role on the income from off-farm work opportunities (Fig. 6B): the majority of farmers engaged in off-farm activities are within an hour of the nearest market.

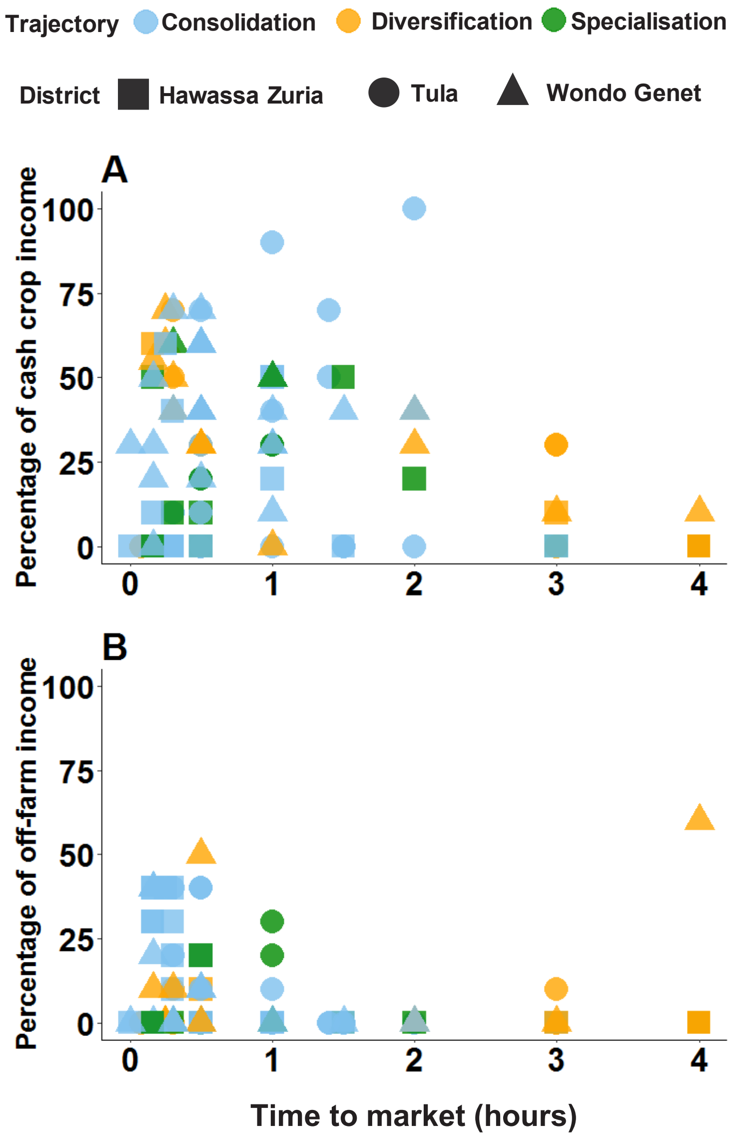


Figure 6: Percentage of cash crop income (A) and ratio of off-farm activity income (B) in relation to the time to reach the nearest market per trajectory.

4.4 Consequences for landscapes

From the 1970's to the 1980's the land cover/land use changes in the Hawassa area consisted of the replacement of forest and grasslands areas by croplands (Fig. 5) as reported by Negash and Niehof (2004) and Reid *et al.* (2000). Landscape changes included a reduction in field sizes and an increase of perennial crops (khat and enset) at the expense of annual crops, grasslands, and bare soil. The main consequences of the landscape changes are habitat loss for wildlife and a decrease in water availability (Shewangizaw, 2010; Dessie and Kinlund, 2016). In Wondo Genet, the expansion of the khat resulted in a decline of natural forests and an associated forest fragmentation in major khat producing areas, a decline in food crop production, and soil erosion from steep land cultivation (Reynolds *et al.*, 2010). Farmers reported that attacks on their maize fields by baboons was one of the reasons they decreased maize production. The decrease in water availability has been reported by previous studies which investigated the effect of land cover/land use change on the hydraulic regime and water volume of Lake Hawassa (Shewangizaw, 2010; Abebe *et al.*, 2018). A remarkable feature on the land classification map (Fig. 5A), is the vanishing of what used to be the Lake Cheleleka in the northeast of Hawassa area, which is now a wetland. In Hawassa Zuria, the decline of forest and current continuous removal of trees and shrubs for firewood is leading to major flood and gully erosion (Gebretsadik, 2014). However, the higher diversity and complexity of Wondo Genet could have a beneficial effect on the biocontrol of major pests (Kebede *et al.*, 2018).

5 Conclusions

Farming systems in the Hawassa area have been subjected to dynamic and rapid changes over the last 30 years. These changes were due to a combined effect of national level policies, regional urban expansion, population growth, extreme climatic conditions, and households' livelihood assets. In addition, other drivers, such as the informal and lucrative land market associated with the proximity of Hawassa town, have had a strong influence on land use changes. Diversification, the intensification of current cropland through mixed-cropping and intercropping, and the orientation towards high value cash crops are among the strategies adopted by farmers to cope with reduced availability of cropland. These socio-ecological changes associated with livelihood strategies and household trajectories resulted in changes in landscape structure and composition, specifically in fragmentation and diversification, which may have implications for the provision of ecosystem services including, food provisioning. The decrease in forest and continuous cropping with the associated loss of soil fertility is already impacting current productivity and might have a severe negative impact on the future agricultural production potential of the area. A better understanding of interlinkages and trade-offs among ecosystem services and the spatial scales at which the services are generated, used, and interact is needed in order to successfully inform future land use policies. More concretely, one priority should be the investment in natural capital in the form of reforestation, whatever the future rural or urban land use orientation of the Hawassa area would be. This will require an important coordination between the institutions involved in the governance of the overall landscape (e.g. agriculture, environment ministries, urban expansion planners, and farmer associations). It would be valuable to also engage youth associations in these efforts, as the lack of access to land and a general disinterest in farming is already pushing many young people towards urban areas.

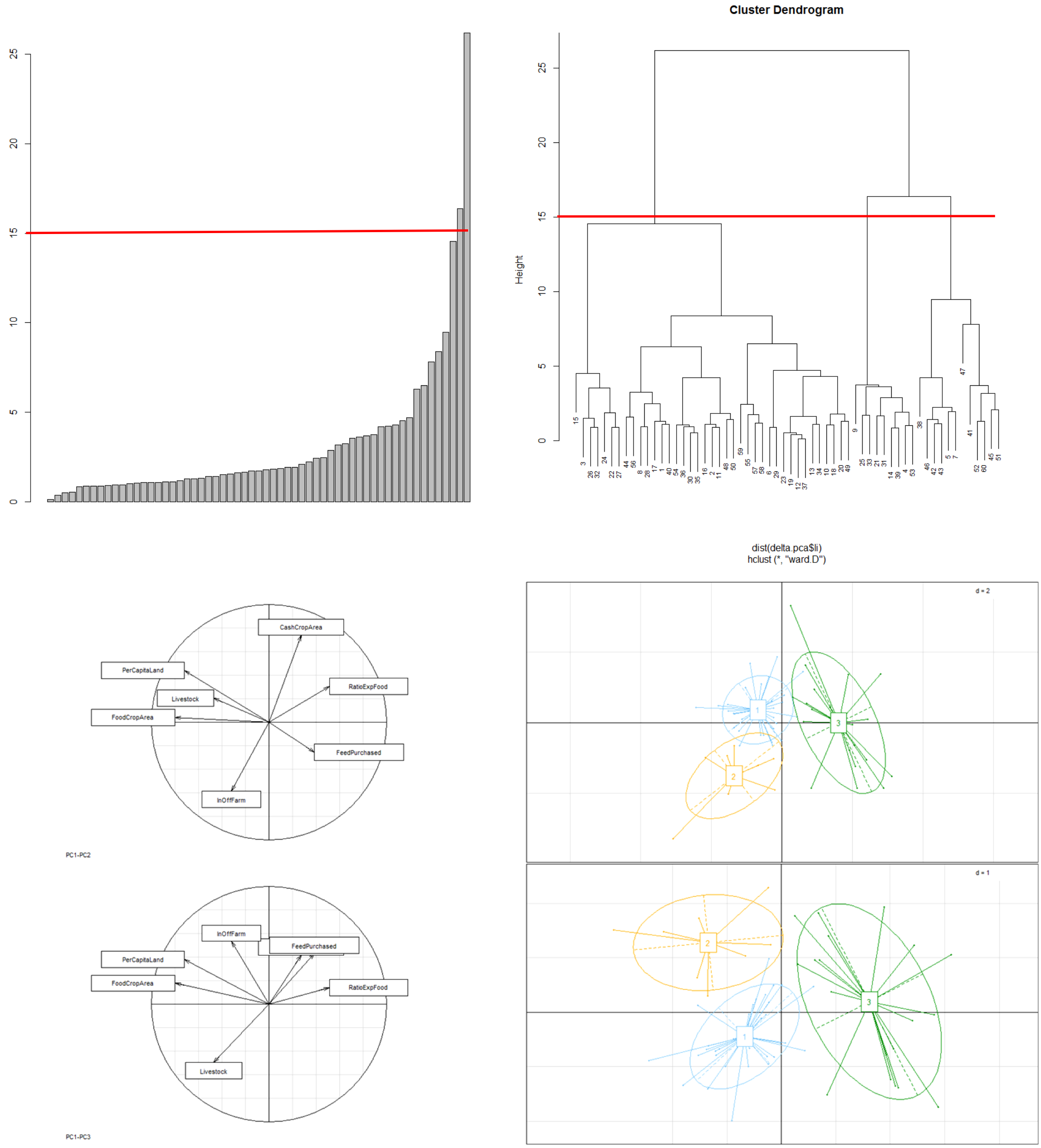
6 Acknowledgments

We thank Kassahun Lemi Woyessa, Abraham Kifle for their support in conducting the focus group discussions. We also thank the EIAR-Hawassa Maize Centre staff members: Zerihun Haile, Tesefaye Degefu Maeden Tadesse, Tewabech Telahun for their expertise as enumerators. We are very grateful to the farmers who participated in the survey and the focus group discussions.

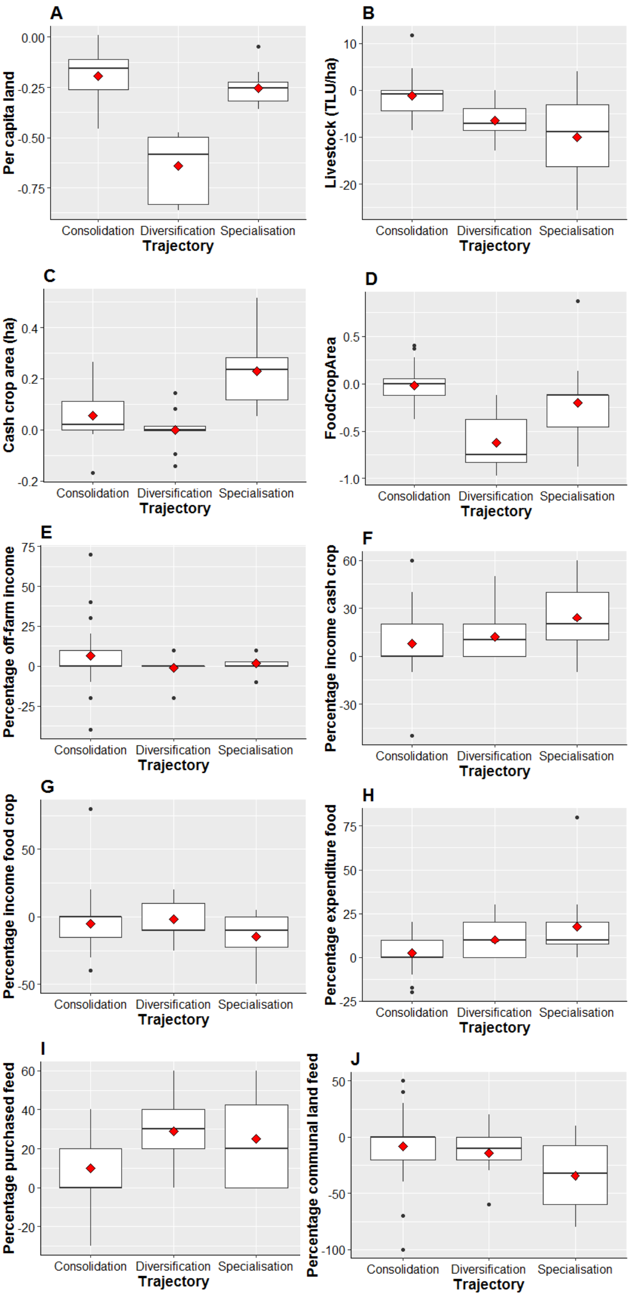
Appendix 1: Self-categorisation criteria obtained from the focus group discussions

Criteria	Description
Selected by farmers in the three districts	
Food security	Food self-sufficient family with surplus for market sale (1); Food self-sufficient family (2); Partially food self-sufficient family with off-farm activity (3); Food insecure family, dependent on external support (4)
Livestock size	More than ten cattle, small ruminants with transporting animals (1); pair of oxen, cows, small ruminants (2); single or no oxen, cow with /out small ruminants (3); no livestock (4)
Arable land size	> 1ha (1); >0.5 ha (2); <0.5 ha (3); <0.25 (4) ha or landless
Use of agricultural technologies	Use of fertilisers and improved seeds regularly (1); using inputs occasionally (2) and using inputs very occasionally (3); can't afford purchasing inputs (4)
Selected by farmers in two districts (Wondo Genet and Tula)	
Home garden crop diversity	Produce diverse food and cash crops (1); produce different crops (2);, focusing on food crops (maize, enset) (3)
Irrigation	Own water pump or point and produce different crops three times per annum 91); hire or borrow water pump and produce different crops 92); use furrow or hand spray, have no access to irrigation water (3)
Educating children	Can send children to private schools (1); can send children to public school (2); send children to public school but do not fulfil all needs (3); unable to send children to
Selected by farmers in one of the three districts (Tula)	
Number of coffee trees	300-400-coffee trees (1); 30-40 coffee trees (2); 5-7 coffee trees (3); no coffee tree (4)
Maize productivity	Can harvest up to 60 quintals per ha (1); up to 15 quintals per ha (2) and (3); up to 10 quintals per ha (4)
Housing type	Can afford housing in urban area to rent out or live in (1); corrugated roof housing (2) and (3); thatched roof housing (4)

Appendix 2: Principal component analysis of trajectories of change of farming systems: three types of trajectories can be observed: consolidation (type 1), diversification (type 2), and specialisation (type 3).



Appendix 3: Changes in farm structure and production orientation of the three trajectories (consolidation, diversification, and specialisation).



Chapter 3

Implications of changes in land cover and landscape structure for the biocontrol potential of stemborers in Ethiopia

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Abstract

The land cover and structure of agricultural landscapes may influence the abundance and diversity of natural enemies of crop pests. However, these landscapes are continuously evolving due to changing land uses and agricultural practices. Here, we assess changes in land use and landscape structure in a landscape in the Rift Valley region of Ethiopia and explore the impact these changes are likely to have on the capacity of the landscape to support communities of natural enemies of maize stemborers *Busseola fusca* (Fuller). Land use and landscape structure were assessed in three periods over the last 30 years using focus group discussions with farmers and land use analysis through remote sensing. Natural enemies were sampled in maize fields adjacent to simple hedgerows, complex hedgerows, enset fields, and khat fields at 1, 10, and 30 m using pitfalls and yellow pan traps in 2014 and 2015. The landscape analysis indicated that landscapes in the study area changed from maize-dominated to more diverse small-scale and fragmented agroecosystems with a higher proportion of perennial crops. Maize fields adjacent to enset and complex hedgerows hosted significantly more predators (15.1 ± 9.8 and 22.3 ± 5.1 per trap at 1 m from the border, respectively) than maize fields adjacent to khat and simple hedgerows (7.2 ± 1.1 and 7.3 ± 1.7 per trap at 1 m from the border), and the effects of border type decreased with distance from the border. The abundance of parasitoids and parasitic flies were not influenced by border type. Our findings suggest that the changes in land use and landscape structure may have influenced the capacity of the landscape to support populations of natural enemies of stemborers in different ways. On the one hand, smaller field sizes have resulted in more field borders that may support relatively high predator densities; on the other hand, the area of khat increased, and the area of enset decreased, both of which may have a negative effect on predator densities. The overall outcome will depend on the interplay of these opposing effects.

1. Introduction

Agriculture benefits from biocontrol services provided by natural enemies of crop pests (Losey & Vaughan, 2006). Natural enemies require resources, such as food and shelter, which may be scattered in space and time across the landscape. The composition and spatial arrangement of crop and non-crop habitats in the landscape mosaic may therefore influence abundance and diversity of natural enemies and the biocontrol function they provide (Bianchi *et al.*, 2006; Landis *et al.*, 2008; O'Rourke *et al.*, 2011; Woltz *et al.*, 2012). However, agricultural landscapes are not static but subject to continuous changes. For instance, land use dynamics and changing agricultural practices may lead to changes in land cover (the biophysical cover of the earth's surface) and landscape structure (the spatial pattern of landscape elements and the connections between them). Such changes may influence resource availability for natural enemies and the disturbance levels they are subjected to (Rand *et al.*, 2006; Tscharntke *et al.*, 2005). Yet little is known about the consequences of land cover changes for the natural enemy complex across agricultural landscapes and their potential to suppress crop pests (Werling *et al.*, 2014). Such information is even scarcer in sub-Saharan Africa than in Europe or North America (Lemessa *et al.*, 2015b; Shackelford *et al.*, 2013).

African agroecosystems are complex socio-ecological systems that are managed for multiple outcomes, including food, nutritional security, and income generation. They also tend to be diverse; for example, in the Rift Valley region of Ethiopia, agroecosystems are generally fine- grained landscape mosaics composed of hedgerows (e.g. *Euphorbia* spp., *Lantana* spp.), agricultural fields, grasslands, forest patches and scattered trees. Dominant crops include maize (*Zea mays* L.), enset (*Enset ventricosum* (Welw.) Cheesman, a perennial tuber crop), khat (*Catha edulis* Forsk, a perennial stimulant crop), coffee (*Coffea arabica* L.), common beans (*Phaseolus vulgaris* L.) and teff (*Eragrostis tef* Zucc.) Trotter, a small grain cereal). These crops are generally produced in small fields of usually less than one hectare, combined with multipurpose trees, and grazed by livestock (Abate *et al.*, 2000; Abebe *et al.*, 2006; Lemessa *et al.*, 2013).

In the Hawassa area, in the Rift Valley region of Ethiopia, there has been a trend of decreasing maize production and increasing cash crop production, particularly khat and sugar cane (Abebe, 2013; Abebe *et al.*, 2009). Because of the doubling of the population in the last 30 years (Dira and Hewlett, 2016) and lack of off-farm employment opportunities, farms have been subdivided into ever smaller farms and parcels, and non-cropped land has been converted to agriculture. These changes may impact the population of natural enemies of crop pests through two concomitant effects: (i) different crops and crop border vegetation types may provide different resources, microclimates, and disturbance levels for natural enemies, and (ii) field size may affect the crop colonisation process by natural enemies.

Maize is a major food crop in the Rift Valley region of Ethiopia, where yields are often low (average of 2.4 t ha−1 in 2013; Kassie *et al.*, 2014) because of low input use, erratic rainfall patterns, degraded soils, and pest infestations (Worku *et al.*, 2011). The stemborer *Busseola fusca* (Fuller) (Lepidoptera: Noctuidae) is a major pest of maize in the region (Gebre-Amlak, 1989; Getu *et al.*, 2001), where crop losses may be as high as 26% by the first generation and up to 100% by the second (Gebre-Amlak, 1989). Typically, farmers in the Rift Valley do not control *B. fusca* with insecticides because they often cannot afford them, and insecticides are not very efficient against larvae that tunnel into maize stems and cobs (Kfir *et al.*, 2002). There is a suite of natural enemies that attack different stages of *B. fusca*, and may provide top-down control (Bonhof *et al.*, 1997; Gounou *et al.*, 2009). However, little is known about the impact of the above-mentioned changes in land use and landscape structure on the natural enemy complex and on the biocontrol potential of *B. fusca*.

This paper aims to fill this knowledge gap (i) by analysing how agroecosystems have changed in the last three decades in terms of land cover and landscape structure in a study landscape of the Rift Valley region of Ethiopia and (ii) by assessing how adjacent crops and habitats influence the abundance of important natural enemy groups of *B. fusca* in maize fields in the same landscape. We hypothesise that (i) changes in social, economic, and political drivers have resulted in changes in land use and landscape structure between 1980's and 2014, and that (ii) maize fields adjacent to relatively stable habitats (hedgerows and enset fields) host a larger community of natural enemies than maize fields adjacent to more disturbed land uses (maize and khat fields).

2. Material and methods

2.1 Study area

The study area is located in the district of Tula near Hawassa Lake in the Ethiopian Rift Valley (latitude 7°0′25′′–6°56′35′′ N and longitude 38°27′58′′–38°29′47′′ E; Fig. 1). The area has a moist to sub-humid warm subtropical climate with annual precipitation ranging from 750 to 1200 mm in a bimodal distribution pattern from March to April and June to August (Dessie and Kleman, 2007). The landscape is heterogeneous and the average farm size is below one hectare of arable land (Dessie and Kinlund, 2008; Dessie and Kleman, 2007). Farms are dominated by mixed crop-livestock systems with maize, bean, enset, and khat as main crops (maize and bean are often intercropped in the same field).

2.2 Focus group discussions

To assess farmers' knowledge and perceptions about important historical periods of land cover change and the nature of these changes, a focus group discussion was conducted with 20 key informants from Tula. Participants were asked to draw a timeline to identify periods of major changes in land cover and to estimate the proportion of each land cover type and major crops. The discussions revealed that the years 1984 (the start of the communist Derg regime), and 1998 (the end of the same regime, represented key transitions for land cover change. These milestone years were used for selecting satellite images for land cover analysis.

2.3 Land cover classification

A quantitative land cover analysis of the Hawassa area was conducted for 1984, 1998, and 2014 using Landsat 8 OLI/TIRS data for 2014 and Landsat 5 TM data for 1984 and 1998. All images had a 30×30 m resolution. The analysis focused on an area of 5×6 km area around Tula, referred to as the study area in the rest of the paper (Fig. 1). After radiometric correction, the different bands of each image were stacked into a single image. An object-based classification was conducted for 1984, 1998, and 2014 in which related pixels were grouped in objects using eCognition (Blaschke, 2010), and cropped and non-cropped areas could be distinguished. Using a phenology-based classification approach, cropland was further subdivided into the following classes: annual, perennial, perennial dominated mixed crops, and annual dominated mixed crops (Wang *et al.*, 2011). Fields were classified as mixed crops when their size was smaller than the resolution of the image (30 × 30 m) and could not be classified as annual or perennial crops. The accuracy of the classification was assessed for 1984 using aerial images from 1972 and a topographic map from 1988; it was 77.1% accurate. For 2014, the accuracy was assessed by ground truthing with 30 GPS points per class and was 75.8%. These accuracy levels fall within the 67–87% range that has been reported in other pixel-based classification analyses in Ethiopia (Meshesha *et al.*, 2013). Changes in land cover were assessed as the difference in the land cover class (in ha and percentage) through pixel-by-pixel comparisons between 1984 and 1998 and between 1998 and 2014 using Erdas software (Lu *et al.*, 2004).

2.4 Landscape metrics

To assess changes in landscape structure between 1984, 1998, and 2014, we selected landscape sectors of one km radius centred around each of the 16 focal maize fields selected for the natural enemies density assessment (see below; Fig. 1). The area of perennial crops, mixed crops, and annual crops were assessed within each sector for 1984, 1998, and 2014. The proximity index between annual and perennial crops, patch density, and edge density of each land cover type were calculated using Fragstats (McGarigal *et al.*, 2002). The proximity index (without dimension) is a measure of the closeness of patches and is derived by dividing the summed patch area by the nearest patch to patch distance between annual and perennial crops. High values of the proximity index indicate small distances between annual and perennial crops and can be considered as a proxy for the potential insect population exchange between annual and perennial crops. Patch density is calculated as the number of patches of each land cover class per unit area (3.14 km^2). Edge density ($m\ ha^{-1}$) is a measure of the perimeter to area ratio of patches calculated for each land cover class by dividing the total edge length of patches by the area of the landscape sector (3.14 km^2).

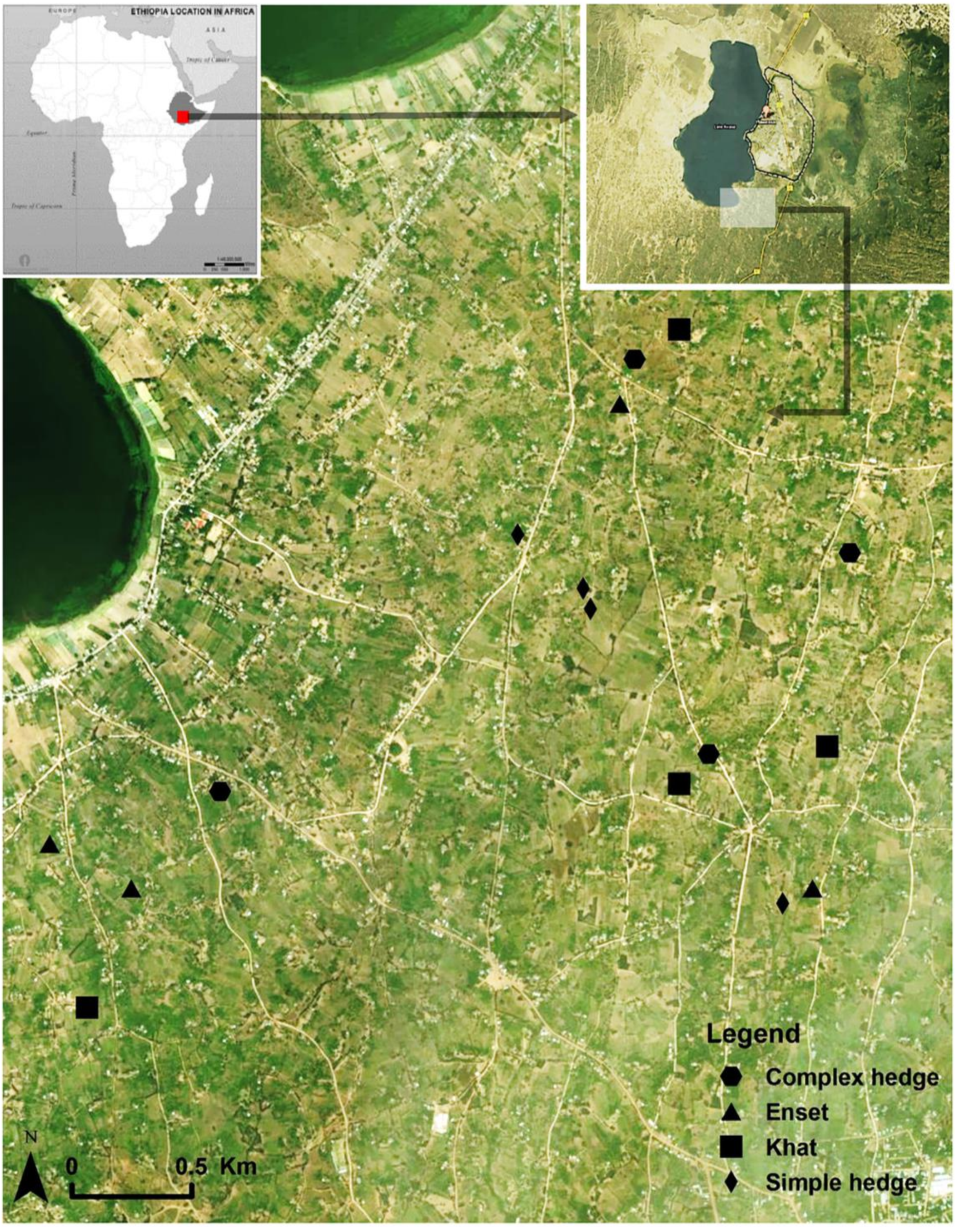


Figure. 1. Location of the study area and focal maize fields for natural enemy sampling. The study area is located in Tula, south of Lake Hawassa in the Rift Valley of Ethiopia.

2.5 Arthropod sampling and identification

The abundance and diversity of arthropods were assessed in maize fields in Tula in 2014 and 2015. Farmers' maize fields that bordered an enset field, a khat field, a 'simple' hedgerow, and a 'complex' hedgerow were selected. Four fields were selected for each maize field-border combination for a total of 16 maize fields. All enset crops were at least 3 m high, while khat crops (also perennial) were at least 0.5 m high. Hedgerow-maize interfaces were at least 30 m long, and hedgerows were classified as 'simple' or 'complex' based on a visual assessment of vegetation density and diversity (Bayley, 2001). Hedgerows with less than 50% vegetation cover and less than eight plant species were considered 'simple', while hedgerows with vegetation cover of 75% or higher, more than 8 plant species and at least 2m wide were considered 'complex' (Appendix 1). The maize fields were at least 40 × 30 m, and had a minimum density of 4 plants per m2. Maize was intercropped with bean in 15 fields, and with enset in one field. Tilling and weeding are common cultivation practices in maize and khat fields, but not in enset.

Yellow pan traps and pitfall traps were placed in the maize fields at 1, 10 and 30 m from the maize field-border interface. Each field had two transects of traps, separated by 10 m, hence each field had six yellow pan traps and six pitfall traps. The pitfall and pan traps were placed at 1 m distance from each other and referred to as sampling station. Pitfall traps consisted of a 10 cm diameter plastic cup, filled with 30 ml water and a droplet of detergent to break the surface tension. A cover was placed over the trap at 5–10 cm height to prevent rainwater infiltration, without inhibiting arthropod movement. The yellow pan traps consisted of 20 cm diameter yellow plastic dishes filled with 30 ml water and a droplet of detergent and placed at an 80 cm height on a pole. The traps were emptied after three days and arthropod samples were transferred to plastic tubes with 70% ethanol. In 2014, two samplings were conducted in the first week of October when maize plants were mature, while in 2015 one sampling was conducted in the first week of October when maize plants were mature and a second one in the first week of November when maize plants were senescent.

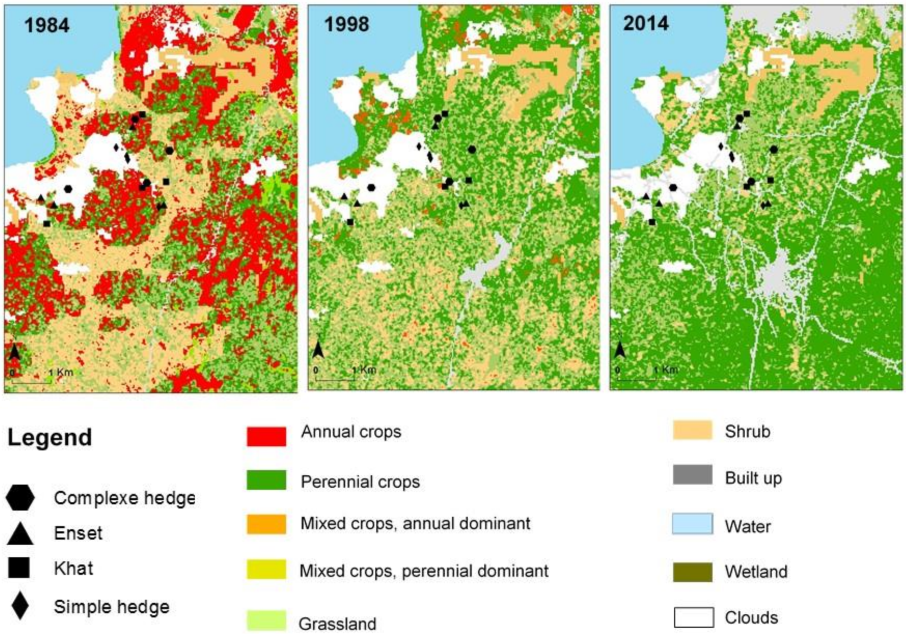


Figure 2. Land cover classification based on the analysis of Landsat images of Tula for the years 1984, 1998 and 2014.

Arthropod samples were sorted, and natural enemies of stemborers were identified at the family level using the identification keys of Polaszek (1998) and Getu *et al.* (2001), and sorted by morphospecies. All other specimens were identified at the order level. All specimens were counted and classified as parasitoid wasps, parasitic flies, ants, rove beetles, spiders, and other predators (Appendix 3).

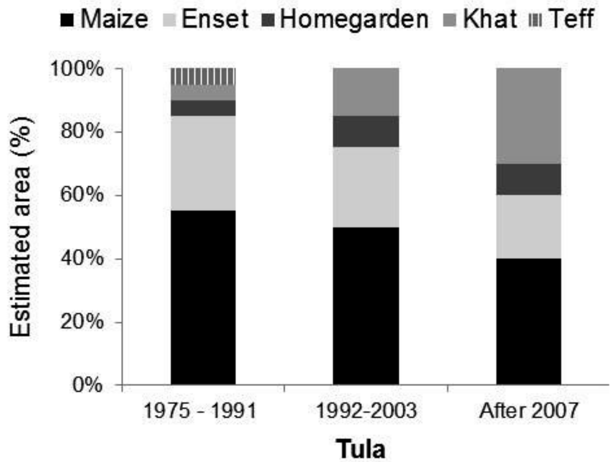


Figure 3. Proportion of crop types in Tula during three time periods as stated by farmers during a focus group discussion.

2.6 Data analysis

The relationship between the abundance of five stemborer natural enemy groups (parasitoids and parasitic flies combined, ants, rove beetles, spiders, and other predators) and border types were analysed using generalised linear mixed models. Border type (enset, khat, simple hedgerow and complex hedgerow), distance from the border (1, 10, and 30 m), year (2014 and 2015), and maize stage (mature and senescing) were fixed factors, and the variable "field" was taken as a random factor. The data from the traps in the two transects (pseudo-replicates) were pooled. The data from the pitfalls and yellow pans were analysed both separately and as pooled samples per sampling station. Here, we report the results of the analysis with the pooled pitfall and yellow pan samples.

In all the models, four discrete stochastic distributions were considered for the error distribution of the data: Poisson, negative bi-nominal, zero-inflated Poisson and zero-inflated negative binominal. The models, with farm as random factor, were fitted using glm (for Poisson distribution), glm.nb (for negative binominal distribution), and zeroinfl functions (for zero inflated Poisson and negative binominal distributions) using the R packages MASS (Venables and Ripley, 2002) and PSCL. Akaike's Information Criterion corrected for finite sample sizes (AICc) was used to rank and select models (Burnham and Anderson, 2003). The negative binomial error distribution had the lowest AICc in all analyses. Model selection of explanatory variables was conducted using the dredge procedure in R package MuMIN. This procedure generates a complete set of sub-models with combinations of the terms of the full model and sorts the sub-models on the basis of AICc values and associated Akaike weights.

3. Results

3.1 Land cover change

The land cover analysis indicated major changes in the study area between 1984 and 2014. The area of perennial crops increased by 173%, while the area of annual crops, grassland, bare soil and mixed crops decreased by 98%, 90%, 53% and 44%, respectively (Fig. 2; Appendix 2). The focus group discussion in Tula confirmed these trends and indicated that maize was the dominant crop in the 1980's with an estimated cover of 55%, which decreased to 40% in 2014 (Fig. 3). Khat increased from less than 5% to 30%, homegarden increased from 5% to 10%, and enset decreased from 30% to 20% (Fig. 3). Maize is mostly intercropped with bean.

The changes in land cover are also reflected in the structure of the landscape. The mean area of perennial crops in the sectors around focal maize fields increased (Fig. 4A), while the patch density decreased slightly from 1984 to 2014 (Fig. 4B). This indicates that perennial crops cover a larger proportion of the landscape and are arranged in larger or more interconnected patches. The area, patch density, and edge density of mixed crops remained more or less stable (Figs. 4A–C). In parallel there has been a strong decrease of the area, patch density and edge density of annual crops (Figs. 4A–C), indicating that maize is grown in smaller fields, which are included in the mixed crop category. The proximity index increased three-fold between 1984 and 2014, indicating shorter distances between annual and perennial crops. This suggests that the landscape of the study area has become increasingly dominated by small-scale mosaics of mixed and perennial crops.

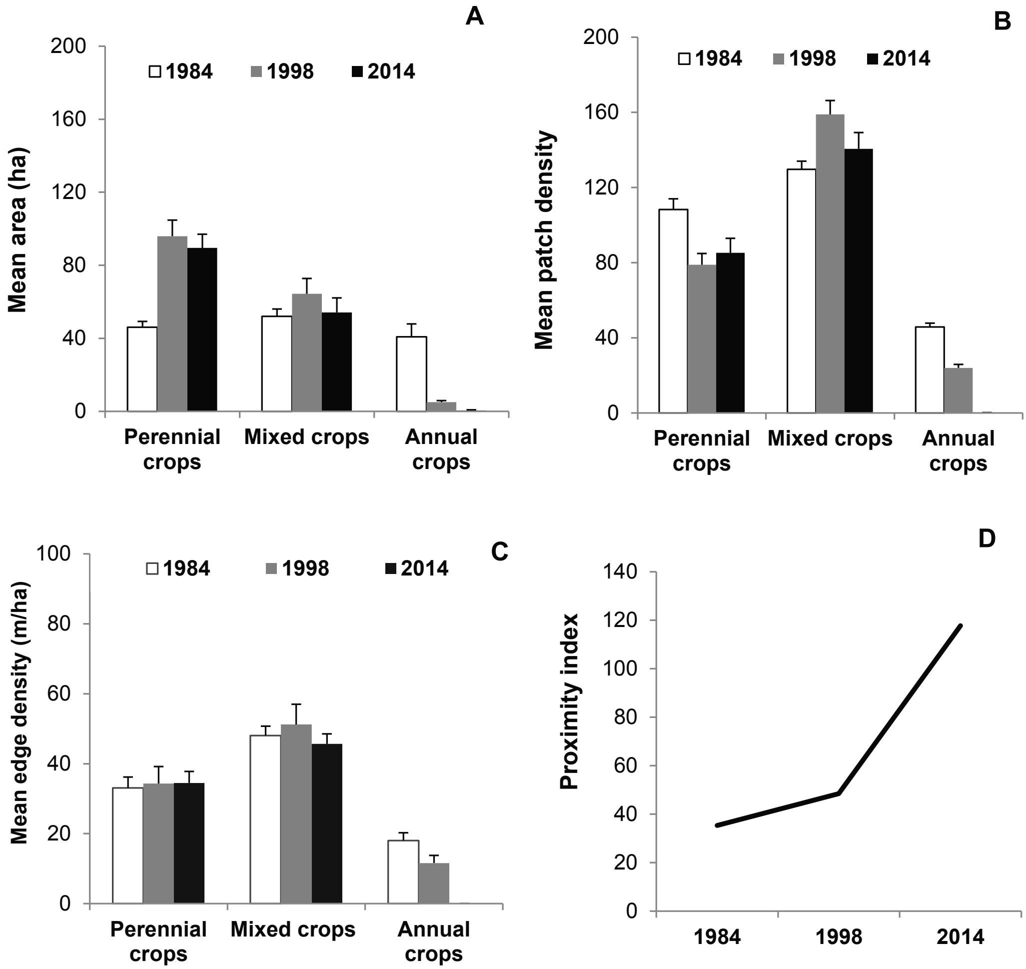


Figure 4. Area (A), patch density (B), edge density (C) of perennial, mixed, and annual crops, and proximity index between annual and perennial crops (D) in Tula in 1984, 1998, and 2014. Perennial crops include enset and khat, and annual crops are dominated by maize (and teff in the 1980's). Mixed crops represent adjoining perennial and annual crops with field sizes smaller than 30 x 30 m. Error bars indicate SEM, (–) stands for dimensionless.

3.2 Abundance of natural enemies of maize stemborers

In 2014 and 2015 a total of 690 samples were collected, yielding 25,360 specimens belonging to 146 morphospecies from nine orders (Diptera, Hymenoptera, Coleoptera, Hemiptera, Arachnida, Orthoptera, Neuroptera, Phthiraptera, and Lepidoptera; Appendix 3). Out of the total specimens, 35.6% were considered to be potential natural enemies of *Busseola fusca*, which consisted of Formicidae (56%), Staphylinidae (25%), parasitoid wasps (14%), spiders (14%), and parasitic flies (10%).

The outputs of the generalised linear mixed models indicated that (i) maize fields adjacent to enset and complex hedgerows had significantly higher abundances of predators as compared to maize fields adjacent to khat and simple hedgerows, and (ii) there were significant interactions between border type and distance and between border type and year (Table 1; Fig. 5). These interactions indicate that the effect of border type on predator abundance in maize vary in different years and at different locations within the field and can therefore not be generalised. The positive effect of enset and complex hedgerow on predator abundance was most pronounced at the crop interface, 1 m within the maize field (Fig. 5A). By contrast, border types did not influence the abundance of parasitoids and parasitic flies in maize fields, and their abundance was only significantly affected by the maize stage, with lower abundances in senescing maize (Table 2; Fig. 5D). When focusing on the main predator groups, regression analysis indicated that ants were most abundant near complex hedgerow-maize interfaces (Fig. 6A), rove beetles were most abundant near enset-maize interfaces and complex hedgerow-maize interfaces (Fig. 6B), and spiders were not influenced by border type and distance from the field edge (Fig. 6C).

Table 1 Estimates of the most parsimonious model for the abundance of predators with a negative binomial error distribution. The variables are border type (enset, khat, simple hedgerow, and complex hedgerow), distance from border (1, 10, and 30 m), and year (2014 and 2015). "Field" was taken as a random variable, BorderKhat, Distance1m, and Year2014 were reference variables.

	Estimate	**Std. Error**	**z value**	**Pr(>|z|)**	
Intercept	1.989	0.231	8.597	0.000	***
BorderEnset	**0.923**	**0.327**	**2.820**	**0.005**	**
BorderHedge complex	**1.121**	**0.310**	**3.620**	**0.000**	***
BorderHedge simple	-0.081	0.314	-0.258	0.796	
Distance10m	0.327	0.261	1.253	0.210	
Distance30m	0.172	0.265	0.650	0.516	
Year2015	0.019	0.222	0.084	0.933	
BorderEnset:Distance10m	**-0.782**	**0.365**	**-2.146**	**0.032**	*
BorderHedge complex:Distance10m	**-1.192**	**0.363**	**-3.281**	**0.001**	**
BorderHedge simple:Distance10m	-0.444	0.360	-1.233	0.218	
BorderEnset:Distance30m	**-0.818**	**0.368**	**-2.222**	**0.026**	*
BorderHedge complex:Distance30m	**-0.774**	**0.368**	**-2.106**	**0.035**	*
BorderHedge simple:Distance30m	-0.204	0.360	-0.566	0.572	
BorderEnset:Year2015	**-1.210**	**0.306**	**-3.960**	**0.000**	***
BorderHedge complex:Year2015	-0.239	0.305	-0.782	0.434	
BorderHedge simple:Year2015	0.167	0.300	0.559	0.576	

Significance codes: 0 '***' 0.001 '**' 0.01 '*'

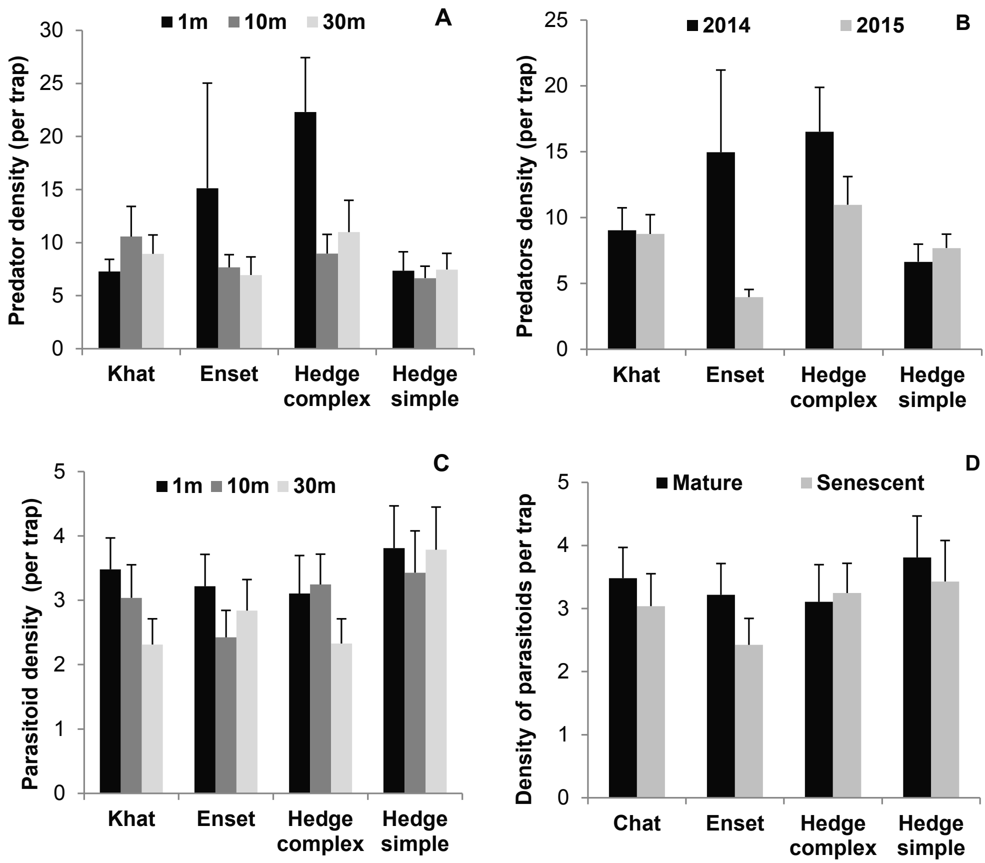


Figure 5. Mean abundance of predators (A and B) and parasitoids and parasitic flies (C and D) of maize stemborers in maize fields by border type for 2014 and 2015 (A and B respectively) and maize stage (C and D respectively). Error bars indicate SEM.

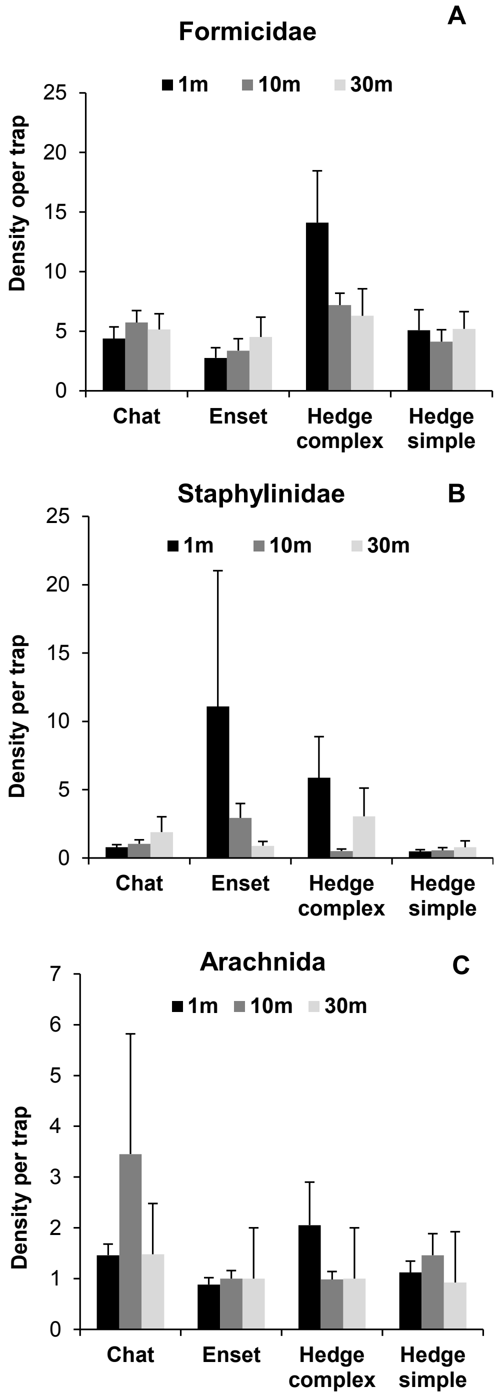


Figure 6. Abundance of Formicidae (A), Staphylinidae (B), and Arachnida (C) in maize fields in yellow pans and pitfall traps in 2014 and 2015. Error bars indicate SEM.

4. Discussion

While there is increasing recognition that landscape context can influence natural enemy communities, little is known about the influence of changes in landscape context on natural enemy populations and the associated potential for biocontrol (Chaplin-Kramer *et al.*, 2011). We show that our study area in the Rift Valley region of Ethiopia has become more fine-grained due to farm subdivisions, resulting in smaller field sizes evidenced by the disappearance of the annual crop class, which includes annual crop fields larger than 30×30 m and a strong increase in the proximity index for annual and perennial crops (Fig. 4). In addition, the focus group discussion revealed that maize monocrop have been progressively replaced by khat. We also show that the abundance of some, but not all, stemborer natural enemy groups in maize crops are positively influenced by adjoining complex hedgerows and enset fields. This effect was more prominent at the border of the maize fields for predators but not for parasitoids and parasitic flies.

Ethiopian agricultural landscapes are continually changing because of social and economic drivers, such as population growth (Dira and Hewlett, 2016) and changes in farmer livelihood strategies, often resulting in a shift from food crops to cash crops (Assefa and Bork, 2014; Meshesha *et al.*, 2013) and the subdivision of fields into smaller units. The changes in landscape composition of Tula confirm this trend, exemplified by the reduction in the proportion of enset and maize (food crops), an increase in the proportion of khat (cash crop) and homegardens (Fig. 3), and a strong increase of the proximity index (Fig. 4D). Therefore, the remaining maize fields tend to have a higher perimeter-area ratio (because of reduced field sizes) and are more likely to be bordered by a perennial element (because of the increase in the area perennial crops).

Our findings indicate that maize fields bordered by an enset field or a complex hedgerow are associated with higher predator densities than maize fields bordered by a khat field or a simple hedgerow (Fig. 5). Enset vegetation is structurally complex and provides a more humid microclimate than maize fields, while complex hedgerows are relatively undisturbed habitats that may provide floral resources for natural enemies (e.g. Lantana camara L.). While khat is a perennial crop, it has a relatively simple vegetation structure and is often treated with chemical insecticides, which may explain the relatively low predator density at khat-maize interfaces (Fig. 5). In addition, there has been increasing number of homegardens in Tula because of the increase in population density. Homegardens can be very diverse in composition and structure (Abebe *et al.*, 2006), providing high quality resources for nesting and foraging for a diverse natural enemy community (Lemessa *et al.*, 2015b). The common practice of maize-legume intercropping can result in increased parasitism rates (Skovgard and Päts, 1996; Chabi-Olaye *et al.*, 2005) and lower stemborer densities than under maize monocropping (Songa *et al.*, 2007; Midega *et al.*, 2014). Thus, the changes in crop types in Tula during the last three decades have likely influenced predator densities in maize agroecosystems, which can be positive (e.g. enset-maize and complex hedgerow-maize interfaces) or negative (e.g. khat-maize interfaces).

While predators have been associated with suppression of stemborers, there is little quantitative information available on the stemborer life stages they attack (Bonhof, 2000; Getu *et al.*, 2001). In our study, ants and rove beetles were the two most abundant predator groups, which have been reported to feed on stemborer eggs and larvae (Bonhof, 2000). The association of ants with enset fields and complex hedgerows is in line with results of Lemessa *et al.* (2015a), who found that ant abundance was positively related to tree cover. Enset fields may also offer favourable conditions for rove beetles through the provision of a litter layer of fallen leaves and the presence of animal manure which is used as an amendment (Amede and Taboge, 2007). The influence of neighbouring habitat on spider abundance was not clear, and there was no apparent spatial pattern in the fields. This suggests that spiders may have colonised these habitats by ballooning, which may involve dispersal at a scale of several kilometres (Schmidt and Tscharntke, 2005; Bianchi *et al.*, 2017).

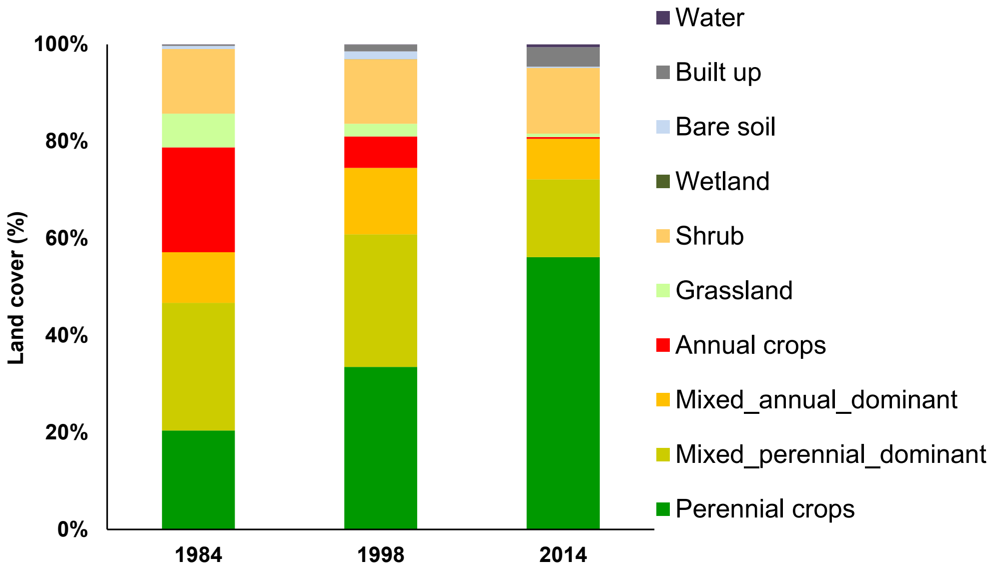
Parasitoid abundance was relatively low and could be related to the fact that we sampled during the maturity and senescence stages of maize when resource levels in maize are low (Getu *et al.*, 2001; Yitaferu and Walker, 1997). However, our findings are in line with other studies reporting typical parasitism rates in stemborer larvae below 10% (Kebede, unpublished data; Mailafiya *et al.*, 2011). The abundance of parasitoids and parasitic flies was not related to the distance from bordering habitats, which is in line with data from mark-recapture studies showing that parasitoids can easily cross distances in the order of tens of metres (Schellhorn *et al.*, 2014).

5. Conclusions

Overall, our study shows that the agricultural landscape of Tula is highly dynamic and has become more fine-grained with a higher proportion of khat. These findings suggest that the changes in land use and landscape structure may have influenced the capacity of the landscape to support populations of natural enemies of stemborers in different ways. The smaller field sizes have resulted in more field borders that can support relatively high predator densities in the case of maize-enset and maize-complex hedgerow interfaces. The small maize fields may also foster an effective colonisation by predators from adjoining crops and habitats, as the distance from the field edge to the field interior is often less than 30 m, well below the colonisation distance of most natural enemies (Bianchi and van der Werf, 2003; Tscharntke *et al.*, 2007). On the other hand, the area of khat increased and the area of enset decreased, which may have a negative effect on predator abundance. The overall outcome of the landscape changes for natural enemy abundance and the associated potential for stemborer control will depend on the interplay of these opposing effects and merits further research.

Appendix 1: Photos of the four border types of maize fields: chat field (A), enset field (B), simple hedgerows (C and D) and dense hedgerows (E and F).

Appendix 2: Land cover composition (%) of Tula in 1984, 1998 and 2014 based on Landsat image analysis.



Appendix 3: Abundance (mean ± SE) and diversity of natural enemies of *Busseola fusca* by order, (sub) family, number of morphospecies and sampling method (pitfall and yellow pan) in Tula in 2014 and 2015.

					2014			2015	
Functional trait group	**Order**	**(Sub) Family**	**Morphospecies**	**N**	**pitfall**	**yellow pan**	**N**	**pitfall**	**yellow pan**
Predators	Hymenopte	Formicidae	5	241	12.28±1.58	0.28±0.05	1	9.12±1.10	0.47±0.13
	Coleoptera	Staphylinida	8	136	0.48±0.06	6.60±3.29	3	1.62±0.45	0.86±0.35
	Arachnida	Araneidae	8	564	2.68±0.66	0.26±0.04	3	2.16±0.36	0.34±0.05
	Hymenopte	Vespidae	1	184	0.02±0.01	0.94±0.10	1	0.05±0.02	0.73±0.11
	Coleoptera	Coccinellida	2	8	0.04±0.02	0.01±0.01	7	0.04±0.03	0.01±0.01
	Dermaptera	Forficulidae	2	0	0	0	4	0.01±0.01	0.01±0.01
Total Predators			26	452	15.48±1.72	13.01±3.28	2	8.09±1.23	2.43±0.40
Parasitoid flies	Diptera	Tachnidae	2	619	0.01±0.01	3.21±0.30	28	0.17±0.05	1.71±0.20
	Hymenopte	Chalcidoidae	15	540	0.91±0.10	1.90±0.17	2	0.56±0.08	0.88±0.10
Parasitoids wasps	Hymenopte	Ichneumonid	5	115	0.06±0.02	0.54±0.06	1	0.10±0.03	0.58±0.08
	Hymenopte	Unknown	5	128	0.15±0.09	0.52±0.07	7	0.12±0.08	0.36±0.07
	Hymenopte	Braconidae	2	20	0.01±0.01	0.09±0.03	3	0.02±0.01	0.18±0.05
Total Parasitoids			29	142	1.14±0.11	6.26±0.38	7	0.98±0.12	3.71±0.28
Other	Diptera		36	111	10.48±0.76	47.42±2.91	2	3.51±0.39	10.74±0.62
	Orthoptera		5	344	1.74±0.14	0.05±0.03	3	1.94±0.17	0.17±0.07
	Coleoptera		17	295	1.10±0.10	0.43±0.05	4	2.03±0.19	0.68±0.12
	Hemiptera		10	326	0.20±0.04	1.50±0.16	2	0.49±0.10	0.93±0.24
	Hymenoptera		6	60	0.10±0.09	0.21±0.07	7	0.15±0.08	0.37±0.07
	Phthiptera		4	79	0.35±0.07	0.06±0.02	3	0.14±0.03	0.09±0.03
	Neuroptera		4	26	0.01±0.01	0.13±0.04	1	0.03±0.02	0.07±0.02
	Lepidoptera		1	9	0	0.05±0.02	4	0.18±0.03	0.13±0.03
	Other		9	99	0.49±0.07	0.03±0.01	5	3.05±0.88	0.13±0.07
Total Other			92	123	14.49±0.82	50.81±2.97	3	11.51±1.0	13.33±1.05

Chapter 4

Landscape composition overrides field level management effects on maize stemborer control in Ethiopia

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Abstract

Lepidopteran stemborers are an important pest of maize in Africa. While farmers adopt cultural control practices at the field scale, it is not clear how these practices affect stemborer infestation levels and how their efficacy is influenced by landscape context. The aim of this three-year study was to assess the effect of field and landscape factors on maize stemborer infestation levels and maize productivity. Maize infestation levels, yield and biomass production were assessed in 33 farmer fields managed according to local practices. When considering field level factors only, plant density was positively related to stemborer infestation level. During high infestation events, length of tunnelling was positively associated with planting date and negatively associated with the botanical diversity of hedges. However, the proportion of maize crop in the surrounding landscape was strongly positively associated with length of tunnelling at 100, 500, 1000, and 1500 m radii, and overrode field level management factors when considered together. Maize grain yield was positively associated with plant density and soil phosphorus content and only weakly negatively associated with the length of tunnelling. Our findings not only highlight the need to consider a landscape approach for stemborer pest management, but they also indicate that maize is tolerant to low and medium infestation levels of stemborers.

1. Introduction

In Africa, maize (*Zea mays* L.) and sorghum (*Sorghum bicolor (L.) Moench*) are among the most important field crops providing food, feed, and fuel (Smale *et al.*, 2011). While over 70 million tons of maize were produced in 2016 (FAOSTAT, 2016), maize production is constrained by pests, disease, drought, and low soil fertility (Smale *et al.*, 2011). In East Africa, the most important insect pests associated with maize are lepidopteran stemborers, including the noctuid *Busseola fusca* (Fuller) and the crambid *Chilo partellus* (Swinhoe) (Mwalusepo *et al.*, 2015). Reported average yield losses due to stemborers in Ethiopia range from 12% to 40% of the total production depending on borer species, as well as agro-climatic zone, maize variety, cropping system, and soil fertility level (Kfir *et al.*, 2002; Mgoo *et al.*, 2006). Current stemborer pest management in sub-Saharan Africa largely focuses on field scale management based on recommendations for fertilisation (Mgoo *et al.*, 2006; Wale *et al.*, 2006), trap crops (Pickett *et al.*, 2014), crop rotation, or intercropping (Chabi-Olaye *et al.*, 2005; Belay and Foster, 2010) and do not consider management practices at the landscape level. While landscape effects on stemborer infestation has been demonstrated (Kebede *et al.* 2018b), little is known about the efficacy of farmer's agronomic practices to control maize stemborer infestation levels and how this is influenced by landscape context.

In Ethiopia, maize is grown by nine million smallholder households under diverse agro-ecological and socioeconomic conditions (Abate *et al.*, 2015). Farmers mostly rely on cultural pest management practices to manage stemborers because chemical pest management is costly and minimally effective. For instance, maize-bean intercropping is common and has been associated with reduced stemborer infestation and increased abundance of their natural enemies (Belay *et al.*, 2008; Kebede *et al.*, 2018). Furthermore, manipulation of the timing of maize planting is common in Ethiopia (Gebre-Amlak *et al.*, 1989). Many farmers plant maize within the same week after the first effective rains when the required soil moisture is reached, leading to a synchronization of maize crops in the landscape and spreading stemborer infestation risk. While early or late planting may reduce infestation (Gebre-Amlak *et al.*, 1989; Getu *et al.*, 2001), maize planting dates tend to vary widely with current erratic rainfall patterns, making stemborer control based on planting date very hazardous. Finally, soil tillage is recommended to control the remaining larvae or pupae in post-harvest maize stubbles by exposing stubbles to the sun or by burying them in the ground (Päts, 1996).

Besides these recommended practices, other management practices and agroecosystem properties may influence stemborer infestation as well. Plant density may affect the resource concentration for stemborers and therefore promote stemborer hosts finding success and oviposition preference (Kfir *et al.*, 2002). Nitrogen fertilisation may enhance maize attractiveness and therefore enhance stemborer development rates, but it may also increase the tolerance of maize to stemborer attacks (Debebe *et al.*, 2008). Hedgerows surrounding maize fields may provide resources and shelter for natural enemies of maize stemborers (Kebede *et al.* 2018) or, depending on the species composition of hedgerows, provide alternative host plants for maize stemborers. It is likely that management practices aiming to increase maize productivity, such as increasing plant density and fertilisation and removing hedgerows to free land for crop production, may result in increased stemborer infestation levels (Kfir *et al.*, 2002). However, the implications of such trade-offs for stemborer population dynamics and maize production are not clear. Besides management practices at the field level, pest pressure can be influenced by factors operating at the landscape level (Karp *et al.*, 2018). For instance, the availability of (alternative) host plants is associated with higher pest densities (O'rourke *et al.*, 2011), while habitats that support natural enemies of pests may generate an increased top-down suppression of pests (Rusch *et al.*, 2016). Therefore, the composition of a landscape, in particular host plant availability and habitats for natural enemies, may influence crop pests infestation levels (Tscharntke *et al.*, 2005; Schellhorn *et al.*, 2008).

While maize stemborer infestation may be affected by factors operating at different spatial scales, it is unclear how field and landscape factors interact to moderate stemborer infestation levels. The aim of this three year study was to assess the effect and interactions of management practices at the field level and landscape factors on maize stemborer infestation levels and maize productivity. We expected that management practices that increase host plant availability and quality at both the field and landscape level would increase stemborer infestation. Furthermore, we expected that stemborer infestation would negatively affect maize yield and above-ground biomass.

2. Materials and methods

2.1 Study area

The study was conducted in the Hawassa region in the Ethiopian Rift Valley between 7˚03'11" to 7˚08'4" N latitude and 38˚15'17" to 38˚38'47"E longitude (Fig. 1). The area is characterised by a moist to sub-humid warm subtropical climate. Annual precipitation ranges from 750 to 1200 mm in a bimodal distribution pattern, expected in March to April and June to August (Dessie and Kleman, 2007). The average land holding per household is below one hectare of arable land and the dominant crops are maize, enset (*Ensete ventricosum*), khat (*Catha edulis*), vegetables, and homegarden systems (Mellisse *et al*., 2017). *B. fusca* is the dominant maize stemborer species in the area (Abate *et al*., 2012). The landscape is dominated by small-scale annual crops in the east and is characterised by more complex mosaics of crop and non-crop patches in the west. We selected 33 maize fields which were embedded in landscapes that represented the local gradient of landscape complexity (Fig. 1).

2.2 Stemborer infestation and maize yield assessment

Maize infestation was assessed by destructive sampling of ten randomly selected plants per field in 2013 and 20 plants per field in 2014 and 2015 at the senescence stage. The same fields were assessed during the three years of this study. From each plant we recorded the number of stemborer holes in the stem, the stemborer tunnelling length inside the stem, the number of larvae and pupae in the whole plant, and the proportion of the cob(s) surface that was damaged. Maize grain moisture content (%) was assessed using a Dickey John portable grain moisture tester (http://www.dickey-john.com/product/m3g/). Maize grain yield was calculated at the plot level by multiplying the fresh weight by the dry matter content and was converted into tonnes of dry matter per hectare. Maize stems and leaves were weighed *in situ*, and a sub-sample was oven dried for 48 hours at 70°C to assess the dry matter content.

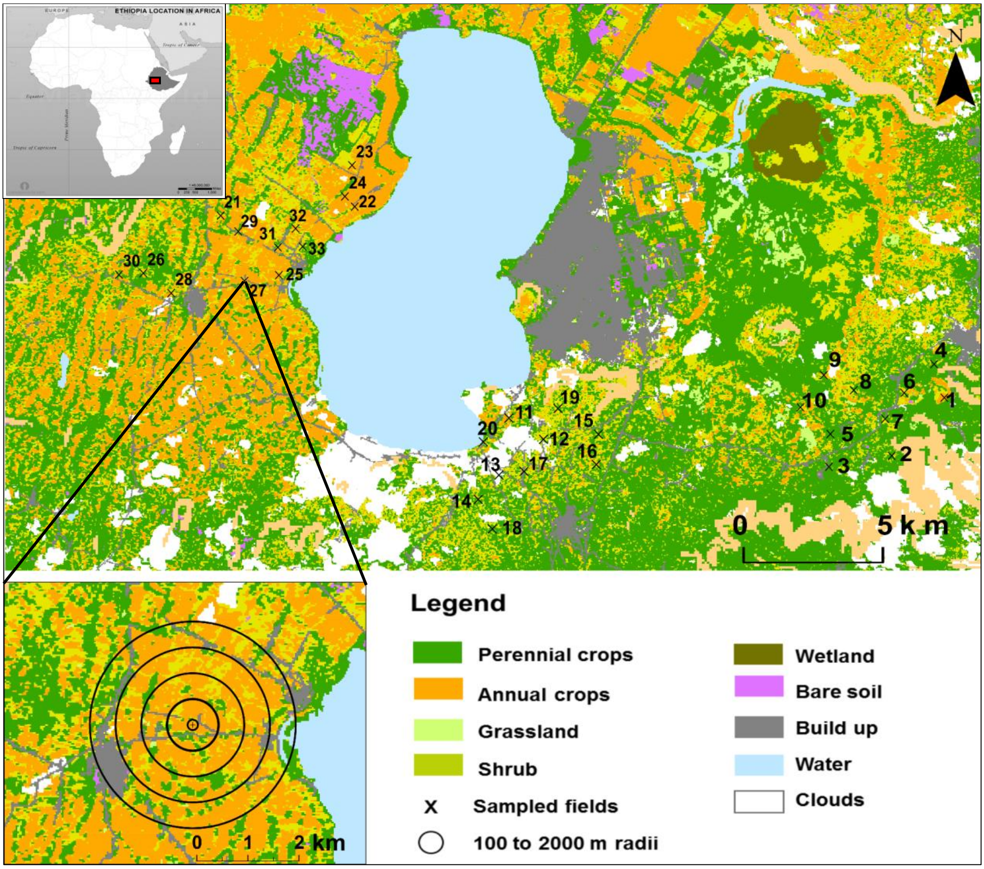

Figure 1: Location of the study landscape and the sampled fields (numbered from 1 to 33) around Lake Hawassa in the Rift Valley region of Ethiopia, and overview of the five radii (100 to 2000 m).

2.3 Factors at the field level

The owners of each of the 33 maize fields were interviewed on their management practices during three consecutive maize growing seasons. We recorded the planting date, the variety of maize, and the quantity of fertiliser applied. Since farmers all used urea and diammonium phosphate (DAP) as fertilisers, we calculated the total N input by summing the amount of N in the urea (46%) and in the DAP (18%). Plant density was assessed by counting and averaging the number of plants within a quadrat of 2 m^2 at three locations in each maize field. We assessed the perimeter area ratio of the maize fields, recorded the plant species composition of hedgerows surrounding each field in 2 m sections at 10 m intervals (Miller and Ambrose, 2000), and calculated the

Shannon-Wiener diversity index of the plant species was calculated (Shannon and Weaver, 1949).

To assess soil fertility and structure, soil samples (150 cm^3) were taken at 0-10 cm, 10-20 cm and 20-30 cm depths at three points on a diagonal transect across each of the 33 fields. Fresh composite samples were weighed and dried at air temperature and then sieved (less than 2 mm), and 50 gram sub-samples were collected for chemical analysis. The remaining soil was oven-dried for 48 hours at 105˚C (Carter, 1993), and bulk density was calculated. For the analysis of total N and P, samples were digested with a mixture of H_2SO_4–Se and salicylic acid, and total N and P was measured spectrophotometrically (Novozamsky *et al.*, 1983). The organic matter of the soil was assessed gravimetrically by dry combustion of the organic material in a furnace at 500-550°C. We calculated the total amount of C, N, and P for each 10 cm soil layer by dividing the total weight of C, N, and P at each layer by the bulk density. Total C, N, and P from 0-30 cm were calculated for each field by summing the amounts of the three layers (Kim *et al.*, 2016).

2.4 Factors at the landscape level

Data on landscape composition were obtained from a quantitative land cover analysis using a Landsat 8 OLI/TIRS satellite image from 2014 with a resolution of 30x30 m (Kebede *et al.*, 2018). Using a phenology-based classification approach, annual crops (mostly maize), perennial crops, grassland, shrubs, water, wetland and built up areas were identified (Fig. 1). We calculated the percentage of each land use type from the total area within a radius of 100, 500, 1000, 1500, and 2000 m around each focal maize field. The percentage of maize within the five radii were considered for further statistical analysis.

2.5 Data analysis

2.5.1 Data exploration and variable reduction

Stemborer infestation data recorded at the plant level were averaged per field. The degree of correlation between variables was assessed through a principal component analysis (PCA). This analysis revealed that the number of stemborer holes per plant, the proportion of cob damage, the length of tunnelling, and the number of larvae were strongly correlated. We selected the length of tunnelling as a response variable of infestation for further statistical analysis as this proxy captures information about stemborer infestation and damage throughout the growing season, and has been reported as the best predictor of yield loss (Ndemah, 1999). As the proportion of maize and perennial crops in the landscape were strongly negatively correlated, we used only the proportion of maize for further statistical analysis. The variables so selected were used to run a second PCA (Fig. 2).

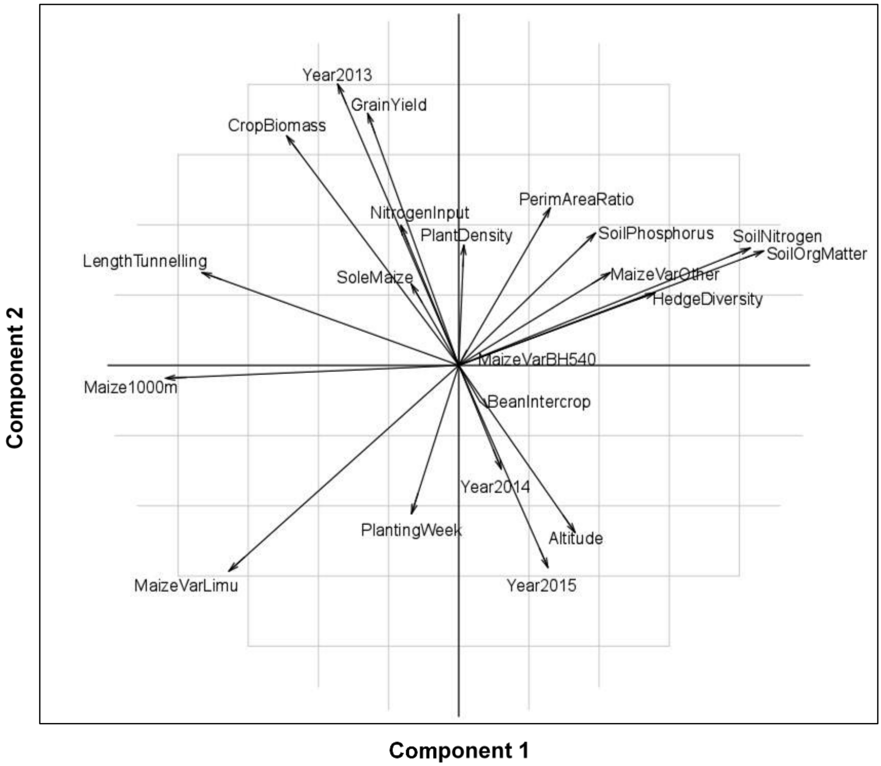

Figure 2: Plot of Principal Component Analysis (PCA) of response and explanatory variables at the field and landscape level. Since the proportion of maize at 100, 500, 1000, 1500 and 2000 m were highly correlated, we only present the proportion of maize at 1000 m because this had the highest PCA loading.

2.5.2 Statistical models

The relationship between the length of tunnelling, maize grain yield, and above-ground maize biomass (response variables) and management, soil, and landscape level factors (explanatory variables) were assessed using linear mixed models. Length of tunnelling was $\log_{(x+1)}$-transformed to meet normality requirements. In a first step, we considered a model with only management factors as explanatory variables, including perimeter area ratio, hedge diversity, soil organic matter, soil phosphorus, planting date, plant density, nitrogen input, maize variety, and cropping system as fixed factors and year and field as random factors. In a second step, we added landscape level factors (proportion of maize at 100, 500, 1000, 1500 and 2000 m radii around focal maize fields). The interaction between year and planting date, cropping system, plant density, N input, and maize variety, and the interaction between the proportion of maize at 100 to 2000 m and the cropping system and planting date were not significant and not considered further. Akaike's Information Criterion (AIC) was used to compare and rank the models at the five spatial scales (Burnham and Anderson, 2003).

Models for the response variables maize grain yield and above-ground maize biomass included soil organic matter, soil nitrogen, soil phosphorus, planting date, nitrogen input, plant density, maize variety, cropping system, and the relative length of tunnelling as fixed factors. The relative length of tunnelling was calculated as the ratio between the length tunnelling and above-ground maize biomass to represent a relative measure of stemborer infestation. The variables year and field were included in the model as random factors again. Non-significant interactions between year and cropping system and between year and planting date were removed.

As our dataset included records of high and low infestation levels (e.g. between years), and the effectiveness of pest management practices may depend on infestation level, we used quantile regression to assess the relationship between response and explanatory variables in more detail (Cade *et al.*, 1999). Quantile regression is an extension of ordinary least squares regression, which typically assumes that associations between explanatory and response variables are the same at all quantile levels (Thomson *et al.*, 1996). Here we used quantile regression to assess the relationship between the response variables length tunnelling and grain yield with management variables along the 10%, 25%, 50%, 75% and 90% quantiles.

All analyses were conducted in R (R Core Team, 2012) using 'ade4' package (Dray *et al.*, 2007) for the PCA, 'lmer' function for fitting linear mixed-effects models from the lme4-package (Bates *et al.*, 2014), and 'quantreg' for quantile regressions (Koenker *et al.*, 2018).

3. Results

A total of 1550 maize plants were sampled in 2013, 2014, and 2015 to assess stemborer infestation levels, maize yield, and maize above-ground biomass. A total of 1602 stemborer holes and 949 larvae were recorded. Stemborer infestation levels differed between years and were highest in 2013 (Table 1). The first principal component of the PCA captured variables related to landscape features (e.g. proportion of maize and soil characteristics) and explained 21.3% of the variation (Fig. 2). The second principal component overly reflected management variables (e.g. nitrogen input, planting date, plant density, and maize variety) and variability between years, and explained 15.2% of the variation. The first five principal components explained 64.8% of the variation (Eigenvalue = 1.39).

Table 1: Overview of a selection of response and explanatory variables (mean ± SE) in 2013, 2014, and 2015.

	2013	**2014**	**2015**
Length tunnelling (cm)	18.4 ± 2.52	6.05 ± 1.00	7.99 ± 1.94
Cob damage (%)	4.04 ± 0.82	0.72 ± 0.21	2.36 ± 0.61
Total holes (count)	2.00 ± 0.23	0.78 ± 0.19	0.74 ± 0.18
Number of larvae per plant	1.36 ± 0.18	0.30 ± 0.05	0.51 ± 0.16
Dry grain yield (t ha-1)	4.96 ± 0.28	4.48 ± 0.30	3.96 ± 0.26
Crop biomass (t ha-1)	7.21 ± 0.80	6.71 ± 0.61	5.78 ± 0.54
Nitrogen input (kg ha-1)	70.8 ± 11.6	52.0 ± 6.44	45.8 ± 6.49
Planting date (week number)	16.5 ± 0.41	17.2 ± 0.35	21.2 ± 0.57
Plant density per 2 m^2	8.99 ± 0.18	8.16 ± 0.33	9.73 ± 0.45

3.1 Factors influencing stemborer infestation at the field level

When considering field scale variables only, infestation increased with increasing plant density (P = 0.039; Table 2). This effect was most pronounced at high infestation levels (Fig. 3A). Other management variables had no significant effect on stemborer infestation levels. Yet quantile regressions analysis revealed that stemborer infestation was negatively associated with hedge diversity at high infestation levels (Fig. 3B, Table 3), positively associated with planting date at high infestation levels (Fig. 3C, Table 3), and positively associated with nitrogen input at intermediate (75% quantile) infestation levels (Fig. 3D, Table 3).

Table 2: Determinants of log(x+1)-transformed length of tunnelling in maize plants using a linear mixed model when considering field scale factors. Year and field were random variables. Maize variety BH540 and the cropping system maize-bean intercrop were reference variables. Significant effects are shown in bold (*P* < 0.05).

	Estimate	**Std. Error**	**p-value**
Perimeter area ratio	0.326	0.403	0.424
Hedge diversity	-0.172	0.149	0.260
Soil organic matter	-0.023	0.023	0.333
Soil nitrogen	-0.061	0.281	0.829
Soil phosphorus	0.007	0.103	0.945
Planting date	0.029	0.040	0.471
Nitrogen input	-0.002	0.003	0.539
Plant density	0.107	0.051	**0.039**
Maize variety (Limu)	0.161	0.289	0.579
Maize variety (Other)	0.192	0.270	0.480
Cropping system (Sole Maize)	0.190	0.198	0.339

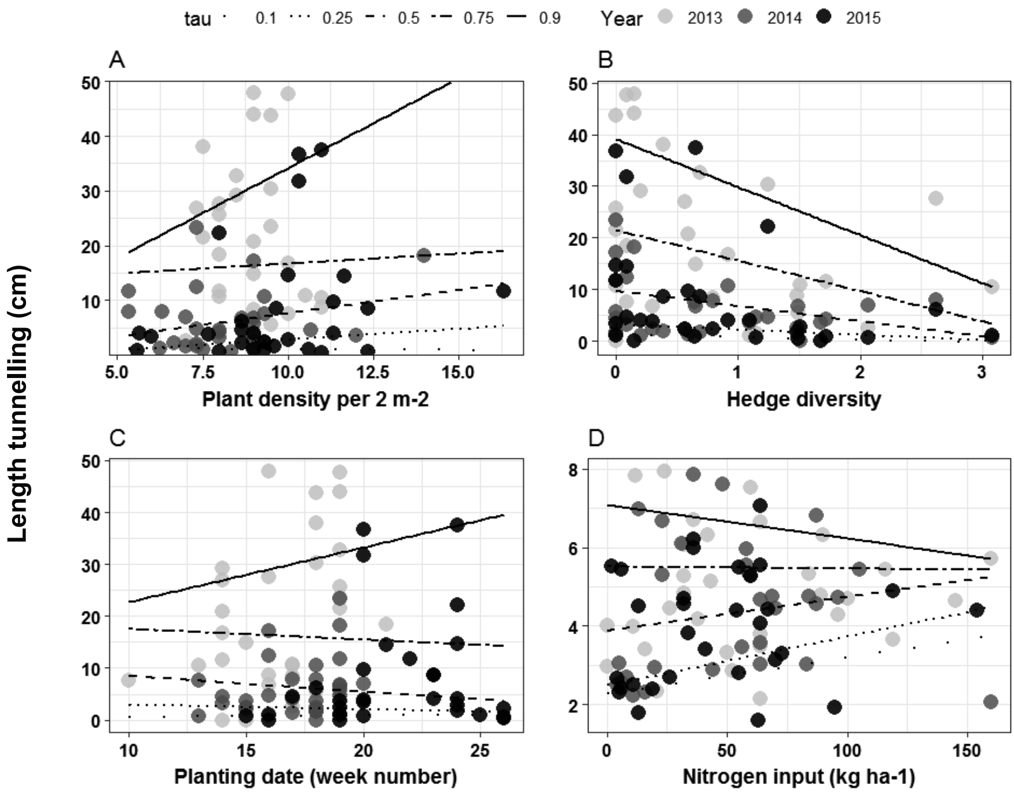

Figure 3: Quantile regressions at 10%, 25%, 50%, 75%, and 90% of the length tunnelling for the field scale variables plant density (A), hedge diversity (B), planting date (C), and nitrogen input (D).

Table 3: Overview of results of quantile regressions for the length tunnelling and grain yield at 10%, 25%, 50%, 75%, and 90% quantiles. Significant effects are shown in bold (*P* < 0.05).

	tau	Estimate	Std. Error	t value	Pr(>|t|)
		Length tunnelling			
Plant density	0.10	-0.030	0.196	-0.15	0.880
	0.25	0.412	0.355	1.16	0.249
	0.50	0.726	0.542	1.34	0.184
	0.75	0.670	1.704	0.39	0.695
	0.90	3.283	2.729	1.20	0.232
Hedge diversity	0.10	-0.478	0.402	-1.190	0.237
	0.25	-1.014	0.678	-1.497	0.138
	0.50	-2.937	1.313	-2.237	**0.028**
	0.75	-5.897	2.015	-2.927	**0.004**
	0.90	-9.289	4.006	-2.319	**0.023**
Planting week	0.10	0.029	0.072	0.394	0.694
	0.25	-0.089	0.167	-0.532	0.596
	0.50	-0.300	0.384	-0.781	0.437
	0.75	-0.205	0.889	-0.231	0.818
	0.90	1.055	1.213	0.870	0.387
Nitrogen input	0.10	-0.007	0.008	-0.831	0.408
	0.25	-0.002	0.020	-0.082	0.935
	0.50	0.024	0.037	0.636	0.527
	0.75	0.151	0.080	1.883	**0.063**
	0.90	0.039	0.185	0.210	0.834
		Grain yield			
Nitrogen input	0.10	0.009	0.007	1.273	0.206
	0.25	0.012	0.005	2.630	**0.010**
	0.50	0.009	0.006	1.350	0.180
	0.75	-0.001	0.006	-0.092	0.927
	0.90	-0.009	0.008	-1.086	0.280
Planting date	0.10	-0.127	0.057	-2.219	0.029
	0.25	-0.138	0.072	-1.911	0.059
	0.50	-0.086	0.069	-1.245	0.217
	0.75	-0.026	0.071	-0.368	0.713
	0.90	-0.022	0.079	-0.275	0.784

3.2 Factors influencing stemborer infestation at the landscape level

When considering field and landscape level variables together, the length of tunnelling was positively related with the proportion of maize at 100 m (*P < 0.001)*, 500 m (*P < 0.05)*, 1000 m (*P < 0.001)* and 1500 m (*P < 0.001*; Table 4) around the focal maize fields. At 2000 m, this effect was only marginally significant (*P* = 0.095). AIC indicated that the models with the proportion of maize at 100, 1000, and 1500 m received most support from the data.

3.3 Factors influencing maize grain and biomass yield at the field scale

Maize grain yield was significantly positively associated with plant density (*P < 0.001*) and soil phosphorus content (*P < 0.01*; Table 5). In addition, grain yield was marginally negatively associated with the relative length of tunnelling (*P = 0.060*). Quantile regressions analysis revealed that grain yield was significantly positively associated with nitrogen input for the 25% lower yields and was not affected by planting date (Fig. 4, Table 3). Crop biomass was positively associated with plant density (*P* = *0.028*).

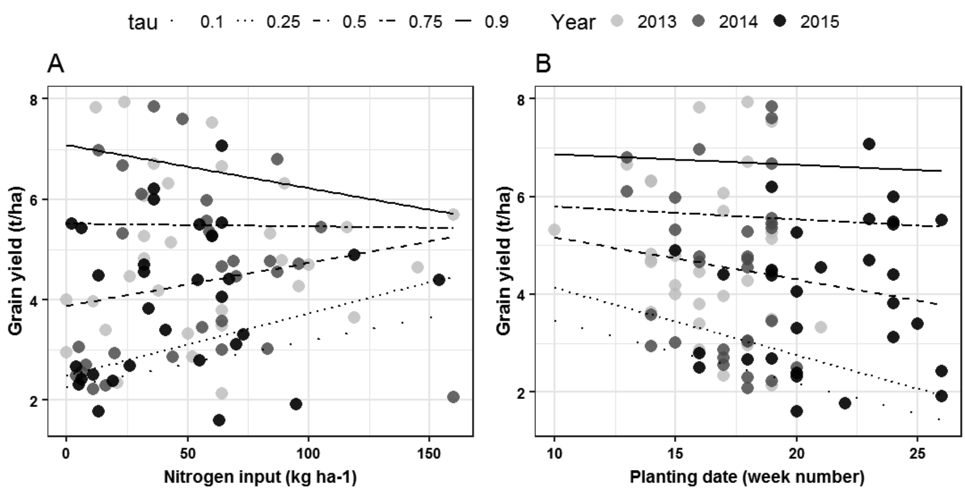

Figure 4: Quantile regressions at 10%, 25%, 50%, 75%, and 90% of the grain yield and nitrogen input (A) and the grain yield and planting date (B).

Table 4: Determinants of $\log_{(x+1)}$-transformed length of tunnelling in maize plants using a linear mixed model at five spatial scales, i.e. radii from 100 to 2000 m around the sampled fields. Year and field were random variables. Maize variety BH540 and the cropping system maize-bean intercrop were reference variables. Significant effects are shown in bold ($P < 0.05$), marginally significant effects are underlined ($0.05 < P < 0.1$). AIC values that differ by less than 2 indicate little difference in support from the data to models.

	100m			**500m**			**1000m**			**1500m**			**2000m**		
	Estimate	Std. Error	p-value	Estimate	Std. Error	p-value	Estimate	Std. Error	p-value	Estimate	Std. Error	p-value	Estimate	Std. Error	p-value
Altitude	-4.230	4.998	0.406	-1.994	5.764	0.732	-4.648	4.839	0.347	-3.931	4.987	0.439	-5.567	5.397	0.313
Perimeter area ratio	0.208	0.384	0.591	0.283	0.410	0.494	0.243	0.376	0.523	0.287	0.384	0.460	0.217	0.414	0.604
Hedge diversity	-0.087	0.129	0.509	-0.111	0.138	0.428	-0.018	0.132	0.894	-0.011	0.137	0.936	-0.063	0.151	0.679
Soil organic matter	-0.012	0.020	0.554	-0.012	0.022	0.575	-0.010	0.020	0.631	-0.010	0.020	0.624	-0.013	0.022	0.575
Soil nitrogen	-0.007	0.243	0.977	-0.025	0.260	0.924	-0.013	0.236	0.957	-0.004	0.241	0.986	-0.019	0.267	0.945
Soil phosphorus	-0.118	0.098	0.242	-0.066	0.103	0.528	-0.093	0.094	0.331	-0.093	0.096	0.340	-0.059	0.105	0.578
Planting date	0.013	0.038	0.739	0.019	0.039	0.628	0.005	0.038	0.899	0.009	0.038	0.815	0.017	0.039	0.657
Nitrogen input	-0.003	0.003	0.347	-0.003	0.003	0.301	-0.004	0.003	0.163	-0.004	0.003	0.155	-0.003	0.003	0.267
Plant density	0.068	0.049	0.168	0.076	0.051	0.137	0.052	0.050	0.300	0.060	0.050	0.231	0.082	0.051	0.113
Maize variety (Limu)	0.025	0.290	0.932	0.098	0.290	0.736	-0.010	0.295	0.974	-0.025	0.297	0.933	0.038	0.299	0.900
Maize variety (Other)	0.234	0.263	0.375	0.211	0.268	0.433	0.117	0.267	0.661	0.099	0.269	0.712	0.139	0.275	0.615
Cropping System (Sole maize)	0.127	0.196	0.519	0.167	0.200	0.407	0.117	0.197	0.553	0.106	0.197	0.594	0.103	0.201	0.612
Ratio of maize at 100m	0.013	0.005	**0.008**												
Ratio of maize at 500m				0.013	0.006	**0.048**									
Ratio of maize at 1000m							0.021	0.007	**0.005**						
Ratio of maize at 1500m										0.024	0.008	**0.008**			
Ratio of maize at 2000m													0.019	0.011	<u>0.095</u>
Akaike information criterion (AIC)	*288.02*			*293.54*			*289.92*			*290.19*			*293.55*		

Table 5: Determinants of maize grain yield and crop biomass using a linear mixed model with explanatory variables at the field level. Year and field were random variables. Maize variety BH540, the cropping system maize-bean intercrop were reference variables. Significant effects are shown in bold($P < 0.05$), marginally significant effects are underlined ($0.05 < P < 0.1$).

	Grain yield			Above-ground biomass		
	Estimate	Std. Error	p-value	Estimate	Std. Error	p-value
Soil organic matter	-0.006	0.038	0.869	-0.115	0.086	0.189
Soil nitrogen	-0.320	0.488	0.516	0.602	1.089	0.585
Soil phosphorus	0.531	0.184	**0.007**	0.385	0.402	0.348
Planting date	-0.067	0.054	0.230	0.250	0.170	0.144
Nitrogen input	0.001	0.004	0.740	0.004	0.011	0.712
Plant density	0.333	0.076	**0.000**	0.493	0.221	**0.028**
Maize variety (Limu)	0.388	0.423	0.362	-0.686	1.302	0.600
Maize variety (Other)	-0.008	0.392	0.983	-1.451	1.155	0.213
Cropping system (Sole maize)	-0.011	0.284	0.969	1.209	0.849	0.158
Relative length tunnelling	-0.200	0.104	<u>0.060</u>	-0.423	0.310	0.177

4. Discussion

In this study, we assessed how factors at the field and landscape levels affected maize stemborer infestation and how this impacted maize grain yield and biomass production. We found that the proportion of maize around the focal maize fields a measure of landscape uniformity had a strong positive effect on stemborer infestation levels at distances ranging from 100 to 1500 m. When considering field level factors only, plant density was the only factor that significantly increased stemborer infestation levels. Yet at high infestation levels, late planting was associated with increased stemborer infestation levels and hedge diversity with decreased infestation levels. While maize productivity was positively associated with plant density and soil phosphorus content, it was only weakly affected by stemborer infestation, highlighting the capacity of maize to compensate for herbivory.

4.1 Landscape context overrides field management practices for the control of maize stemborers

The proportion of maize in the landscape was the most dominant factor explaining maize stemborer infestation levels, overriding the effect of field management practices (Table 4). The positive association between maize in the landscape and stemborer infestation levels can be explained by the fact that maize is a source habitat with positive stemborer population growth rates, resulting in individuals spilling over to nearby habitats (Pulliam, 1988; Rand *et al*, 2006). The population growth rates in maize are likely to be high because farmers do not apply chemical insecticides, and maize stems are stored in piles near homesteads, constituting a direct source of carry-over populations of *B. fusca* (Gebre-Amlak, 1988). While the dispersal capacity of stemborers has not been directly measured, records on the geographic range expansion of resistance development against Bt toxin suggest that *B. fusca* can move up to 50 km in a year (Kruger *et al.*, 2011; Dupas *et al.*, 2014). This suggests that the *B. fusca* females that laid egg batches in the focal maize fields could have easily crossed 2000 m, which was the largest radius considered in our study. Furthermore, the resource concentration hypothesis predicts that herbivorous insects are more abundant in large patches of host plants because these patches are easier to locate and herbivores stay longer in those patches (Root, 1973). Since females of *B. fusca* do not seem to have a strong sensory system to detect preferred host plants at a distance (Calatayud *et al.*, 2008), host finding success in maize-dominated landscapes is likely to be higher than in landscapes with only few maize fields. Thus, our findings of higher stemborer infestations in maize-dominated landscapes are likely be moderated by an enhanced reproduction potential and increased host finding success, with a positive feedback between these mechanisms.

4.2 Management factors can influence infestation during high infestation years

When considering only factors at the field level, plant density was the only factor that was significantly related to stemborer infestation levels (Table 2). However, at high infestation levels, plant diversity in hedges was negatively associated with stemborer infestation (Fig. 3B). More diverse hedgerows may provide better life-support functions for natural enemies of stemborers, such as food resources and shelter, which could potentially lead to enhanced natural enemy colonisation of maize fields and stemborer suppression (Kebede *et al.*, 2018). Although current recommendations for cultural control of maize stemborers promote increasing within-field diversification to stimulate natural enemies, the potential contribution of hedgerows has seldom been considered (Lawani, 1982; Getu *et al.*, 2001). Therefore, the role of the diversity of plants in hedgerows may be a promising area for further research on biological control.

Farmers are well aware of the importance of the strategic planning of the maize planting date at the right moisture content of the soil for stemborer control in the study area. Previous research in the same area showed that delaying planting until after April/early May can result in serious crop losses (Gebre-Amlak *et al.*, 1989). Thus, early planting as soon as the rain starts is the recommended has been recommended practice to reduce crop damage by *B. fusca*. Our findings suggest that late planting is associated with higher infestation rates only at high infestation levels (Fig. 3.C) without significantly influencing maize productivity (Table 5). Thus, the efficacy of maize planting date as a strategy for the control of stemborers may merit further investigation, particularly because current recommendations are based on research conducted more than 25 years ago, and major changes in land use have happened in this period (Kebede *et al.*, 2018a).

Nitrogen input did not significantly influence stemborer infestation levels at the field (Table 2) and landscape levels (Table 4). This finding contrasts with studies that report that NPK fertilisation favours stemborer infestation (Debebe *et al.*, 2008; Chabi-Olaye *et al.*, 2008). However, the reported fertilisation rates which increased stemborer infestation were 60 to 120 kg ha^{-1} of nitrogen and were higher than the rates used in our area (yearly averages ranging between 54 and 70 kg ha^{-1} of nitrogen input); they were also below the recommended rates for this region, i.e 92 kg ha^{-1} of N (Tamene *et al*, 2017). In addition, the applied fertilisation might not be completely taken up by the maize plants due to soil texture which affects the mineralisation rate (Kayser *et al.*, 2011), phosphorus deficiency (Nziguheba, 2007) suboptimal timing of the application or rainfall conditions (rainfall shortage after urea application). While the effect of nitrogen fertilisation on stemborer infestation is generally reported as positive (Debebe *et al.*, 2008; Chabi-Olaye *et al.*, 2008) it is likely that there are many confounding factors, including rainfall, soil moisture, and other soil properties which determine the effect.

Intercropping maize with beans did not significantly reduce stemborer infestation. This contrasts with earlier reports of reduced stemborer infestation levels in maize-legume intercropping systems (Chabi-Olaye *et al.*, 2002; Belay *et al.*, 2008). However, in the intercrops of our study there was only a very low density of common bean, which was also reflected in the low bean yields reported by farmers. Apparently, the density of beans was too low to influence host plant finding by stemborer females in a meaningful way.

4.3 Limited impact of stemborer infestation on maize grain and biomass yields

Contrary to our initial hypothesis, maize grain yield was only marginally significant affected by the relative length tunnelling, and there was no significant negative relationship between the relative length tunnelling and maize biomass. These findings can be explained by the relatively low stemborer densities observed during the three years of the study (less than two larvae per plant on average), which is not expected to lead to significant yield losses (Van Rensburg *et al.*, 1988). Moreover, besides pest attack, other factors, such as soil fertility, are likely to have a stronger limiting effect on yield. Indeed, at low grain yield levels, there was a positive association between N input and grain yield (Fig. 4A, Table 3). However, based on this three year study, we conclude that maize productivity is tolerant to low and medium infestation levels of stemborers.

5. Conclusions

Our study confirms the findings of a growing body of literature that reports that landscape effects can influence pest population dynamics (Karp *et al*, 2018), and for the case of *B. fusca* in Ethiopia, the proportion of maize in the landscape overrides the impact of field level management practices. We also show that the impact of current stemborer infestations on maize grain and biomass yield is limited, likely due to low infestation levels during the three years of our study. The contrasting historic and current findings of the impact of stemborers on maize yield, ranging from up to complete crop failure in the 1980's (Gebre-Amlak *et al.*, 1989), and the limited impact found in our study suggest that the ongoing conversion of maize crops to other crops, such as enset and khat during the last decenia, may have reduced stemborer populations (Kebede *et al.* 2018). Such scenario would be in line with findings of simulation studies that highlight the potential role of changes in agricultural land uses for herbivores and predators (Bianchi *et al.* 2007) but also show that pest dynamics cannot be understood without a much wider perspective on the socio-economic context.

6. Acknowledgments

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Chapter 5

Unpacking the push-pull system: Assessing the contribution of companion crops along a gradient of landscape complexity

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Abstract

The push-pull system, a stimulo-deterrent cropping strategy consisting of intercropping cereals with herbaceous legumes and surrounded by fodder grasses, is presented as a promising crop diversification strategy for smallholder farmers in Africa as it may contribute to maize stemborer *Busseola fusca* (Fuller) suppression while improving soil fertility and providing feed for livestock. The push-pull system has often been assessed at plot level and as a package (e.g. Maize + *Desmodium* + Napier grass). However, it is unclear how the system performs in different landscape settings or when companion crops are changed to better meet household needs. Here we evaluate the potential of the push-pull system to suppress maize stemborer infestations in three landscapes in the Rift Valley region of Ethiopia along a gradient of landscape complexity. Within each landscape, experimental plots were established on four representative smallholder farms. At each farm we used a split-plot factorial design with main plots surrounded or not by Napier grass and subplots consisting of sole maize, maize-bean, or maize-*Desmodium*. We assessed stemborer infestation levels and maize grain and stover yields during two years, as well as natural enemies abundance and egg predation at two maize development stages in the second year. In the simple landscape, which was dominated by maize, all treatments had high stemborer infestation levels, irrespective of within-field crop diversity; the presence of Napier grass was associated with higher predator abundance, while egg predation rates were the highest in the maize-bean intercrop. In the intermediate complexity landscape, subplots with sole maize had higher stemborer infestation levels compared to maize-bean or maize-*Desmodium*. In the complex landscape, infestation levels were low in all treatments. However, none of these effects led to significant differences in maize grain and stover yields among treatments in any of the landscapes. The benefits of the push-pull system accrued from the companion crops (bean, *Desmodium,* and Napier) rather than from stemborer suppression per se. Our findings highlight the importance of the surrounding landscape in mediating the performance of the push-pull system, provide new insights on the contribution of the different components of push-pull system, and can guide the design of ecologically intensive agroecosystems.

1. Introduction

There is increasing interest in multipurpose cropping systems able to deliver a range of products and services to meet the multiple needs of rural smallholder families and that capitalise on ecological processes rather than external inputs. In large parts of Africa, maize (Zea mays L.) is an important staple crop providing food, feed, and fuel (Shiferaw *et al.*, 2011). However, maize production can be severely compromised by pests, disease and parasitic weeds in many parts of the region (Reynolds *et al.*, 2015). Maize stemborers *Busseola fusca* and Chilo partellus are considered to be the most damaging insect pests, causing variable but sometimes devastating yield losses. Stemborer infestation is severe in Southern Ethiopia, where maize production is further limited by declining soil fertility (Corral-Nuñez *et al.*, 2014) and un-predictable rainfall (Muluneh *et al.*, 2015). These factors, in combination with decreasing farm size, threaten food security, as well as household incomes (Mellisse *et al.*, 2018). There is a need for affordable strategies that can reduce pest incidence below economic thresholds while improving soil fertility and fodder production.

Crop diversification strategies may offer scope for enhancing natural suppression of stemborers (Chabi-Olaye *et al.*, 2008). While the use of chemical pesticides is a common control method across the world, it is not effective for stemborer control because of the cryptic behaviour of the larvae in the stems. Moreover, chemical insecticides are often too expensive for smallholder farmers and often have adverse effects on non-target biota (including natural enemies), the environment, and human health (Rusch *et al.*, 2010). Crop diversification strategies may contribute to reducing crop losses by pests by limiting the pests' ability to locate host plants (Poveda *et al.*, 2008), by repelling pests via plant-mediated semiochemicals (Bakthavatsalam, 2016), or by stimulating the abundance and diversity of natural enemies that may provide top-down control of pests (Mailafiya *et al.*, 2011; Pickett *et al.*, 2014). However, the effectiveness of pest suppression potential depends critically on the composition – in terms of species and cultivars – of the cropping system (Zhang *et al.*, 2013), while the crop assemblage should meet the requirements of the household in terms of food, feed, and/or cash.

The push-pull system is a crop diversification strategy based on intercropping maize with a legume species such as *Desmodium* spp., whose semiochemicals repel stemborers ("push" effect), bordered by a trap crop (e.g. *Pennisetum purpureum* or Brachiaria spp.), which attracts stemborers ("pull" effect) (Cook *et al.*, 2007; Khan *et* *al.*, 2010; Zhang *et al.*, 2013). This system is also associated with enhanced suppression of the parasitic weed Striga, enhanced soil fertility through N-fixation by the legume *Desmodium* spp., and increased food and feed production (Cook *et al.*, 2007; Belay and Foster, 2010). Perennial fodder crops alter the attractiveness of the crop habitat for potential natural enemies of stemborers in maize fields. For instance, Khan et al (2001) demonstrated that the parasitism of stemborers in push-pull systems is enhanced through attraction of parasitoids to molasses grass. Similarly, Mammo (2012) found that Napier and Sudan grass attracted predators of stemborers, such as ants, earwigs and spiders. The adoption of the push-pull system may be further stimulated by replacing the *Desmodium* spp., which can only be used for feed, with a multipurpose grain legume such as common bean, which is an important source of protein in local diets (Fischler, 2010). Beyond their ability to fix nitrogen, legume crops produce secondary metabolites as defence compounds against herbivores (Wink, 2013). Indeed, traditional maize/bean or maize/cowpea intercropping systems are less prone to stemborer infestations (Chabi-Olaye *et al.*, 2002; Belay and Foster, 2010), and tend to provide higher maize yield than sole maize (Songa *et al.*, 2007; Seran and Brintha, 2010). However, the push-pull system has often been assessed as a package, and the contribution of each component is not clear. In addition, the performance of the push-pull system based on *Desmodium* spp. and other legume crops in different landscape contexts is not well known.

Despite the considerable research effort on push-pull systems, most studies have focused on assessing the effectiveness of this system at the field scale, often in research stations, without considering the effect of the surrounding landscape (Midega *et al.*, 2014; Eigenbrode *et al.*, 2016). Landscape context can influence the pest and natural enemy interactions by providing resources and shelter (Eigenbrode *et al.*, 2016). For instance, while maize fields function as reproduction habitats for stemborers, perennial crops may support natural enemies in maize-based cropping systems (Kebede *et al.*, 2018). Landscape factors that drive stemborer and natural enemy population dynamics at relatively large spatial scales may interact with within-field crop diversity factors that moderate stemborer repelling and attracting effects at smaller spatial scales. It is yet unclear how such interactions unfold in African smallholder landscape settings. Moreover, the push-pull system based on Napier-*Desmodium* may not fulfil the needs of smallholder farmers without livestock. In these cases, replacing the feed crop *Desmodium* by common bean may be beneficial, and

Napier, which is also used for feed, may be less desired by farmers. There is a need to assess the performance of the different crop combinations and system components in the push-pull cropping system to meet the needs of different production situations of smallholders while considering the landscape context (Eigenbrode *et al.*, 2016).

This paper has two objectives. The first objective is to assess the agronomic and pest suppression potential of push-pull systems in landscapes of increasing complexity, from landscapes dominated by maize to landscapes dominated by perennial crops and semi-natural vegetation. For this, we assessed the stemborer infestation levels in maize, the abundance of generalist predators, the associated predation rates, and maize grain and stover yields. Based on previous studies (Cook *et al.*, 2007; Khan *et al.*, 2008b; Pickett *et al.*, 2014), we hypothesised that the push-pull system would suppress stemborers and result in higher maize yield, irrespective of the landscape setting. The second objective is to assess the performance of the alternative push-pull systems by varying or omitting one of the companion crops. We compared the performance of the traditional push-pull system based on Napier-maize-*Desmodium* (*Desmodium uncinatum* jacq) to the performance of Napier-maize-common bean (*Phaseolus vulgaris* L.) and Napier-maize; we also assessed the performance of these three cropping systems without Napier. We expected that replacing *Desmodium* with common bean and omitting the Napier trap crop would result in higher stemborer infestation levels and lower maize yields.

2. Materials and methods

2.1 Study area

The study area is located in the Hawassa region in the Ethiopian Rift Valley between 7°03′11′′ to 7°08′4′′ N latitude and 38°15′17′′ to 38°38′47′′ E longitude (Fig. 1). The area is characterised by a moist to sub- humid warm subtropical climate. Annual precipitation ranges from 750 to 1200 mm in a bimodal distribution pattern and is expected in March to April and June to August (Dessie and Kleman, 2007). *Busseola fusca* is the major maize stemborer species found in the area. The average land holding per household is below one hectare of arable land (Dessie and Kleman, 2007; Dessie and Kinlund, 2016). We selected representative landscapes in three districts: Hawassa Zuria, Tula, and Wondo Genet, along a gradient of decreasing annual/perennial crops ratio. We refer to these three landscapes as simple, intermediate, and complex landscapes, respectively. Hawassa Zuria is dominated by maize, while Wondo Genet contains a substantial proportion of woody semi-natural habitat and the perennial crops khat (*Catha edulis*) and enset (*Ensete ventricosum*). Tula has an intermediate proportion of maize and semi-natural habitat. Data on landscape composition and configuration were obtained by combining Landsat satellite images and focus group discussions with farmers (Kebede *et al.*, 2018).

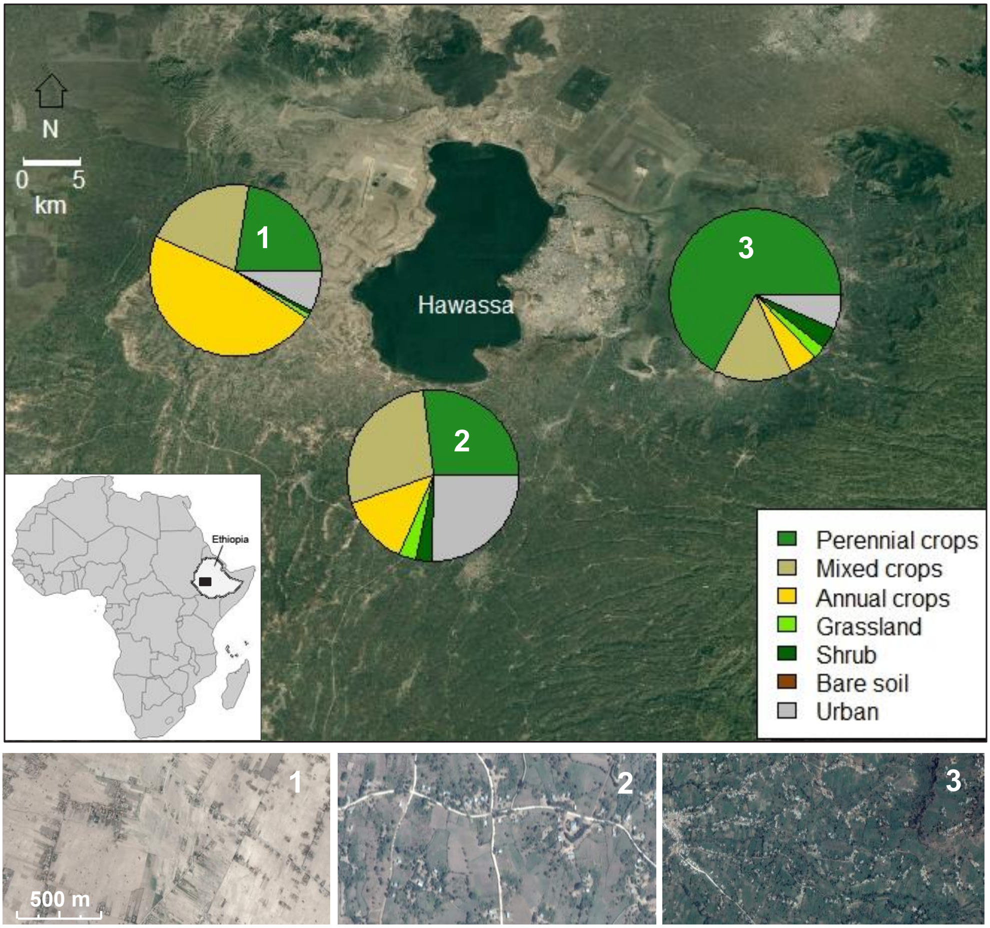


Figure 1. Location of the study landscapes around Lake Hawassa in the Rift Valley region of Ethiopia: Simple (1), intermediate (2), and complex (3) landscapes. The simple landscape (1) is dominated by maize, the diverse landscape (3) by perennial crops and late successional non-crop vegetation, and (2) the intermediate landscape has a mixed composition of maize, perennial crops, and non-crop vegetation.

2.2 Experimental design and plot management

Prior to the installation of the experimental plots, we evaluated the performance of five Napier grass genotypes (four genotypes of *Pennisetum purpureum*: 16 803, 16 786, 16 837, and 14 984; and one of *Pennisetum riparium*: Sodo 88) obtained from the International Livestock Research Institute (ILRI) in Ethiopia. In the simple landscape we planted three rows of each genotype and replicated the experiment in three sites (Kebede, unpublished data). Based on the performance in terms of stemborer larvae density, leaf eating by stemborer, and biomass productivity, we selected the genotype 16 803 for the push-pull experiment (Appendix 1). In each landscape, experimental fields were established on four farms for a total of 12 fields. Each field was divided in two blocks separated by 5 m and surrounded by Napier grass or not (Fig. 2). Napier was planted a month prior to maize planting in 2014 at inter and intra-row spacing of 75 cm and 50 cm, respectively, using stem cuttings of *Pennisetum purpureum* (Genotype 16 803). Each block was divided in three plots (10x7.5 m) with an inter plot distance of two metres, the maximum distance possible given the small size of farmers' fields in the area. Three cropping systems were randomly assigned to each plot: sole maize, maize-silverleaf *Desmodium* uncinatum, and maize-common bean (Fig. 2). The commonly used maize variety in the study area BH540 was planted at inter and intra-row spacing of 75 cm and 30 cm, respectively. We applied 100 kg ha^{-1} diammonium phosphate (DAP) at planting and top-dressed the crop with 100 kg ha^{-1} of urea, following national recommendation rates. In each landscape, the time of planting, weeding, and harvest were as per farmers' practice.

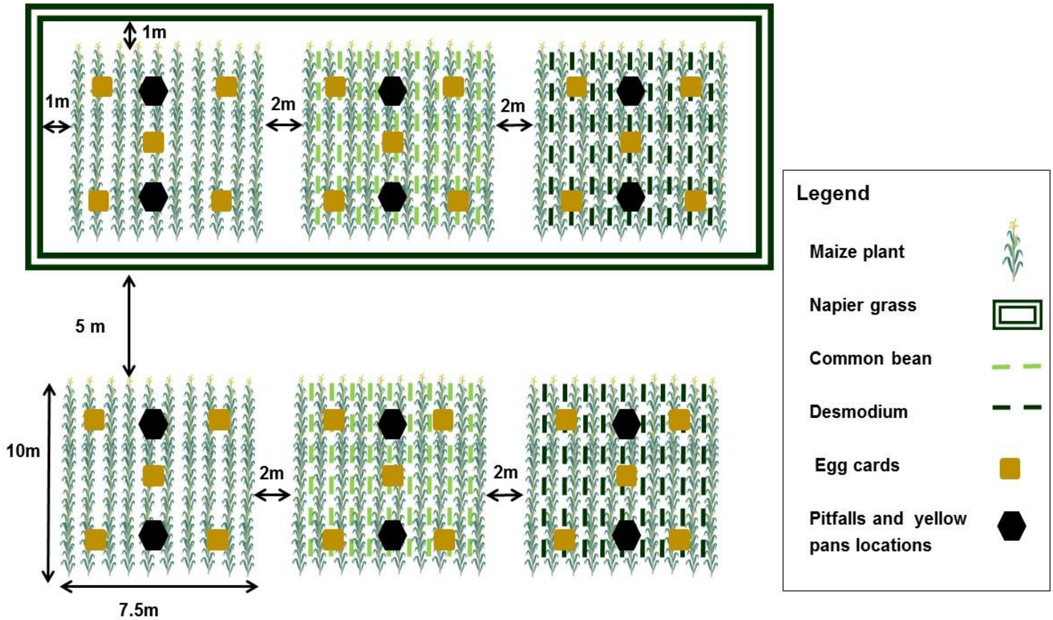


Figure. 2. Experimental design of the study. Four farms were selected in each of the three landscapes. In each farm a randomized block design was established, with two blocks (absence or presence of Napier grass) and three cropping systems randomly assigned within blocks (sole-maize, maize common bean, and maize-*Desmodium*).

2.3 Stemborer infestation and yield assessment

Maize infestation was assessed by randomly selecting twenty plants per plot at grain filling and maturity stages in 2014 and 2015. From each plant we recorded the number of holes in the stem, the stemborer tunnel length in the stem, the number of live and dead larvae, the number of pupae, and the proportion surface damage of the cob(s). Maize grain moisture (%) content was assessed using Dickey John portable grain moisture tester (http://www.dickey-john.com/product/ m3g/). Maize grain yield in tonnes of dry matter per hectare (t DM ha -1) was calculated at plot level by multiplying the fresh weight by the DM content and converted into tonnes per hectare. Maize stems and leaves were weighted in situ, and a subsample was oven dried during 48 h at 70 °C and maize stover yield (t DM ha -1) calculated. The yield of common bean was assessed by destructive harvesting of five sections of one metre of bean plants along the row and assessing the fresh and dry weight of grain and crop residues.

2.4 Generalist predator abundance and egg predation

The abundance of natural enemies of maize stemborers and egg predation were assessed in each of the 72 plots during grain filling and maturity in 2015. The arthropod community was sampled by placing yellow pans and pitfall traps at two locations within each sub-plot (Fig. 2) for three days as described in Kebede *et al.* (2018). Arthropod samples were sorted and generalist predators were identified at the order, or family level following the identification key of Polaszek *et al.* (1998) and Bonhof *et al.* (1997). Specimens belonging to the order Araneida, the families Forficulidae, Staphylinidae and Formicidae, and the genus Cheilomenes were considered as main predators of maize stemborers (Kfir, 1997). Parasitoid abundance was low and was not analysed . To assess egg predation, we prepared cards with Ephestia kuehniella eggs by sprinkling the eggs uniformly on a standardized sticky area of 28.27 mm2 using a hole punch and removed excess eggs that did not touch the sticky surface. Five egg cards were placed in each subplot in a Z-shape pattern in the plot interior, at least two metres from the plot border (Fig. 2). The egg cards were stapled at the top of maize plants in the leaf sheaths, which is the natural place where female stemborer deposit egg batches, and were left in the field for three days. The fraction of eggs removed by predators was assessed by comparing pictures before and after field exposure using ImageJ software (https://imagej.net/Welcome).

2.5 Data analysis

The number of holes, number of larvae, proportion of cob damage, and length of tunnelling were pooled for the 20 plants in each plot. To reduce the number of response variables associated with stemborer infestation we assessed the Pearson correlation between the number of holes, proportion of cob damage, length of tunnelling, and number of larvae. Since the four proxies were significantly correlated ($P < 0.001$; $R = 0.74$ or higher; Appendix 2), we selected length of tunnelling for further analysis because this proxy captures information about stemborer infestation and crop damage throughout the growing season. The length of tunnelling was $\log_{(x+1)}$-transformed, and the relationships between this transformed variable and landscape and crop diversity variables were analysed using a linear mixed model (Eq. (1)):

$$\boldsymbol{Y_{ijk} = \alpha + \beta LN_i + \gamma NP_j + \lambda CR_k + \tau(LN_i * NP_j) + \delta(LN_i * CR_k) + \mu(NP_j * CR_k) + \rho\,(LN_i * NP_j * CR_k)} \qquad \textbf{(1)}$$

where, **Yijk** represents the log(x+1)-transformed length of tunnelling, $\mathbf{LN_i}$ is the landscape (simple, intermediate or complex), $\mathbf{NP_j}$ is Napier grass (presence or absence), CR_k is the cropping system (sole maize, maize-bean, or maize-*Desmodium*) and where α, β, γ, λ, τ, δ, μ, and ρ represent regression coefficients for the main and interaction effects. "Farm" was nested in "landscape" and both "farm" and "year" were considered random effects. The same model structure and analysis was applied for the response variables maize grain and stover yields.

The response variables "generalist predator abundance" and "egg predation" (fraction of the Ephestia eggs removed) were count and binomially distributed data respectively and were analysed using generalised linear mixed models. For "generalist predator abundance" we tested a Poisson and negative binomial error distribution with "farm" as random factor and selected the negative binomial error distribution because this model had the lowest Akaike Information Criterion (AICc) value. For "egg predation", we used a logit link function. We used a similar model structure as presented in Eq. 1, but since these data were collected over a single year (2015) at two maize development stages (grain filling and physiological maturity of the maize), we adjusted Eq. 1 by removing "year" and adding "maize development stage" as a fixed factor. All analyses were conducted in R (R Core Team, 2012) and we used the chart.Correlation function from PerformanceAnalytics package for constructing correlation plots (Peterson and Carl, 2018), the lmerTest package for linear mixed models (Kuznetsova *et al.*, 2017), and the GLMER function in the lme4-package for generalised linear mixed models (Bates *et al.*, 2014).

3. Results

3.1 Stemborer infestation

The length of stemborer tunnelling in maize stems was significantly influenced by the landscape context (P < 0.01; Table 1; Fig. 3) with the highest length of tunnelling in the simple landscape. However, there were also significant landscape by cropping system interactions in the intermediate landscape where the length of tunnelling was higher in sole maize (P < 0.05) compared to maize-bean or maize-*Desmodium* cropping systems. These interactions indicate that the stemborer suppression potential of push-pull systems may differ in different landscape settings.

Table 1. Determinants of $\log_{(x+1)}$-transformed length of tunnelling in maize plants using a linear mixed model. Landscape complexity (simple, intermediate, or complex), Napier (presence or absence), cropping system (sole maize, maize-bean, or maize-*Desmodium*) were fixed variables, while farm was nested in landscape and year was taken as a random variable. The diverse landscape, the maize-*Desmodium* cropping system, and the presence of Napier were reference variables. Significant effects (P < 0.05) are shown in bold.

	Estimate	Std. Error	*P*-value
Intermediate	0.562	0.403	0.188
Simple	1.647	0.402	**0.001**
Napier absence	-0.030	0.099	0.760
Sole maize	-0.166	0.140	0.238
Maize-bean	0.181	0.142	0.206
Intermediate *Napier absence	0.119	0.143	0.406
Simple *Napier absence	-0.013	0.141	0.928
Intermediate *Sole maize	0.512	0.200	**0.012**
Simple *Sole maize	0.158	0.197	0.425
Intermediate *Maize-bean	-0.475	0.202	**0.020**
Simple *Maize-bean	-0.195	0.199	0.329
Napier absence * Sole maize	-0.081	0.140	0.561
Napier absence * Maize bean	0.140	0.142	0.326
Intermediate *Napier absence *Sole maize	0.008	0.200	0.967
Simple *Napier absence * Sole maize	0.029	0.197	0.885
Intermediate *Napier absence * Maize-bean	-0.121	0.202	0.552
Simple * Napier absence * Maize-bean	-0.141	0.199	0.482

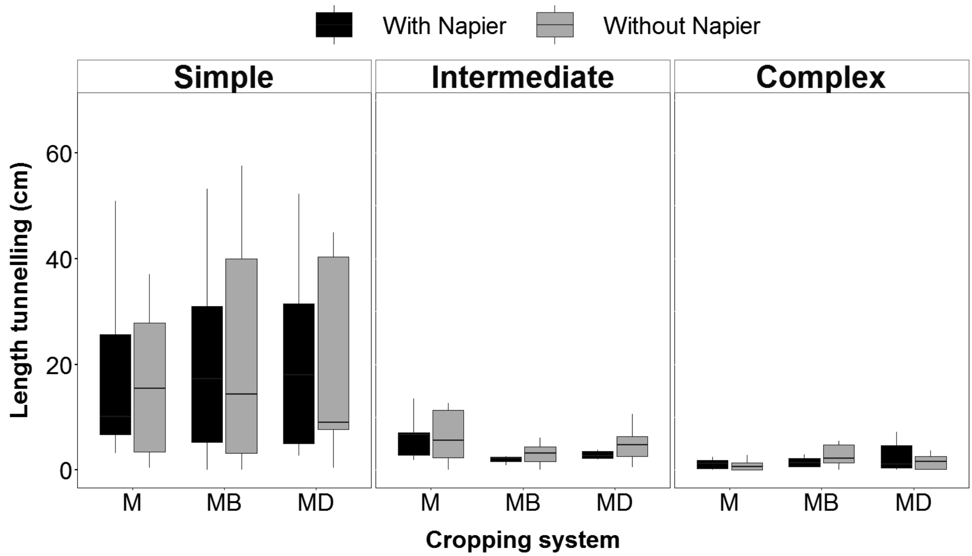


Figure 3. Boxplots of length tunnelling per cropping system (sole maize (M), maize-common bean (MB), or maize-*Desmodium* (MD)) and per landscape (simple, intermediate, or complex) in the absence or presence of Napier grass.

3.2 Generalist predator abundance and egg predation

The interaction between landscape and the presence of Napier grass had a significant effect on the abundance of generalist predators, with the highest abundance in the simple landscape when Napier grass was present ($P < 0.01$; Table 2; Fig. 4A). In general, sole maize supported a low abundance of predators ($P < 0.05$), however, the interaction between cropping system and landscape had a significant effect on predator abundance, with higher predator abundance in sole maize plots located in the landscape of intermediate complexity. The generalist predator community was dominated by ants (Formicidae), followed by spiders (Araneae). The abundance of ants was high in the three landscapes but relatively higher in the maize-*Desmodium* cropping system with Napier in the complex landscape (Fig. 5). However, the observed differences in predator abundance did not affect egg predation rates. In fact, egg predation was mostly affected by maize development stage with higher predation at maturity ($P < 0.01$; Fig. 4B) and was lower in maize-bean cropping system ($P < 0.05$, Table 2). In the landscape of intermediate complexity, egg predation rates were highest in the maize-*Desmodium* cropping system (Fig. 4B), but differences were not significant.

3.3 Crop productivity

Maize yield was not significantly influenced by landscape, presence or absence of Napier grass, and intercropping (Appendix 3.1). Common bean grain yield in the maize-bean cropping system was 0.64 ± 0.10, 1.03 ± 0.10, and 1.15 ± 0.18 t DM ha^{-1} in the simple, intermediate, and complex landscape, respectively (Appendix 3.2), with significantly higher yield in the complex and intermediate landscape compared to the simple landscape (Appendix 3.3). In the maize-bean-Napier cropping system, bean grain yield was 0.76 ± 0.09, 1 ± 0.18, and 1.4 ± 0.17 in the simple, intermediate, and complex landscape, respectively (Appendix 3.2), with significantly higher bean yield in the complex landscape compared to the intermediate landscape (Appendix 3.3).

Table 2 Estimates of the model for the abundance of generalist predators with negative binomial distribution and egg predation with logit link function. The variables landscape diversity (diverse, intermediate or simple), Napier (presence or absence), cropping system (sole maize, maize-bean, or maize-*Desmodium*), and maize development stage (grain filling and maturity) were fixed variables. Farm was taken as a random variable nested in landscape. the diverse landscape, the maize-*Desmodium* cropping system, the presence of Napier, and the maize development stage maturity were reference variables. ($P < 0.05$) are shown in bold.

	Generalist predators			**Egg predation**		
	Estimate	Std. Error	p-value	Estimate	Std. Error	p- value
Intermediate	-0.473	0.257	0.066	1.680	5.238	0.7484
Simple	-0.073	0.256	0.775	0.815	0.518	0.1158
Napier absence	0.094	0.071	0.187	0.395	0.340	0.2445
Sole maize	-0.255	0.102	**0.013**	0.259	0.469	0.5813
Maize-bean	-0.062	0.101	0.541	-1.067	0.499	**0.0325**
Maturity	-0.113	0.085	0.185	1.390	0.428	**0.0012**
Intermediate * Napier absence	-0.175	0.106	0.098	-1.959	5.234	0.7082
Simple * Napier absence	-0.304	0.102	**0.003**	-0.739	0.476	0.1201
Intermediate * Sole maize	0.337	0.148	**0.023**	-1.219	5.254	0.8165
Simple * Sole maize	0.161	0.145	0.268	-0.318	0.662	0.6311
Intermediate * Maize-bean	-0.106	0.149	0.477	-2.079	5.262	0.6929
Simple * Maize-bean	-0.075	0.145	0.605	0.900	0.679	0.1849
Napier absence * Sole maize	-0.129	0.103	0.209	0.126	0.470	0.7884
Napier absence * Maize bean	0.037	0.102	0.715	-0.368	0.493	0.4552
Intermediate * Napier absence * Sole maize	0.148	0.148	0.317	0.894	5.254	0.8649
Simple * Napier absence * Sole maize	0.025	0.146	0.863	-0.408	0.663	0.5386
Intermediate * Napier absence * Maize-bean	-0.072	0.150	0.633	1.312	5.262	0.8031
Simple * Napier absence * Maize-bean	-0.100	0.145	0.493	0.641	0.678	0.3441

4. Discussion

While the push–pull system is relatively well studied and promoted in East Africa as a practice that can suppress stemborer and Striga infestations (Khan *et al.*, 2008a), improve soil fertility (Khan *et al.*, 2011), and generate higher economic returns than sole maize (Kipkoech *et al.*, 2006; Khan *et al.*, 2008b), this is the first study – to the best of our knowledge – that examines the performance of the push-pull system in farmers' field conditions along a gradient of landscape complexity. In addition, we assessed the effects of the "push" (*Desmodium*/bean) and "pull" (Napier) effects separately to explore opportunities to adjust the system to farmers' realities by changing companion crop species. Trap crops and repellent crops occupy space that many farmers would preferably allocate to food crops. We tested the impact of replacing *Desmodium* with common bean and removing Napier grass on the performance of the push-pull system (stemborer and natural enemy abundances). We observed that stemborer infestation levels were negatively associated with landscape complexity, while crop diversification (including or not a legume intercrop and Napier grass) did not influence stemborer infestation in both the simple and the complex landscapes. Yet intercropping decreased stemborer infestation in the landscape of intermediate complexity. Generalist predator abundance tended to be lower in sole maize as compared to maize intercropped with legumes, but this was not the case in the landscape of intermediate complexity. Generalist predator abundance was positively associated with the presence of Napier grass in the simple, maize-dominated, landscape. Although the impact of stemborer infestation on maize yield was not significant, the yield of bean, *Desmodium,* and Napier grass in the push-pull plots represented net gains in terms of food and feed production. These findings provide new insights on the performance of the different components of push-pull in different landscape contexts and can guide the design of ecologically intensive agroecosystems. Underlying mechanisms are explored below.

4.1 Stemborer infestation decreases with increasing landscape complexity

Stemborer infestation rates were higher in the simple, maize-dominated landscape of Hawassa Zuria than in the intermediate and complex landscapes (Fig. 1 and 3). Midega et al (2014) reported that increased grassland ratios within a radius of 400 m around push-pull and sole maize fields led to lower stemborer infestation and higher maize yields. Since grasslands are potential host habitats of stemborers, they may attract stemborers that would otherwise infest maize plant and thus may reduce infestation in maize crops. However, maize remains the favourite host plant for stemborers, and the positive association between the proportion of maize in the landscape and stemborer infestation is demonstrated in this study.

4.2 Push-pull is only effective in landscapes of intermediate complexity

The ‘intermediate complexity landscape hypothesis’ postulated by (Tscharntke *et al.*, 2005) predicts that biodiversity-based management actions are more effective in landscapes of intermediate complexity than in simple or complex ones. In simple landscapes, there is too little habitat to support effective natural enemy densities, such that management actions are not effective because of the lack of colonisation of natural enemies from the surrounding landscapes. In complex landscapes, the densities of natural enemies may already be high, such that further improvement by habitat management does not lead to further improvement in natural pest regulation. In this study, in the simple and complex landscapes, both the trapping and repellent effects exerted by Napier grass and legume intercrops were not effective. In the simple landscape with a high stemborer abundance, female stemborers were easily able to locate maize plants for egg deposition, independent of the presence of legumes or Napier grass nearby. In contrast, in the complex landscape with few stemborer host plants, stemborer populations and the associated egg deposition were likely to be low, masking potential effects of crop diversification strategies. These findings suggest that further research and implementation of push-pull system should consider the composition of the surrounding landscape for an effective control of stemborer.

4.3 Effect of companion crops on the abundance of generalist predators

The presence of Napier grass increased the abundance of generalist predators (mostly ants) in the simple, maize-dominated landscape. The presence of Napier in the landscape of intermediate complexity tended to increase the abundance of generalist predators ($P = 0.098$). Given the limited amount of semi-natural habitats in the simple landscape, Napier grass could be acting as a physical trap providing shelter for natural enemies (Shelton and Badenes-Perez, 2006). Generalist predators were less abundant in sole-maize crops. These findings are corroborated by previous studies, which showed higher abundance of generalist predators in a push-pull system compared to sole maize (Midega *et al.*, 2004). Such higher abundance of predators is believed to be a result of the presence of associated crops (Midega and Kahn, 2003) and hamper host finding in the system (Eigenbrode *et al.*, 2016) and not only a response to high stemborer abundance.

Egg predation rate was influenced by the development stage of maize. Females of *B. fusca* lay eggs in the leaf sheaths where they are less vulnerable to predation. In the study area, two to three generations per cropping season can occur (Azerefegne and Gebre-Amlak, 1994). The position at which the eggs are found correlates with the developmental stage of the plant (Van Rensburg *et al.*, 1987). With increasing plant age, leaf sheaths fit more loosely around stems making egg batches more visible and accessible to predators, which can explain the higher egg predation rate at maturity compared to grain filling maize development stage (Fig. 4B).

Moreover, in the intermediate complexity landscape the presence of *Desmodium* increased egg predation rates slightly as compared to sole-maize or maize-bean cropping systems (Fig. 4B). Common bean is harvested about three months after simultaneous planting with maize, leaving the ground bare in between maize rows, while *Desmodium* is a perennial plant that covers the maize inter-row throughout the season. Thus, at maize maturity, maize-*Desmodium* cropping systems present a comparative advantage for generalist predators due to the stable and undisturbed shelter that *Desmodium* plants offers. In the simple landscape, sole Napier (i.e. trap crop only) was effective in reducing stemborer infestation, corroborating the findings by Van den Berg and Van Hamburg (2015) who demonstrated that Napier planted along two contours of maize fields (in order not to hamper mechanical operations in maize fields) was effective in the control of stemborers. These findings show the specific effect and contribution of the companion crops in the push-pull system in terms of supporting predator abundance and egg predation in contrasting landscapes and demonstrate the merit of further context-specific optimisation of the design of push-pull systems.

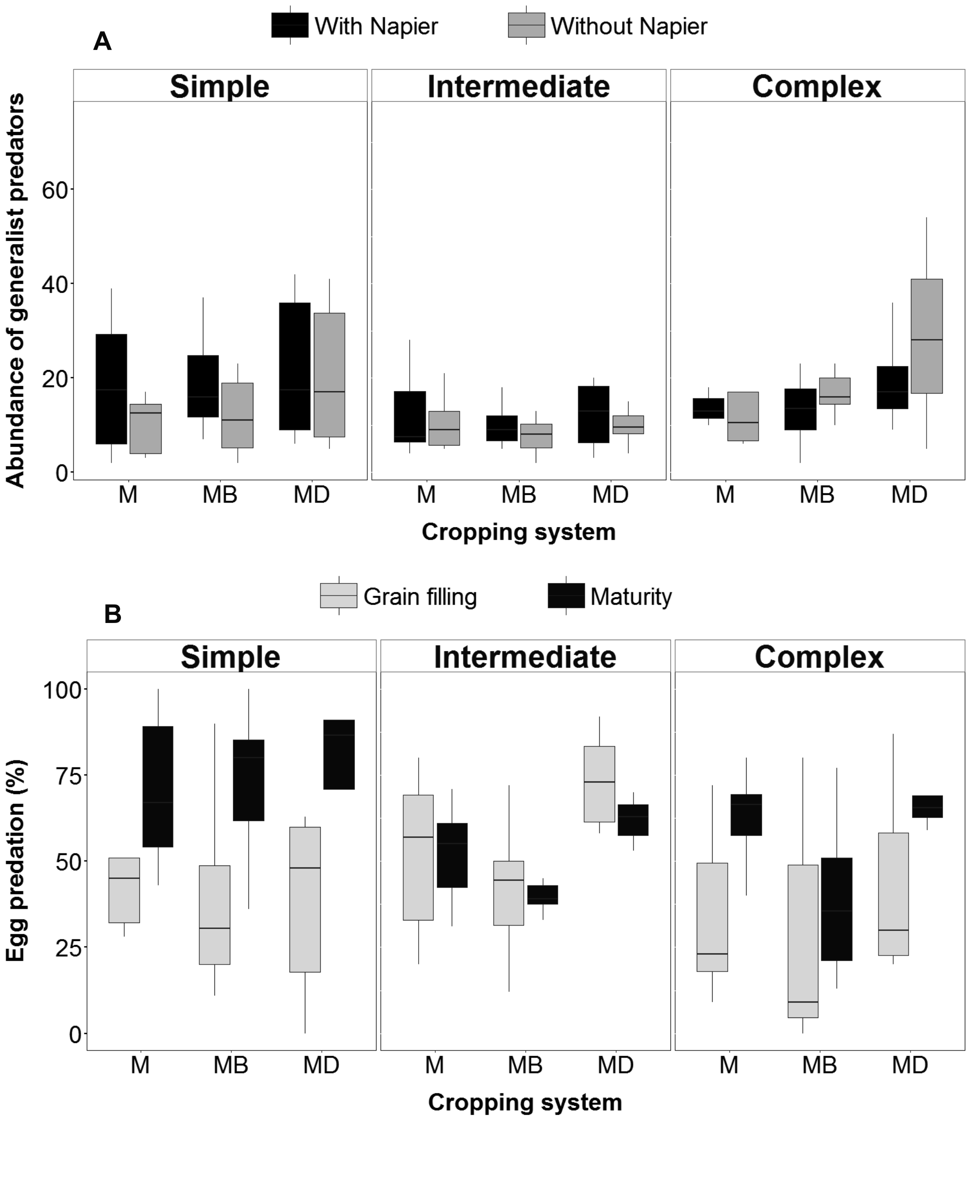


Figure 4. Boxplots of total predator abundance in the absence or presence of Napier grass (A) and egg predation at two maize stages, grain filling and maturity (B), per cropping system (sole maize (M), maize-bean (MB), or maize-*Desmodium* (MD)) and per landscape (simple, intermediate, or diverse).

4.4 Push-pull had no effect on maize yield but generated other benefits

Maize grain and stover yields were not significantly influenced by stemborer infestation. This result contrasts with previous research in Ethiopia which reported average yield losses due to *B. fusca* between 12% to 40% of the total production depending on agro-climatic zone, maize variety, cropping system, and soil fertility level (Kfir *et al.*, 2002, Mgoo *et al.*, 2006). The limited impact of stemborer on maize yield in our study can be explained in two ways. First, in our experiment, all plots received the recommended fertilisation for the region (100 kg ha^{-1} of urea and 100 kg kg^{-1} of DAP), which is higher than typically applied by smallholder farmers. The higher maize vigour may have allowed maize plants to compensate for crop injury caused by stemborers. Second, 2014 and 2015 were low infestation years with mean stemborer densities of less than 0.6 larvae per plant (Kebede *et al.* in prep). The low infestation level has most likely obscured the negative association between stemborer infestation level and yield.

The adoption of the push-pull system by farmers has been limited in Kenya (Fischler, 2010), possibly due to farmers' reluctance to replace food crops, such as common bean, with a fodder crop and the reluctance to reduce maize production area in favour of a companion trap crops. Our study shows that push-pull systems did not reduce maize grain yield but rather increased the overall productivity of the system over two years (Appendix C). In the simple landscape, common bean was associated with similar or higher generalist predator abundances and egg predation rates than *Desmodium*. However, in contrast to common bean, *Desmodium* produces highly effective inhibitory compounds against Striga (Hassanali *et al.*, 2008). Therefore, a push-pull system with *Desmodium* may be advantageous in areas with Striga infestations, which was not the case of the study area.

Farming systems in Ethiopia and most of Africa are small-scale integrated crop-livestock systems. However, feed production in these systems is often not sufficient to feed the animals throughout the year, and the nutritional quality of the feed is often less than optimal (Tripathi *et al.*, 2006). Napier grass can be very productive with 35–40 t DM ha^{-1} per year when nitrogen is not a limiting factor (Oliveira *et al.*, 2014). Integrating Napier grass and *Desmodium* in farming systems can increase feed supply to support livestock production (Tittonell *et al.*, 2009). This is even more pertinent for our study area where farm sizes are small (less than 1 ha) and communal grasslands waning (Kebede *et al.*, 2018). Push-pull systems may not only impact stemborer, but also other lepidopteran pests of maize and other cereals (Hassanali *et al.*, 2008). This is particularly relevant for the control of the invasive fall armyworm *Spodoptera frugiperda*, which recently invaded Africa and poses a major threat to food security and livelihoods in large parts of the continent (Day *et al.*, 2017). Our study suggests that Napier grass can potentially stimulate generalist predators, such as ants, but that this effect depends on landscape context. Since ants can be predators of fall armyworms in Latin America (Perfecto and Sediles, 1992), diversified maize cropping systems which support ants may be less prone to fall armyworm infestations.

4.5 Limitation of the study

While experiments under farmers' fields aim at reflecting reality, the 5 m distance between the two Napier grass sub-treatments in our study (i.e. with or without Napier grass) may have been a limitation of the experimental design, since semiochemical interferences are plausible in the field within such short distances (Eigenbrode *et al.*, 2016). However, since farmers' fields were often smaller than 1 ha, between block distances of more than 5 m were unacceptable for farmers as this would compromise food production and household income. Napier grass showed different levels of growth between the three landscapes due to differences in soil fertility and rainfall distribution. While in the diverse and intermediate landscape, Napier grass reached three m or higher acting as a physical barrier to flying pests, whereas it seldom exceeded 2 m in the simple landscape. In general, farmers were hesitant to provide land for the experiment. Farmers perceived the establishment of Napier grass in the middle of the field as a constraint due to the reduction of the area for their food crops and because Napier grass develops a dense and deep root system that can make ploughing more difficult (Van den Berg and Van Hamburg, 2015).

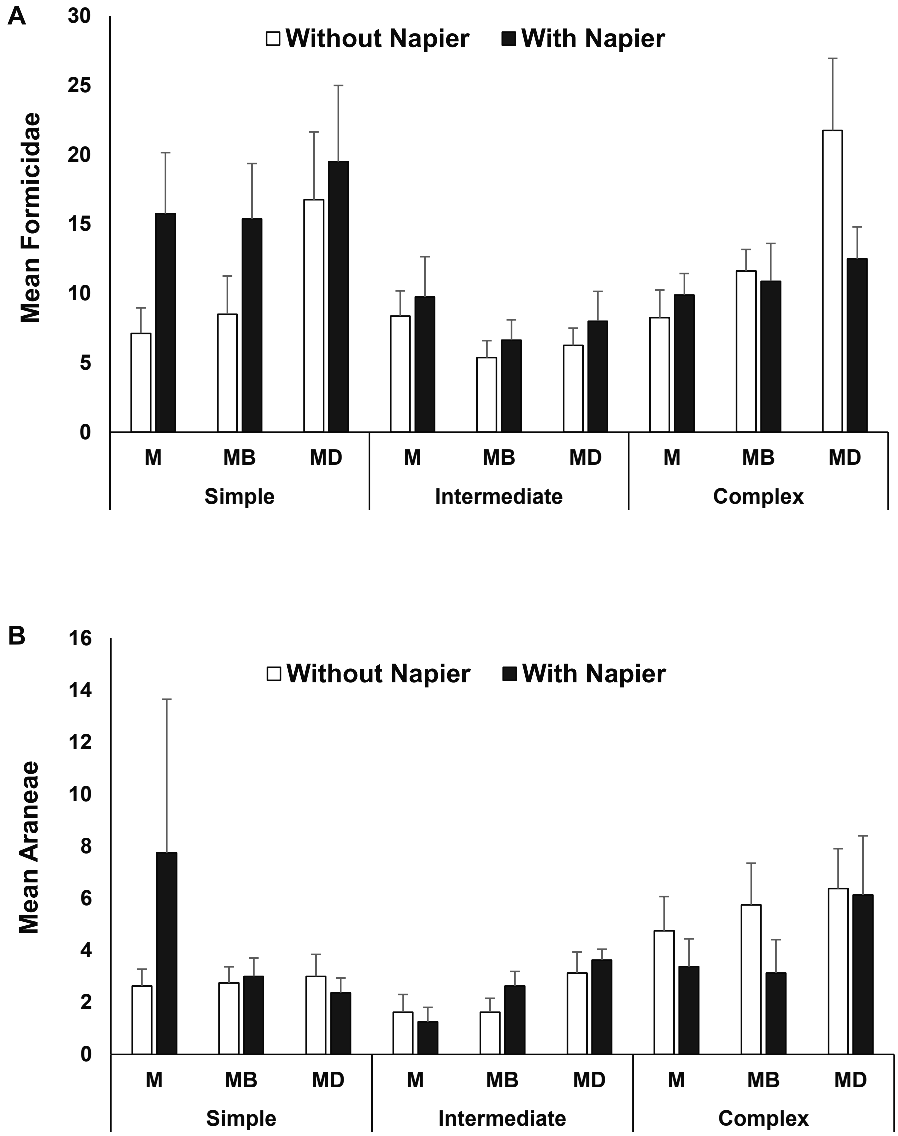


Figure 5. Mean abundance of ants (A) and spiders (B) per cropping system (sole maize (MB), maize-bean (MB), or maize-*Desmodium* (MD)) with (black bars) or without (white bars) Napier grass along a gradient of decreasing annual/perennial crop ratio represented by the simple, intermediate, or complex landscapes. Error bars indicate standard error of the mean.

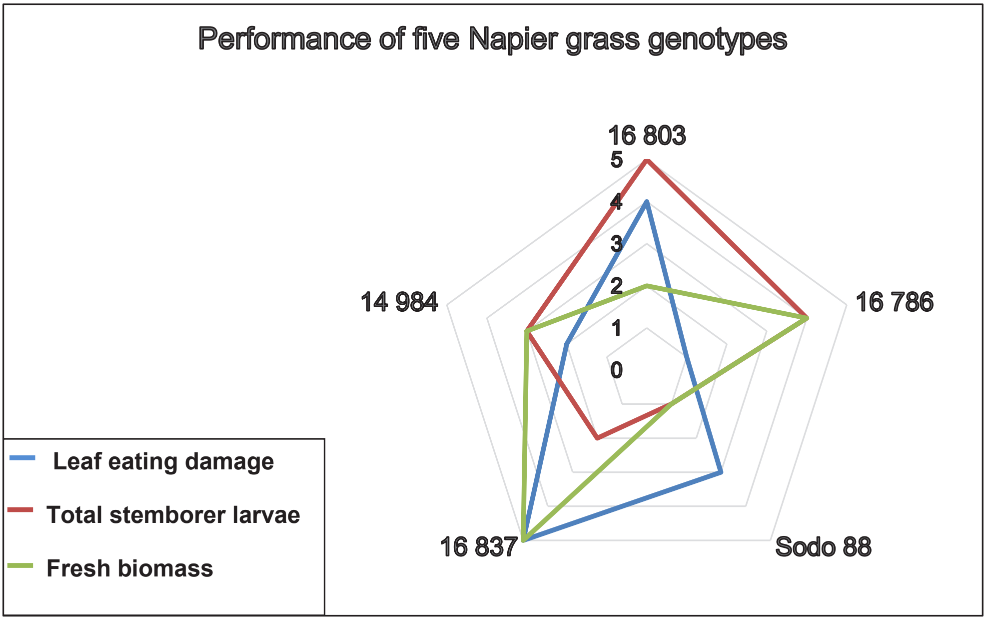
5. Conclusions

Our study demonstrates the importance of the landscape context on the effectiveness of the push-pull system. Push-pull did not have an effect on decreasing stemborer infestation levels in simple or complex landscapes. However, push-pull contributed to decreasing stemborer infestation in the landscape of intermediate complexity where neither host plants nor perennial plants providing habitat to natural enemies were predominant. In addition, we demonstrated that common bean was as efficient as *Desmodium* in repelling stemborer and may replace it in areas where the prevalence of Striga infestations is not a constraint. Common bean also offered additional benefits in the simple landscape by increasing the abundance of general predators and egg predation rate (regardless of the presence or absence of Napier) compared with sole maize or maize intercropped with *Desmodium*. To the best of our knowledge, this is the first study demonstrating that landscape complexity can have an overriding effect on the different semiochemically-mediated components of the push-pull system, which so far has been mainly tested at plot level and as a package.

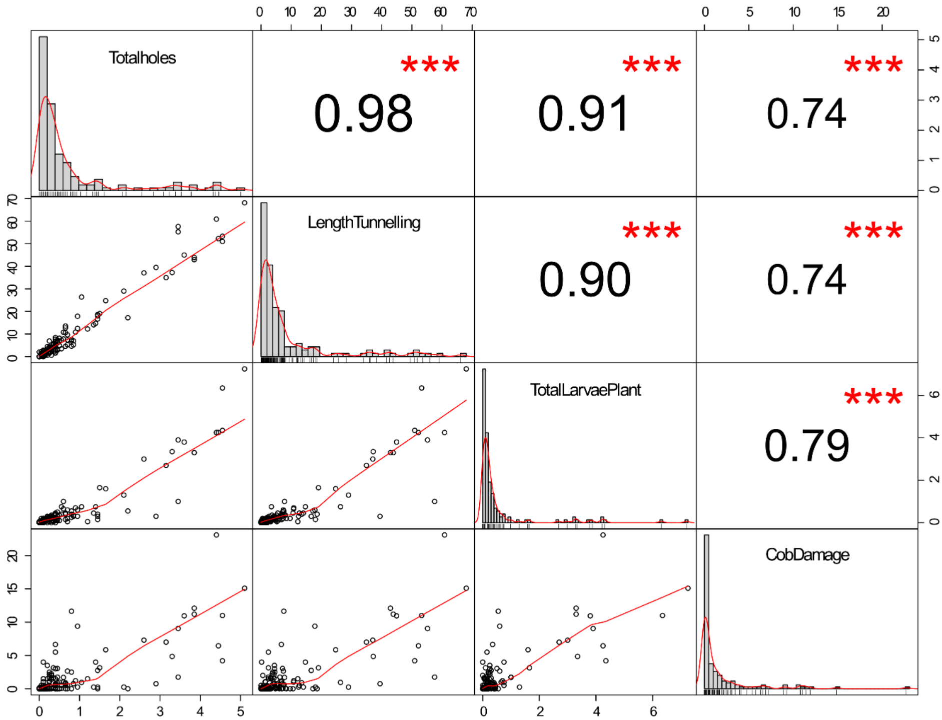
6. Acknowledgments

We acknowledge ILRI for providing the germplasms of Napier grass and Desmodium seeds used. We are grateful to Prof. Zeyaur Khan from the International Centre of Insect Physiology and Ecology (ICIPE) for facilitating the training of the first author in maize stemborer damage identification and push-pull system in Mbita, Kenya in July 2013. This work benefited from the precious expertise of Dr. Ferdu Azerefegne from Hawassa University and the staff of the Ethiopian Institute of Agricultural Research in Hawassa. We thank Dawit Kassahun, Tamet Tesfaye, Abraham Kifle et Anne De Valença for their help during field work and insect identification. We are also very grateful to the farmers who accepted to have the experiment running on their farm.

Appendix 1: Evaluation of Napier grass genotypes (4 genotypes of *Pennisetum purpureum*: 16 803, 16 786, 16 837, and 14 984; and one of *Pennisetum riparium: Sodo 88*) for use as trap crop for the management of African stemborer (*Busseola fusca*) in a push–pull system. Axis units indicates the performance rating of each genotype from low (0) to the best (5).



Appendix 2: Correlation matrix of the proxies for infestation assessment: total holes, length tunnelling, number of larvae, and cob damage

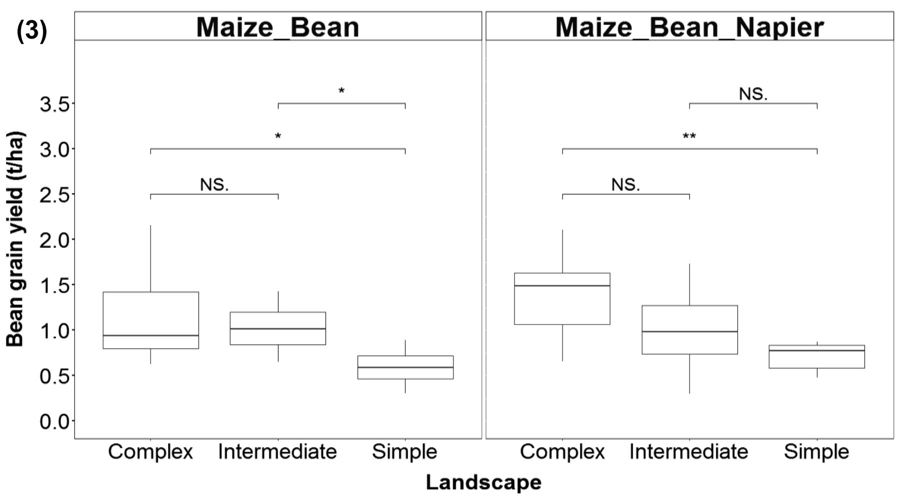


Appendix 3: Mean maize grain yield in t DM/ha per cropping system (Sole-Maize, Maize-bean, or Maize-*Desmodium*) in presence or absence of or without Napier grass and per landscape (Simple, Intermediate, or Complex) (1). Mean bean grain and residue yields and mean dry *Desmodium* productivity in t DM/ha over two years per cropping system (MB: maize-bean (MB), MBN: maize-bean-Napier (MBN)) (2). SEM are given after the sign '±'.

(1)	With Napier			Without Napier		
	M	MB	MD	M	MB	MD
Simple	5.96 ± 0.33	5.45 ± 0.63	4.85 ± 0.34	5.68 ± 0.51	5.05 ± 0.36	5.27 ± 0.52
Intermediate	5.71 ± 0.33	5.30 ± 0.54	5.30 ± 0.33	4.77 ± 0.35	5.00 ± 0.61	5.21 ± 0.50
Complex	6.08 ± 0.61	5.36 ± 0.57	6.51 ± 0.60	5.76 ± 0.96	5.73 ± 0.76	5.45 ± 0.57

(2)	Bean grain yield		Bean residue		*Desmodium*	
	MB	MBN	MB	MBN	MB	MBN
Simple	0.64 ± 0.10	0.76 ± 0.09	0.57 ± 0.10	0.68 ± 0.09	1.94 ± 0.33	1.92 ± 0.14
Intermediat	1.03 ± 0.10	1 ± 0.18	0.72 ± 0.09	0.65 ± 0.07	2.35 ± 0.31	2.14 ± 0.26
Complex	1.15 ± 0.18	1.4 ± 0.17	0.8 ± 0.12	1 ± 0.22	1.93 ± 0.39	1.57 ± 0.20

(3)



Chapter 6

General Discussion

1. Introduction

Understanding ecological processes to inform the design of sustainable and resilient agricultural production systems is a global priority research area. The main objective of this research was to identify pest management strategies at the field, farm, and landscape levels for a sustainable intensification of maize-based production systems. Taking a socioecological approach with spatial (field, farm, and landscape) and temporal (land cover/land use changes over 40 years) components, I assessed which factors affected lepidopteran maize stemborer infestation levels in smallholder agricultural production systems of southern Ethiopia. Currently, major lepidopteran maize pest outbreaks are occurring in sub-Saharan Africa and India, such as the fall armyworm (*Spodoptera frugiperda*); the findings of this study could contribute knowledge on ecological management of these pests and inform more affordable practices for smallholder farmers with lower negative impacts on human health and the environment than chemical treatments.

In this thesis, I used different methods (i) to identify the drivers of farming systems and agricultural landscape changes, (ii) to understand the contribution of landscape elements (e.g. perennial crops, hedgerow types) at providing stemborer biocontrol services, (iii) to explain the factors affecting maize stemborer infestation from field (farmer's management practice) to the landscape level (percentage of host crops), and (iv) to test the impact of landscape composition on the performance of push-pull systems in terms of reducing stemborer infestation levels, predators' abundance, and maize productivity. In the following sections, I discuss the direct implications of this study for ecological design of pest-suppressive landscapes by connecting the findings of the different chapters. First, I capture the lessons learnt from this study to inform current and future agricultural pest management in Africa. Then, I discuss how current practices can be updated in the light of the findings of this research. Third, I discuss whether it is possible to understand and categorise the trajectories of farming systems in sub-Saharan Africa and how taking a landscape approach to agricultural production can make the current debate on the fate of small farms in Africa obsolete. Finally, I conclude and provide suggestions for future research.

2. Maize stemborer infestation levels cannot be explained by field level factors only

2.1 Maize proportion in the landscape is the main factor explaining stemborer infestation levels

In this thesis, I demonstrated that factors explaining maize stemborer incidence vary at field, farm, and landscape levels. Maize stemborer infestation increased with increasing proportion of maize from 100 to 1500 m radii from the focal fields (Chapter 4, Table 4), and that maize proportion within a landscape determined the performance of the push-pull system (Chapter 5). These findings were explained by stemborers' preference of maize as a host and by the resource concentration hypothesis, which suggests that herbivorous insects are more abundant in large patches of host plants because these patches are easier to locate and herbivores stay longer in those patches (Root, 1973). These are the major findings of this thesis, since factors affecting maize stemborer infestation have only been studied at field level (Wale *et al.*, 2007; Calatayud *et al.*, 2014; Haile, 2015). In the Hawassa area, maize monoculture declined over time and has been progressively replaced by perennial crops, such as enset (food crop) or khat (cash crop) (Chapter 2). In addition, population growth and urban area expansion reduced the availability of land and led to more fragmentation of croplands (Chapter 2 and 3). This fragmentation was more pronounced in the southern (intermediate complexity landscape) and eastern (most complex landscape) parts where, in addition, a higher complexity was observed, leading to increased perimeter-area, which was favourable for the biocontrol potential of maize stemborers (Chapter 3). In the intermediate complexity and complex landscapes, stemborer infestation levels were low, probably due to the top-down control mechanism by natural enemy communities (Chapter 5). The population of male stemborer moths was monitored during two cropping seasons from May 2014 and December 2015. The results show the high seasonal variation of the moth population between the two years but relatively small differences between the three landscapes (Fig. 1). This result confirms the suggested top-down control mechanism ongoing in the intermediate and high complexity landscapes where higher abundance of natural enemies support the maintenance of low infestation levels (Fig. 2). In addition, although the presence of non-crop habitats (e.g. grasslands) in the landscapes of intermediate and high complexity can be alternative oviposition sites for stemborer (Yewhalaw *et al.*, 2008), they are not used as refuges by *B.fusca* and have a low carrying capacity (Van den Berg, 2017).

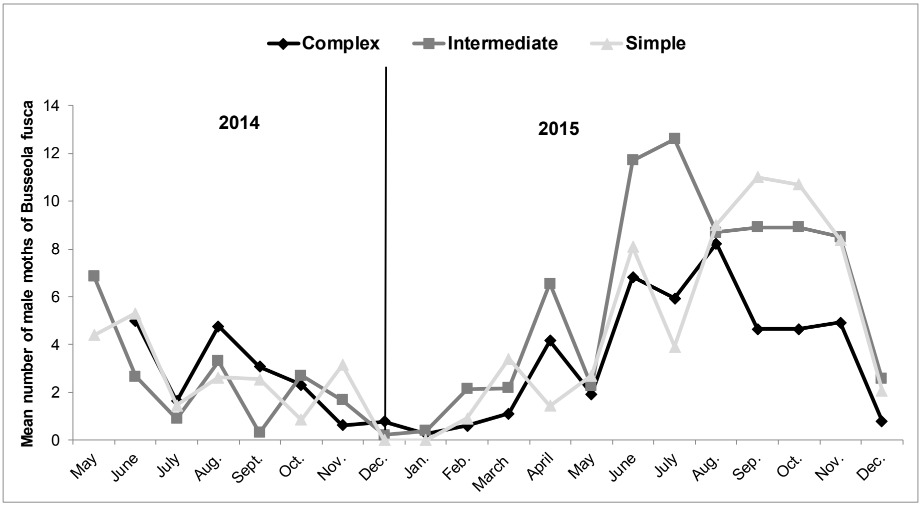


Figure 1: Mean number of male moths of *B.fusca* collected on farmers' fields using pheromone traps during two cropping seasons in the simple (n=13 sites), intermediate complexity (n=12 sites), and complex landscapes (n=12 sites).

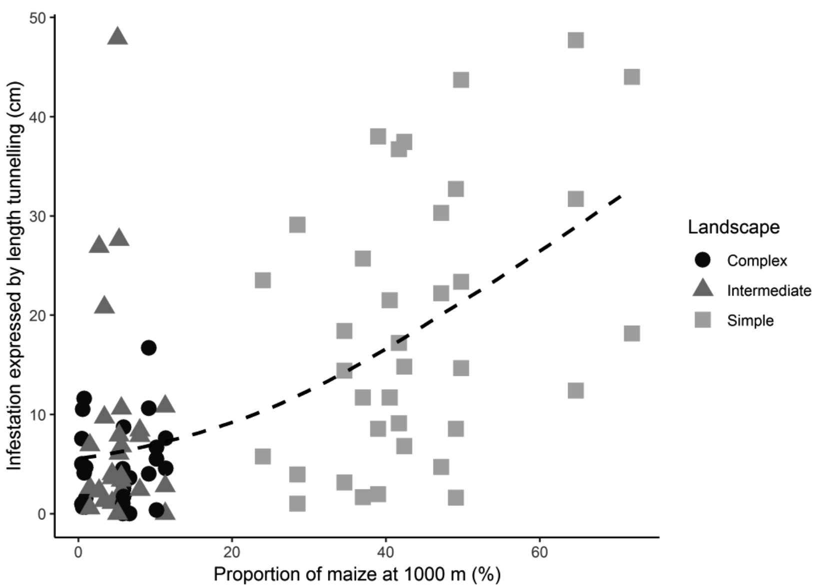


Figure 2: Maize stemborer infestation levels expressed in length tunnelling (cm) in a gradient of landscape complexity, reported here as the proportion of maize at 1000 m from focal fields (data of Chapter 4).

Moreover, the presence of a higher proportion of shrubs and woodlots within the larger landscape context can provide a higher density and diversity of natural enemies (Macfadyen and Muller, 2013). This is an additional argument in favour of the top-down control mechanism provided by the mixed cropping systems of the intermediate complexity and complex landscapes. Another potential mechanism is the hindering of host finding by stemborer moths in the intermediate and complex landscapes due to naturally occurring “trap and repellent” plants or the high diversity between fields and within-field (due to smaller field sizes). Diversification at field and farm levels is currently encouraged by FAO as the most affordable and sustainable solution to reduce the damaging effect of fall armyworms in Africa (FAO, 2018). Khat leaf extracts were found to inhibit feeding activity of stemborer larvae and to cause larval mortality (Tekle, 2002). The proportion of khat is larger in the intermediate and complex landscapes and might have a repellent effect on maize stemborers, but further investigation will be needed to test the presence of this effect.

Recent studies show that the push-pull system can reduce fall armyworm infestations (Midega *et al.*, 2018), yet the mechanisms behind this decrease in infestation were not described. The increased abundance of ants found in the push-pull system (Chapter 5) could be one underlying reason, in addition to the crop diversification effect of the push-pull system in hindering host finding. Still, these effects will depend on the landscape context where the push-pull system is implemented as landscape factors can override the plot level diversification strategy in a maize dominated or complex landscape (Chapter 4 and 5). In a simple landscape, the presence of companion crops increased predator abundance (Chapter 5, Table 2) without reducing the infestation level (Chapter 5, Table 1). These results confirm the landscape-dependency effect of the plot level diversification strategies and of the top-down control by generalist natural enemies (Karp et al., 2018).

2.2 Yet factors at field and farm levels play a role in high infestation years

At the field level, the main factor explaining stemborer incidence was maize planting density (Chapter 4, Table 2). However, during high infestation years, high plant diversity of hedgerows and late maize planting date also influenced stemborer infestations (Chapter 4, Fig. 3). At the farm level, I showed that enset fields and dense hedgerows supported relatively high predator densities, in particular ants and rove beetles (Chapter 3, Fig. 6). Although the focus of this study was on maize stemborers, these generalist predators can control a number of other pests (Philpott and Armbrecht, 2006; Offenberg and Firn, 2015), including the fall armyworm which recently invaded the African continent (Day *et al.*, 2017). In Chapter 4, I showed that the effect of the percentage of the host plant in the landscape was less pronounced at 500 m than at 100, 1000, and 1500 m from the focal fields. This suggests that the diversity of crop and non-crop plants at farm level can contribute to reduced stemborer infestation levels. These findings highlight the need to consider the inclusion of hedgerows and perennial crops for increasing stemborer natural enemy abundance in the maize-based systems. This will enhance the top-down control of stemborers by natural enemies and can extend to the control of other agricultural pests (Chapter 3). In Kenya, the presence of hedgerows at the border of maize fields was reported to lower the number of stemborers (Girma *et al.*, 2000). Hedgerows can also provide other important functions on farmland, including serving as windbreaks, reducing evapotranspiration, storing of organic carbon, promoting infiltration and soil moisture retention, preventing soil and water runoff, and increasing soil biota (Forman and Baudry, 1984).

2.3 Beyond stemborer infestation, soil fertility is the main yield reducing factor

In Chapter 4 and 5, I demonstrated that the proportion of maize in the landscape had an overriding effect on field level management factors and soil characteristics in explaining maize infestation levels. However, in both chapters the differences in infestation observed did not significantly lower maize productivity (Chapter 4, Table 5). This is a major counterintuitive result of this thesis which touches upon two key issues. First, there is a very high variability in the reported yield losses due to stemborers in Ethiopia or other African countries (De Groote, 2002; Chabi-Olaye *et al.*, 2005; Songa *et al.*, 2007). This variability is due to the seasonality of the severity of stemborer attacks, which are perceived by farmers as being more severe in drier years (Chapter 2, Fig. 2). In addition, current reference for potential yield losses due to stemborers in the Hawassa area is still based on research results from the 1980's (Gebre-Amlak *et al.*, 1989) when maize monocrop was dominant in the study area. Since then, the composition and structure of the landscape has changed tremendously, resulting in a different outcome of its potential pest-suppressive capacity. This finding, related to the larger potential landscape effect on pest infestation can directly inform current efforts in assessing yield losses due fall armyworm in sub-Saharan Africa. Historical records of pest outbreaks and their impact on yield are precious knowledge for informing current and future pest incidence, but, with the exception of major invasive pests (Locust), these records are rare in sub-Saharan Africa.

Second, the impact of stemborers infestation in reducing maize yield is dependent on the soil fertility status (Vanlauwe *et al*., 2008) and fertilisation (Chabi-Olaye *et al*., 2008). The simple landscape with a higher percentage of maize was also the one with the lowest soil nitrogen, phosphorus, and organic matter content, while it is also the landscape where higher rates of fertilisation were used to support the annual maize production. Farmers indicated that they needed to continuously fertilise maize fields to assure some production. However, the use of this input might not even reach the expected outcome due to low nitrogen capture and use efficiencies by maize in the area. During two cropping seasons (2014 and 2015), leaves and stem of maize were subsampled from the 33 sites visited (Chapter 4) and analysed for nitrogen content. The result revealed that the N intake variation is low compared to the variation in the amount of fertilisation applied (Fig. 3). Generally, the nitrogen use efficiency of maize production in Ethiopia is reported to be very low, and this is worsened by the bulk fertiliser application rates (without prior soil analysis) proposed to farmers (Abebe and Feyisa, 2017). This situation is leading to a double loss for the farmers who purchased the expensive fertilisers and for the environment. This problem is not unique to Ethiopia; it results from the push by many African governments towards input packages based intensification of agricultural productions (Tittonell *et al*., 2012; Cafer and Rikoon, 2017). There is a need for a more integrated soil fertility management approach which will not only contribute to increased and stable yields but also ensure future productivity.

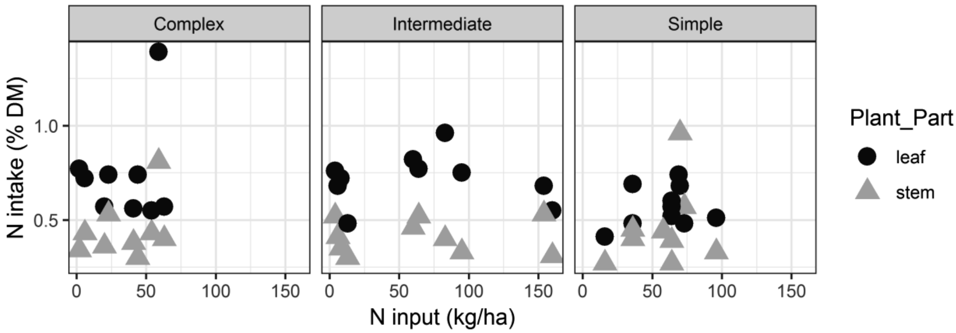


Figure 3: Nitrogen intake by maize (leaves and stem) in relation to nitrogen input (kg/ha) per landscape complexity

3. Farmers' "adoption" or researchers' "adaptation"?

3.1 Adapting the push-pull system to land-constrained farming systems

Currently, the push-pull system is presented as a promising strategy for the control of maize stemborers and parasitic weed Striga and for providing feed for livestock. However, the low adoption rate by farmers questions the suitability of this strategy for smallholder systems (Chapter 5). Instead of being presented as a "package" to farmers, the system may benefit from some adaptation strategies to farmers' needs and to the landscape context. One of the major constraints that impedes the adoption of push-pull by farmers is the allocation of cropland to non-food plants. I demonstrated that *Desmodium* can be replaced by common bean without altering the repelling effect and can even increase egg parasitism. In addition, previous research showed that the area of Napier grass can be reduced to two sides of the maize field and still function as a trap crop for stemborers. However, further adapting the push-pull system to land-constrained farming systems and to the landscape context calls for a change of perspective. Cropping systems in Africa are very often mixed and diversified, which might already support a number of ecological regulation processes (Lemessa and Legesse, 2018). Increasing diversity at farm level and promoting managed hedgerows composed of multi-functional plants (e.g. feed, medicinal or pesticidal plants) can better address the multifunctional nature of small scale subsistence agriculture while taking a long-term solution perspective (Grzywacz *et al.*, 2013; Pumariño *et al.*, 2015). This entails a shift in mindsets from promoting a technological "package" to co-creating knowledge between farmers and researchers, as it is proposed by agroecology

(Tittonell *et al.*, 2012). Therefore, researchers should not engage in field trials based only on knowledge gaps gathered from literature but address farming constraints identified together with farmers. However, the way research is currently dogmatised and conducted does not provide the flexibility to adapt to farmers' needs, thus delaying the impact of research outcome for farmers' livelihoods. During the second year of the on-farm push-pull system experiment (Chapter 5), I have been confronted by a few farmers who wanted to uproot the Napier grass before the end of the experiment. In fact, on farms with low soil fertility, the competition between the maize crop and the Napier grass was clearly visible. However, the constraints of the research agenda in terms of timing and the necessity of field data collection to fulfil the evaluation criteria of a research publication did not give me the flexibility to listen to farmers' needs. Current research funding mechanisms need to be revisited to support more participatory action-oriented research.

3.2 Adapting the planting date strategy to unpredictable weather events

Manipulation of planting dates is one of the best known stemborer management strategies by farmers. Based on a three year data set, I demonstrated that the planting date tended to affect stemborer infestation levels only in high infestation years (Chapter 5). With increasingly erratic rainfalls (Chapter 2, Fig. 1C) and periodic occurrence of unpredictable climate events (Chapter 2, Fig. 2) in the study area, as well as in other parts of the continent, the planting date strategy is not a long term solution. In addition, from a research point of view it is not cost-effective, since to be accurate it will need to be determined for different agro-ecological zones and revised regularly in order to be representative of the changing weather and landscape context. Current planting date recommendation (planting should be no later than end of April) in the Hawassa area has been suggested by Gebre-Amlak *et al. (1989)* on the basis of data from April 1985 to July 1986, just after the most well-known dry period in Ethiopia, which was also associated with high stemborer infestation in the Hawassa area (Chapter 1, Fig. 2). Although the synchronisation of planting time by farmers in the same landscape is a valuable risk sharing strategy, the use of planting date criteria *per se* is not reliable. Instead, improving soil moisture and structure by using cover crops can be a more sustainable stemborer control strategy at the field level. In fact, maize fields in the study area remain bare in between cropping seasons and thus contribute to the degradation and erosion of soils. Intensification of agricultural production in those areas should start by the management of these fields during the dry seasons. Drought tolerant cover crops may bring multiple benefits: increasing soil fertility, reducing soil erosion, increasing feed availability, and also supporting the habitat for beneficial insects (Snapp *et al*, 2005). This adaptation is even more pertinent in a changing climate context, where recurrent droughts and shortening of the long rainy season is observed in East Africa (Rowell *et al.*, 2015). In fact, primarily temperature, and also rainfall, relative humidity, and soil characteristics were found to affect the predicted future geographical distribution of *C. partellus* and *B. fusca* (Mwalusepo *et al.*, 2018). In particular, relative humidity is predicted to strongly influence *B. fusca* distribution. Research results based on modelling of the impact of future climate changes on two main stemborer species in East Africa forecast increased pest activity with significant impact on maize yield losses (Mwalusepo *et al.*, 2015).

4. Agricultural transformation in sub-Saharan Africa: the good, the bad, and the ugly

4.1 Southern Ethiopia: a representation of sub-Saharan Africa agricultural intensification path?

Agricultural landscapes around Hawassa went through a major transformation over the last 40 years due to the combined effects of national level drivers (e.g. agricultural policies, commodity prices, etc.), regional/local level factors (population density, urbanisation, and infrastructure development), farmers' livelihood assets, and unpredictable climate events. The main changes in production orientation were the shift from food to cash crop production, an increased share of off-farm income, and the decrease in available farmland and livestock number (Chapter 2). Farmers still maintain two to three TLU per household for providing milk for the family, for land preparation, and as financial capital (Chapter 2, Table 2). However, the current number of livestock is not enough to assure sufficient manure to maintain soil fertility, leading farmers to rely heavily on inorganic fertilisers in particular for annual crops and khat production (Mellisse *et al.*, 2018). Since the 1990's agricultural policies in Ethiopia have been promoting the use of improved seeds and fertiliser as a way of intensifying cereal production and achieving food security (Spielman *et al.*, 2012). This has led to an increased dependence of farmers on the supply of those inputs. However, seed and fertilisers often fail to be delivered timely or are subject to poor quality, exacerbating the financial burden that farmers already face for purchasing them (Cafer *et al.*, 2015). In addition, instead of an increased productivity, the low organic carbon and nutrient stocks of soils make the response to fertilisers limited and could even negatively impact crop productivity (Abdulkadir *et al.*, 2017). The same scenario is repeated in other parts of Africa (Tittonell and Giller, 2013) and questions the viability of current strategies of African governments that emphasise the use of improved seeds, fertilisers, and pesticides as a way of enhancing agricultural productivity in Africa (Sheahan and Barrett, 2017).

4.2 Farm sizes: too small for whom? Too small for what?

The changes in farming systems observed in Southern Ethiopia are not unique to this part on the country or the continent (Kindu *et al.*, 2013; Jayne *et al.*, 2014) nor to other parts of world (Wagner *et al.*, 2015). In particular, the increased share of off-farm activities and/or cash crop production is a response to decreasing farm sizes due to population pressure, infrastructure development, and favourable market prices (Chapter 2). Farmers in southern Ethiopia were seen to follow three main trajectories of livelihood strategies: diversification, consolidation, and specialisation (Chapter 2). Most land-constrained farmers specialised in khat production when infrastructure, biophysical context, and irrigation access enabled this orientation, not only in the study area but also in other regions of the country (Cafer, 2018).

Generally speaking, the performance and comparison between farms is done in terms of production (yield) and sometimes labour productivity, but other parameters like nitrogen use efficiency, biodiversity above and below ground, or biocontrol potential are not considered. In this research, I demonstrated that small farms with higher perimeter-area ratio and intercropping practices can have a comparative advantage from a biological control perspective (Chapter 3). Looking at the maize productivity in relation to nitrogen use efficiency (Fig. 4), there seems to be a trend of an inverse relationship between farm size and grain yield per unit of nitrogen input.

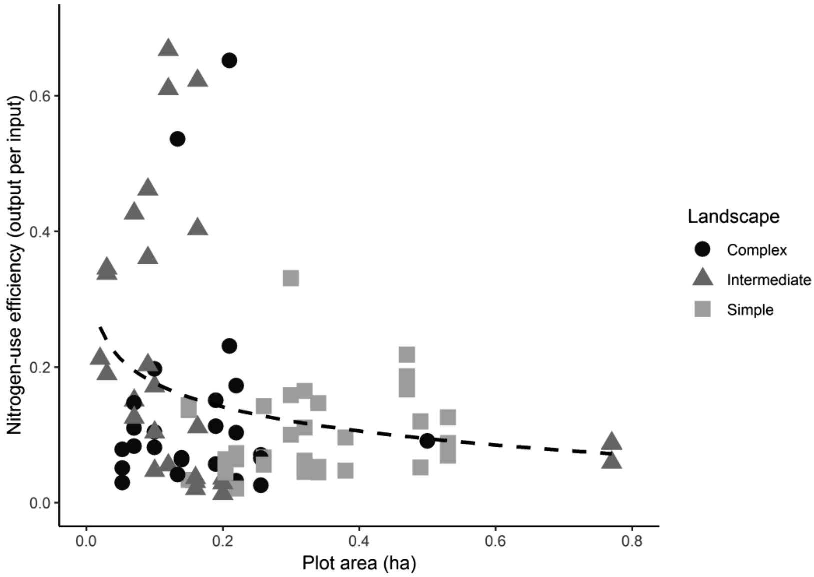


Figure 4: Maize grain yield (in kg ha-1 per kg of nitrogen input) per plot size during three cropping seasons : 2013, 2014, and 2015 (data from Chapter 4).

Although the concern about declining farm sizes and the consequences for food security is a relevant one, the way the performance of small farms is measured should go further than their productivity per unit area. The current debate on farm sizes and on whether a minimum area of land per farm should be guaranteed by law is largely informed by arguments that use the yield of staple crops as a main criterion. When farms are already as small as less than one hectare, increasing the yield of maize or other cereals, even to their potential level, will not be sufficient to address household food security. Measures of performance should also embed the contribution of smallholder farmland to other important aspects of the system that are evident at the farm level and beyond, such as dietary diversity, nutrient use efficiencies, abundance and diversity of natural enemies, and the socio-cultural value of the family farm land.

5. Summary and conclusions

The ultimate goal of this PhD research was to identify management practices at the field, farm, and landscape levels for a sustainable intensification of maize-based production systems that (i) reduce stemborer infestations, (ii) maintain or improve soil fertility, and (iii) improve fodder production for livestock.

The socio-ecological system studied and the relations (positive or negatives) between the components of the system are summarised on the figure below (Fig.5).

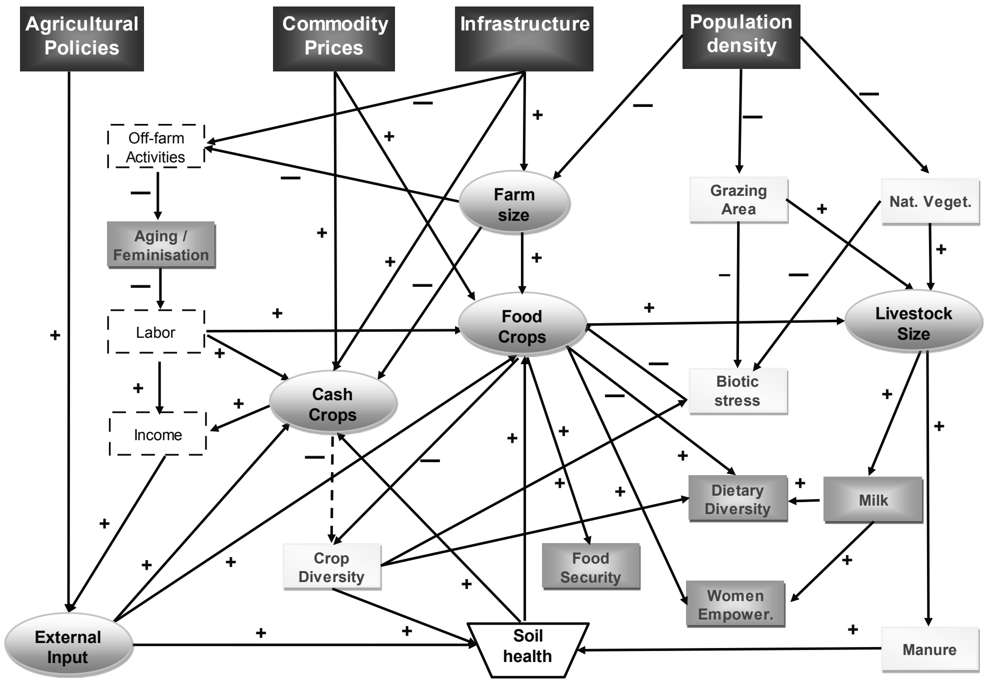


Figure 5: Overview of the system studied representing the system driving forces (agricultural policies, commodity prices, infrastructure, population density), the farm structural components (farm size, food crop area, cash crop area, livestock number, use of external input), natural variables (grazing area, natural vegetation, biotic stress, crop diversity), economic variables (off-farm activities, labor and income), and societal relevant factors (aging, feminisation, dietary diversity, food security, milk production, women empowerment).

The effect of the systems' external driving forces (agricultural policies, commodity prices, infrastructure, population density), the farm structural (farm and livestock size) and functional components (food and cash crops, milk production, dietary diversity) concur to have a direct or indirect effect on the biotic stress (maize stemborer infestation incidence). Although, not directly addressed in this study, aging and feminisation of agriculture is occurring in the study area. In fact, when possible the young generation is leaving the family farms for education or in search for non-agricultural jobs. Moreover, there is generally a clear distinction of gender roles in relation to off-farm activities or seasonal migrations for labour work (Saha *et al.*, 2018).

In a nutshell, in this thesis, I showed that land cover/land use changes in the Hawassa area were driven by the combined effects of national level drivers (e.g. agricultural policies, commodity prices, etc.), regional/local level factors (population density, urbanisation, and infrastructure development), farmers' livelihood assets, and unpredictable climate events. The resulting agricultural landscape shows a gradient of complexity with varying maize stemborer infestation levels and natural enemy abundance. The severity of stemborer infestation is primarily explained by the proportion of maize in the landscape, with infestation increasing with increasing maize proportion. The field level multipurpose cropping system known as "push-pull system" was effective at reducing maize infestation only in the intermediate complexity landscape. The push-pull system can be adapted to farmers' needs and land constrained context by replacing the commonly used Desmodium by common beans or by using only one of the companion crops. Taking maize stemborer pressure as an entry point, I showed that the infestation cannot be explained by field level factors only. Tackling maize infestation issues requires a landscape approach for sustainable pest management. Landscape composition, in particular, could either impact the pest abundance directly by affecting its dispersal, mortality, or reproduction or indirectly by affecting its natural enemies. Yet a landscape design which aims not only at the ecological control of maize stemborers but also addresses other farming constraints (i.e. soil fertility, fodder availability) should also aim at maintaining soil fertility and moisture to avoid crop failure (by using cover crops, increasing rainfall infiltration) and aim at diverse farming systems to increase nutrition and income diversity for smallholder farmers. Diversified farming systems which promote the conservation of natural enemies seem to be an ecologically sound solution, but more research is needed to understand and maximise the efficiency of existing mixed cropping systems. So far, investments in research, policy, and development actions in Africa have not yielded the widespread, beneficial impacts expected. This is due to several reasons including: the lack of coordination between the actors, the interventions based on addressing specific problems without taking a systems approach, the top-down "adoption" approach, and research/policy agendas which are not driven by end-users needs. A systems approach to agriculture production such as agroecology could be the best option to respond to the requirements of the multifunctional small-scale subsistence agriculture in Africa.

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Summary

Worldwide land cover and land use change rapidly due to biophysical and complex socio-economic and political factors. These changes are directly affecting both local and global biodiversity and impeding the ability of agricultural landscapes to provide essential ecosystem services. These changes are particularly evident in sub-Saharan Africa, which is experiencing a rapid transformation in rural and urban areas as a consequence of urbanisation and population growth while simultaneously being the continent in most urgent need for increasing agricultural production and most threatened by climate change and pest outbreaks. There is growing need for alternative agricultural practices that conserve biodiversity and natural regulatory processes in order to meet the rising demands for food and dietary diversity, to mitigate climate change, and to restore degraded landscapes. To better understand the potential of current agricultural landscapes to provide essential ecosystem services, insight is required into the historic trajectories of farming systems, their drivers, and how these drivers shaped current landscapes in terms of composition and structure, as well as the impact they have on ecosystem services. These insights can contribute to informing the design of more sustainable cereal-based agroecosystems for the smallholder multifunctional subsistence agriculture.

Ethiopia is now the second most populated country in Africa with more than 100 million people and a population growth rate of 3% per year. In Ethiopia, cereals are the major staple crops with maize ranking second after teff (*Eragrostis tef*) in acreage and first in total production and productivity. In the Hawassa area, in the Rift Valley of Ethiopia, maize (*Zea mays*) productivity fluctuates widely, and that is caused in part by infestation by maize stemborers. Adults stemborer are nocturnal moths which disperse by flight, while the larval stages have a wide range of host plants. Current recommended pest management practices for stemborers only focus on the plot level and do not take into account the entire farming system or the composition of the surrounding landscape context. Yet farming systems and the associated management practices and landscape contexts are crucial for understanding the population dynamics of stemborers, their natural enemies, and the resulting pest pressure. In Hawassa, there is an ongoing transformation of farming systems, and these changes are influenced by institutional and socio-economic drivers, such as land tenure regulation, market access, and population growth. It is unclear how these drivers influence the dynamics of farming systems and ultimately shape agricultural landscapes and their potential for the provision of food, feed, and energy. The general objective of my work was to identify stemborer management strategies at the field, farm, and landscape levels for a more sustainable intensification of maize-based production

systems that would (i) limit stemborer incidence, (ii) maintain or improve soil fertility, and (iii) improve fodder production for livestock. In particular, I studied how trajectories of farming systems have shaped current agricultural landscapes and assessed the implications for maize stemborer pest pressure and the potential for biocontrol. I quantified the relations between stemborer abundance, farming practices, and maize yields at the plot level and analysed the impact of landscape factors on stemborers and the abundance of their natural enemy. This brings new insight that can inform effective farming practices for increased maize production and stemborer suppression at multiple spatial scales.

In Chapter 2, I assessed how the ongoing expansion of arable land and urban areas is affecting the availability of common resources, such as forest and grazing land, and the availability of biomass for food, feed, and energy. By combining data from (i) farm household surveys, (ii) focus group discussions with farmers, (iii) statistical typology of trajectories of change in farming systems, (iv) remote sensing, and (v) secondary data analysis, I showed that the current farming systems in Hawassa result from the combined effects of past policies, population growth, access to market, urbanisation, and biophysical characteristics. This work has revealed, among other things, that farm sizes declined rapidly over the past four decades and that farmers responded to this constraint by adopting three main livelihood strategies: consolidation, diversification, and specialisation. These trajectories combined with urbanisation led to more fragmented and more complex landscapes.

In Chapter 3, I assessed how the changes in land use and landscape composition and structure in the Hawassa region influenced the capacity of the landscape to support communities of the natural enemy of maize stemborers: *Busseola fusca* (Fuller). Natural enemies were sampled in maize fields adjacent to simple hedgerows, complex hedgerows, enset (*Ensete ventricosum*) fields, and khat (*Catha edulis*) fields at 1, 10, and 30 m using pitfalls and yellow pan traps in 2014 and 2015. The landscape analysis indicated that landscapes in the study area have changed over time from maize-dominated to more diverse small-scale and fragmented agroecosystems with a higher proportion of perennial crops. In maize fields adjacent to enset and complex hedgerows, I found a higher abundance of predators (mostly ants and rove beetles) than in maize fields adjacent to khat and simple hedgerows, and the influence of border type decreases with distance from the border. The abundance of parasitoids and parasitic flies were not influenced by border type. I concluded that in terms of biocontrol service, the changes observed in landscape composition and structure may have influenced the capacity of the landscape to support populations of natural enemies of stemborers in different ways. On the one hand, smaller field sizes have resulted in more field borders that may support relatively high predator densities; on the other hand, the area of khat increased, and the area of enset decreased, which may have had a negative effect on predator densities.

In Chapter 4, I investigated how farmers' management practices at the field scale and landscape context affect maize stemborer infestation levels and maize productivity. Maize infestation levels, yield, and biomass production were assessed in 33 farmer fields managed according to local practices. When considering field level factors only, plant density was positively related to stemborer infestation level. During high infestation events, the length of tunnelling, a proxy of infestation and plant damage, was positively associated with the date of planting and negatively associated with the botanical diversity of hedges. However, the proportion of maize crops in the surrounding landscape was strongly positively associated with the length of tunnelling at 100, 500, 1000, and 1500 m radii. The findings reveal that the landscape context overrides farmers' management practices in explaining maize infestation levels but also indicate that maize is tolerant to low and medium infestation levels of stemborers.

The push-pull system, a stimulo-deterrent cropping strategy consisting of intercropping cereals with legumes and surrounding by fodder grasses, is considered a promising crop diversification strategy for smallholder farmers in Africa as it may contribute to maize stemborer *Busseola fusca* (Fuller) suppression while improving soil fertility and providing feed for livestock. In Chapter 5, I investigated the performance of different push-pull systems in terms of stemborer suppression, predator abundance, and maize productivity in different landscape settings. Within each landscape (simple, intermediate, and complex), experimental plots were established on four representative smallholder farms. At each farm we used a split-plot factorial design with main plots surrounded or not by Napier grass and subplots consisting of sole maize, maize-bean, or maize-*Desmodium*. I assessed stemborer infestation levels and maize grain and stover yields for two years; I also assessed natural enemy abundance and egg predation at two maize development stages in the second year. I demonstrated that the push-pull system was effective in reducing stemborer infestation only in the intermediate complexity landscape, where subplots with sole maize had higher stemborer infestation levels compared to maize-bean or maize-Desmodium. In the simple landscape, which was dominated by maize, all treatments had high stemborer infestation levels irrespective of within-field crop diversity; the presence of Napier grass was associated with higher predator abundance, while egg predation rates were the highest in the maize-bean intercrop. In the complex landscape, infestation levels were low in all treatments. I found no significant difference between the two push crops tested - Desmodium or bean -

suggesting that beans can be used as push crop in push-pull systems with the additional advantage of increasing egg predation rate and being a common maize-bean farmers' practice. However, there was no significant yield differences between the sub-systems nor between the three landscapes. Thus, the benefits of the push-pull system mostly come from the companion crops (bean, Desmodium, and Napier) rather than from stemborer suppression *per se*.

Agricultural landscapes in the Hawassa area went through important transformations over the last 40 years due to the combined effects of national, regional, and local level drivers (agricultural policies, commodity prices, and infrastructures), regional/local level factors (population density and urbanisation), farmers' livelihood assets, and unexpected climate events. The area of maize monocultures declined and was progressively replaced by perennial crops, such as enset (food crop) and khat (cash crop). In addition, population growth and the expansion of urbanised areas have reduced the availability of land and led to more fragmentation of the croplands, with a potential positive benefit for the biocontrol of maize stemborers. Although the push-pull system is a promising crop diversification strategy for smallholder farmers in Africa, its adoption can be limited in land-constrained farming systems, most likely due the farmers' reluctance to replace food crops, such as common bean, with fodder crops. In addition, the development of Napier grass can be hampered when nitrogen is a limiting factor. Therefore, there is a need for developing push-pull systems that use locally available plants. Napier grass could be planted as part of hedgerows to avoid hampering mechanical work of fields. In general, increasing plant diversity of hedgerows and their density can contribute to increasing natural enemy abundance and decreasing maize infestation levels. In addition, the intentional management of hedgerows could also consider adding plants and trees that are multifunctional (e.g. botanicals, feed for livestock, erosion control, carbon storage, beneficials for soil fauna). Above all, given the overriding influence of landscape context over field level management practices and the multifunctional nature of smallholder farming systems, the design of sustainable agroecosystems requires a context-specific and strongly integrative (social, economic and, environmental objectives) approach. Taking maize stemborer pressure as an entry point, I showed that the infestation cannot be explained by field level factors only. Tackling maize infestation issues requires a landscape approach for sustainable pest management. Landscape composition, in particular, could either impact the pest abundance directly by affecting its dispersal, mortality, or reproduction or indirectly by affecting its natural enemies. Yet a landscape design which aims not only at the ecological control of maize stemborers but also addresses other farming constraints (i.e. soil fertility, fodder availability) and aim at maintaining moisture to avoid crop failure (by using cover crops, increasing rainfall infiltration) and diverse farming systems to increase nutrition and income diversity for smallholder farmers. Diversified farming systems which promote the conservation of natural enemies seem to be an ecologically sound solution, but more research is needed to understand and maximise the efficiency of existing mixed cropping systems. A systems approach to agriculture production such as agroecology could be the best option to respond to the requirements of the multifunctional small-scale subsistence agriculture in Africa.

Samenvatting

Wereldwijd veranderen landbedekking en landgebruik snel als gevolg van biofysische en complexe sociaaleconomische en politieke factoren. Deze veranderingen hebben directe invloed op zowel lokale als mondiale biodiversiteit en belemmeren het vermogen van agrarische landschappen om essentiële ecosysteemdiensten te leveren. Deze veranderingen zijn duidelijk zichtbaar in Sub-Sahara Afrika, dat een snelle transformatie doormaakt in landelijke en stedelijke gebieden als een gevolg van verstedelijking en bevolkingsgroei. Tegelijkertijd is er in dit gebied een dringende behoefte aan het verhogen van de landbouwproductie, maar dit wordt bedreigd door klimaatverandering en insectenplagen. Er is een groeiende behoefte aan alternatieve landbouwmethoden die de biodiversiteit beschermen en ecologische processen ondersteunen om te voldoen aan de toenemende vraag naar voedsel en nutritionele diversiteit, inperking van de effecten van klimaatverandering en herstel van gedegradeerde landschappen. Om een beter inzicht te krijgen in de mogelijkheden van de agrarische landschappen om essentiële ecosysteemdiensten te leveren, is inzicht nodig in de historische trajecten van landbouwsystemen, hun drijfveren, hoe deze drijfveren hebben bijgedragen aan de vorming van de huidige landschappen, en de effecten die de veranderingen in het landschap hebben op ecosysteemdiensten. Deze inzichten kunnen bijdragen aan het informeren van het ontwerp van meer duurzame agro-ecosystemen voor kleinschalige multifunctionele zelfvoorzieningslandbouw.

Ethiopië heeft na Nigeria de grootste bevolking in Afrika met meer dan 100 miljoen inwoners en een bevolkingsgroei van 3% per jaar. In Ethiopië zijn graangewassen de belangrijkste voedselgewassen met maïs (*Zea mays*) als tweede na teff (*Eragrostis tef*) in areaal, en als eerste in totale productie en productiviteit. In het Hawassa-gebied, in de Riftvallei van Ethiopië, schommelt de productiviteit van maïs sterk, wat onder meer veroorzaakt wordt door aantasting door stengelboorders. Volwassen stengelboorders zijn nachtvlinders die zich vliegend verspreiden en de larvale stadia hebben een groot aantal waardplanten. De huidige aanbevelingen voor de plaagbestrijding van stengelboorders zijn alleen gericht op veldschaal en houden geen rekening met het landbouwsysteem of de landschapscontext. Landbouwsystemen met bijbehorende beheersmaatregelen en de context van het omliggende landschap zijn echter cruciaal voor het begrijpen van de populatiedynamiek van stengelboorders, hun natuurlijke vijanden en de resulterende plaagdruk. Rondom Hawassa veranderen landbouwsystemen voortdurend, en deze veranderingen worden beïnvloed door institutionele en sociaal-economische factoren, zoals de regulering van grondbezit, markttoegang en bevolkingsgroei. Het is onduidelijk

hoe deze factoren de dynamiek van landbouwsystemen beïnvloeden en het potentieel bepalen van agrarische landschappen om voedsel, voer en energie te produceren. De algemene doelstelling van mijn werk was het identificeren van strategieën op veld-, bedrijfs- en landschapsschaal die bijdragen aan een meer duurzame intensivering van op maïs gebaseerde productiesystemen die (i) stengelboorders onderdrukken, (ii) de bodemvruchtbaarheid handhaven of verbeteren, en (iii) de veevoederproductie voor vee verbeteren. In het bijzonder heb ik onderzocht hoe landbouwsystemen de huidige agrarische landschappen mede hebben vormgegeven, en hoe dit de plaagdruk door stengelboorders en de mogelijkheden voor biologische bestrijding beïnvloedt heeft. Ik kwantificeerde relaties tussen de abundantie van stengelboorders, landbouwmethoden en maïsopbrengsten op veldschaal en analyseerde de effecten van landschapsfactoren op stengelboorders en hun natuurlijke vijanden. Dit levert nieuwe inzichten op voor effectieve beheersmaatregelen voor verhoogde maïsproductie en de onderdrukking van stengelboorders op meerdere ruimtelijke schaalniveau's.

In hoofdstuk 2 heb ik onderzocht hoe de uitbreiding van bouwland en stedelijke gebieden van invloed is op de beschikbaarheid van gemeenschappelijke hulpbronnen, zoals bos en weidegrond, en de beschikbaarheid van biomassa voor voedsel, voer en energie. Door het combineren van gegevens van (i) enquêtes van agrarische huishoudens, (ii) focusgroep discussies met boeren, (iii) een statistische typologie van veranderingen in landbouwsystemen, (iv) remote sensing, en (v) een analyse van secundaire data liet ik zien dat de huidige landbouwsystemen in Hawassa het gevolg zijn van de gecombineerde effecten van beleidsmaatregelen uit het verleden, bevolkingsgroei, markttoegang, verstedelijking en biofysische kenmerken van het landschap. Uit dit onderzoek is onder meer gebleken dat de gemiddelde grootte van boerenbedrijven de afgelopen veertig jaar snel is gedaald en dat boeren hier op drie verschillende manieren hebben gereageerd: consolidatie, diversificatie en specialisatie. Deze factoren, in combinatie met verstedelijking, leidden tot meer gefragmenteerde en complexe landschappen.

In hoofdstuk 3 heb ik onderzocht hoe de veranderingen in landgebruik en landschapssamenstelling en landschapsstructuur rond Hawassa van invloed waren op de capaciteit van het landschap om natuurlijke vijanden van stengelboorders in mais (*Busseola fusca* Fuller) te ondersteunen. Natuurlijke vijanden werden bemonsterd in maïsvelden naast eenvoudige heggen, complexe hagen, enset velden (*Ensete ventricosum*) en qatvelden (*Catha edulis*) op 1, 10 en 30 m van de perceelsrand met potvallen en gele panvallen in 2014 en 2015. De analyse van het landschap wees uit dat landschappen in het studiegebied in de loop van de tijd zijn veranderd van maïs gedomineerd naar meer diverse, kleinschalige en gefragmenteerde agro-ecosystemen met een groter aandeel van meerjarige gewassen. In maïsvelden grenzend aan enset en complexe hagen vond ik een hogere abundantie van predatoren (meestal mieren en kevers) dan in maïsvelden grenzend aan qat en eenvoudige hagen. De invloed van het grenstype op de abundantie van predatoren nam snel af met de afstand tot de perceelsrand. De abundantie van parasitoïden en parasitaire vliegen werd niet beïnvloed door het grenstype. Ik concludeerde dat de veranderingen in de samenstelling en structuur van het landschap mogelijk van invloed zijn geweest op het vermogen van het landschap om de populaties van natuurlijke vijanden van stengelboorders te ondersteunen. Enerzijds hebben kleinere veldgroottes geresulteerd in langere grenzen tussen aanliggende percelen die relatief hoge predatordichtheden kunnen ondersteunen. Anderzijds nam het areaal van qat toe en dat van enset af, wat een negatief effect op de abundantie van predatoren kan hebben.

In hoofdstuk 4 heb ik onderzocht hoe de beheersmaatregelen van boeren op veld- en landschapsschaal de plaagdruk en productiviteit van maïs beïnvloeden. De abundantie van stengelboorders, opbrengst en biomassaproductie van maïs werden bepaald in 33 maïsvelden die volgens de lokale praktijk verbouwd werden. Wanneer alleen rekening werd gehouden met factoren op veldschaal was de plantdichtheid positief gerelateerd aan de abundantie van stengelboorders. Bij hoge abundanties was de lengte van de tunnels, een proxy voor plaagdruk en gewasschade, positief geassocieerd met het tijdstip van aanplant en negatief geassocieerd met de plantendiversiteit in hagen. Het aandeel maïsgewassen in het omringende landschap had een sterk positief effect op de lengte van tunnels in maïs op ruimtelijke schalen van 100, 500, 1000 en 1500 m radius rondom het maïsveld. De studie laat zien dat het effect van landschapscontext op de plaagdruk van stengelboorders belangrijker is dan de beheersmaatregelen op veldschaal, maar laat ook zien dat maïs tolerant is voor een lage en gemiddelde plaagdruk van stengelboorders.

Het push-pull-systeem, bestaande uit mengteelten van graangewassen met peulvruchten en omgeven door voedergrassen, wordt beschouwd als een veelbelovende strategie voor gewasdiversificatie voor kleine boeren in Afrika omdat het kan bijdragen aan de onderdrukking van stengelboorders, het verbeteren van de bodemvruchtbaarheid en het verschaffen van voer voor vee.

In Hoofdstuk 5 heb ik de onderdrukking van stengelboorders, abundantie van predatoren en maïsproductiviteit in verschillende push-pull-systemen en landschappen vergeleken. Binnen elk landschapstype (simpel, intermediair en complex) werden experimentele plots opgezet op vier representatieve boerenbedrijven. Op elk bedrijf gebruikten we een split-plot factoriele proefopzet met blokken, al dan niet omringd door Napiergras, en plots bestaande uit alleen maïs, maïs-boon of maïs-Desmodium. Ik heb de abundantie van stengelboorders en de maïsopbrengst en biomassa gedurende twee jaar bepaald. Ook heb ik in het tweede jaar de abundantie van natuurlijke vijanden en predatie van meelmot eieren bepaald in twee ontwikkelingsstadia van maïs. Ik toonde aan dat het push-pull-systeem alleen effectief was in het verminderen van stengelboorderaantasting in het landschap met een intermediaire complexiteit, waar plots met alleen maïs hogere aantastingsniveaus van stengelboorders hadden in vergelijking met maïs-boon of maïs-Desmodium. In het simpele landschap, dat werd gedomineerd door maïs, hadden alle behandelingen een hoge aantasting van maïsplanten, ongeacht de gewasdiversificatie binnen de plot. De aanwezigheid van Napiergras was geassocieerd met een hogere abundantie van predatoren, terwijl de predatie van de eieren het hoogste was in de mengteelt van maïs-boon. In het complexe landschap waren de aantastingniveaus van stengelboorders laag in alle behandelingen. Ik vond geen significant verschil tussen de twee geteste mengteeltgewassen - Desmodium of boon - wat suggereert dat bonen kunnen worden gebruikt als begeleidend gewas in push-pull-systemen met als bijkomend voordeel dat het de predatie van eieren verhoogt en al een gangbare praktijk is voor boeren. Er waren echter geen significante opbrengstverschillen van maïs tussen de subsystemen noch tussen de drie landschappen. De voordelen van het push-pull-systeem voor de opbrengst komen dus vooral van de begeleidende gewassen (boon, Desmodium en Napier) in plaats van de onderdrukking van stengelboorders in maïs.

Agrarische landschappen rondom Hawassa ondergingen de afgelopen 40 jaar belangrijke veranderingen als gevolg van de gecombineerde effecten van landbouwbeleid, grondstoffenprijzen, infrastructuur, bevolkingsdichtheid, verstedelijking en weersextremen. Het aandeel van maïs in monocultuur nam af en werd geleidelijk vervangen door meerjarige gewassen, zoals enset (voedselgewas) en qat (handelsgewas). Bovendien hebben de bevolkingsgroei en de uitbreiding van verstedelijkte gebieden de beschikbaarheid van land verminderd en geleid tot meer fragmentatie van het agrarisch gebied, met een mogelijk positief effect voor de biologische bestrijding van maïsstengelboorders. Hoewel het push-pull-systeem een veelbelovende strategie voor gewasdiversificatie is voor kleinschalige boeren in Afrika, kan de toepassing in kleinschalige landbouwsystemen beperkt zijn vanwege de terughoudendheid van de boeren om voedselgewassen, zoals bonen, te vervangen door voedergewassen. Bovendien kan de ontwikkeling van Napiergras worden belemmerd wanneer stikstofgehalten in de bodem laag zijn. Daarom is er behoefte aan het ontwikkelen van push-pull-systemen die afgestemd zijn op de lokale omstandigheden. Het Napiergras zou als onderdeel van hagen kunnen worden aangeplant zodat het de mechanische bewerking van het veld niet belemmert. Over het algemeen kan een toenemende plantendiversiteit en vegetatiedichtheid van heggen bijdragen aan het vergroten van de abundantie van natuurlijke vijanden en mogelijk bijdragen aan een lagere plaagdruk. Bovendien zou bij het beheer van heggen ook overwogen kunnen worden om multifunctionele planten en bomen te introduceren (bijvoorbeeld voor de productie van veevoer, erosiebestrijding, koolstofopslag, en stimulering van het bodemleven). Gezien de overheersende invloed van de landschapscontext ten opzichte van beheersmaatregelen op veldschaal en het multifunctionele karakter van landbouwsystemen voor kleinschalige boeren vereist het ontwerp van duurzame agro-ecosystemen een context-specifieke en sterk geïntegreerde benadering (sociale, economische en milieudoelstellingen). Met de plaagdruk van stengelboorders op maïs als startpunt, liet ik zien dat de aantasting niet alleen door factoren op veldschaal kan worden verklaard, maar ook door factoren op landschapsschaal. Het bestrijden van plagen in maïs vereist daarom een landschapsbenadering. Met name compositie van het landschap kan de plaagdruk direct beïnvloeden door de verspreiding, mortaliteit of reproductie van stengelboorders te beïnvloeden, of indirect door de abundantie van natuurlijke vijanden te beïnvloeden. Landschapsontwerpen dienen echter niet alleen gericht te zijn op de biologische bestrijding van plagen, maar ook rekening houden met andere factoren, zoals het op peil houden van vruchtbaarheid, het vasthouden van vocht in de bodem (bijvoorbeeld door het gebruik van cover-crops en het verhogen van infiltratie van regenwater), en het waarborgen inkomenszekerheid en nutritionele diversiteit voor kleinschalige boeren. Gevarieerde landbouwsystemen die populaties natuurlijke vijanden ondersteunen lijken bij te kunnen dragen aan een meer duurzame landbouw, maar er is meer onderzoek nodig om de efficiëntie van bestaande gemengde teeltsystemen te begrijpen en verder te verhogen. Een systeembenadering voor landbouwproductie, zoals agro-ecologie, biedt goed perspectief om multifunctionele kleinschalige landbouw in Afrika verder te ontwikkelen.

Résumé

La couverture et l'utilisation des terres dans le monde changent rapidement en raison de facteurs biophysiques, socio-économiques et politiques complexes. Ces changements affectent directement la biodiversité locale et mondiale et empêchent les paysages agricoles de fournir des services écosystémiques essentiels. Ces changements sont particulièrement évidents en Afrique Subsaharienne, qui subit une transformation rapide des zones rurales et urbaines en raison de l'urbanisation et de la croissance démographique, tout en étant le continent qui a le plus grand besoin d'augmenter sa production agricole et qui est le plus menacé par le changement climatique et les épidémies de ravageurs de culture. Il existe un besoin croissant de pratiques agricoles alternatives préservant la biodiversité et les processus de régulation naturels afin de répondre à la demande croissante de diversité alimentaire et nutritionnelle, d'atténuer les changements climatiques et de restaurer les paysages dégradés. Pour mieux comprendre le potentiel des paysages agricoles actuels à fournir des services écosystémiques essentiels, il est nécessaire de connaître les trajectoires historiques des systèmes agricoles, leurs moteurs et la manière dont ces facteurs ont façonné les paysages actuels en termes de composition et de structure, ainsi que leur impact sur les services écosystémiques. Ces informations peuvent contribuer à éclairer la conception d'agroécosystèmes plus durables pour l'agriculture de subsistance des et multifonctionnelle petits exploitants.

L'Éthiopie est maintenant le deuxième pays le plus peuplé d'Afrique avec plus de 100 millions d'habitants et un taux de croissance démographique de 3% par an. En Éthiopie, les céréales sont les principales cultures de base. Le maïs occupe la deuxième place après le teff (*Eragrostis tef*) en termes de superficie et le premier en termes de production et de productivité. Dans la région de Hawassa, dans la vallée du Rift, la productivité du maïs (Zea mays) fluctue considérablement, dû en partie à l'infestation par le foreur de la tige du maïs. Les foreurs adultes sont des papillons nocturnes qui se dispersent par vol, tandis que les stades larvaires ont un large éventail de plantes hôtes. Les pratiques actuelles de control des foreurs recommandées se concentrent uniquement à l'échelle de la parcelle et ne prennent pas en compte l'ensemble du système d'exploitation agricole ni la composition du contexte du paysage environnant. Cependant, les systèmes agricoles, les pratiques de gestion et les contextes paysagers associés sont essentiels pour comprendre la dynamique de la population des stemborers, leurs ennemis naturels et la pression des ravageurs qui en résulte. À Hawassa, les systèmes agricoles évoluent en permanence et ces changements sont influencés par des facteurs institutionnels et socio-économiques, tels que la réglementation du régime foncier, l'accès aux marchés et la

croissance démographique. On ignore comment ces facteurs influent la dynamique des systèmes agricoles et, en définitive, les paysages agricoles, ainsi que leur potentiel de production d'aliments, de fourrages et d'énergie. L'objectif général de mon travail était d'identifier les stratégies de gestion des planteurs à l''échelle, de la ferme et du paysage en vue d'une intensification plus durable des systèmes de production à base de maïs qui (i) limiteraient l'incidence des planteurs, (ii) maintiendraient ou amélioreraient la fertilité des sols, et (iii) améliorer la production de fourrage pour le bétail. En particulier, j'ai étudié la manière dont les trajectoires des systèmes de production ont façonné les paysages agricoles actuels, évalué les implications pour la pression des des foreurs de la tige du maïs et le potentiel de contrôle biologique. J'ai quantifié les relations entre l'abondance des foreurs, les pratiques agricoles et les rendements de maïs à l'échelle de la parcelle et analysé l'impact des facteurs paysagers sur les foreurs et l'abondance de leurs ennemis naturels. Cela avec l'objectif de produire de de nouvelles connaissances qui permettent d'améliorer les pratiques agricoles afin d' augmenter la production de maïs et supprimer les foreurs à plusieurs échelles spatiales.

Dans le chapitre 2, j'ai évalué l'impact de l'expansion actuelle des terres arables et des zones urbaines sur la disponibilité des ressources communes, telles que les forêts et les pâturages, et sur la disponibilité de la biomasse pour l'alimentation, les aliments pour animaux et l'énergie. En combinant des données provenant (i) d'enquêtes des ménages agricoles, (ii) de discussions de groupe avec les agriculteurs, (iii) de la typologie statistique des trajectoires de changement des systèmes agricoles, (iv) de la télédétection et (v) de l'analyse de données secondaires, j'ai montré que les systèmes agricoles actuels à Hawassa résultent des effets combinés des politiques antérieures, de la croissance démographique, de l'accès au marché, de l'urbanisation et des caractéristiques biophysiques. Ces travaux ont notamment révélé que la taille des exploitations a rapidement diminué et que les agriculteurs ont réagi à cette contrainte en adoptant trois stratégies de subsistance principales: la consolidation, la diversification et la spécialisation. Ces trajectoires combinées à l'urbanisation ont conduit à des paysages plus fragmentés et plus complexes.

Dans le 3ème chapitre, j'ai évalué l'impact des changements dans l'utilisation des sols, la composition et la structure du paysage dans la région de Hawassa, sur la capacité du paysage à soutenir les communautés d'ennemi naturels du foreur de maïs: *Busseola fusca* (Fuller). Les ennemis naturels ont été échantillonnés dans des champs de maïs adjacents à des haies vives de structure simple, des haies vives de structure complexes, des champs d'enset (*Ensete ventricosum*) et de khat (*Catha edulis*) à 1, 10 et 30 m de distance en utilisant des pièges au niveau du sol et à un mètre du sol (siphons jaunes) en 2014 et

2015. L'analyse paysagère a montré que les paysages de la zone d'étude ont évolué au fil du temps, passant de paysages dominés par des champs de maïs à des agroécosystèmes fragmentés, avec une plus grande proportion de cultures pérennes. Dans les champs de maïs adjacents aux parcelles d'enset et des haies à structure complexes, j'ai constaté une plus grande abondance de prédateurs (principalement des fourmis et des coléoptères) que dans les champs de maïs adjacents au khat et aux haies vives de structure simple ; et cette abondance diminuait à mesure que l'on s'éloignait de la zone frontalière. L'abondance des parasitoïdes et des guêpes parasites n'a pas été influencée par le type de culture ou de haies vives adjacentes. J'ai conclu qu'en ce qui concerne le service de control biologique, les changements observés dans la composition et la structure du paysage peuvent avoir influencé sa capacité à supporter les populations d'ennemis naturels des forestiers de différentes manières. D'une part, la taille réduite des champs a eu pour conséquence un plus grand nombre de haies vives pouvant supporter des densités de prédateurs relativement élevées ; par contre, la superficie du khat a augmenté et celle de l'enset a diminué, pouvant avoir un effet négatif sur la densité des prédateurs.

Au chapitre 4, j'ai étudié comment les pratiques agricoles à l'échelle de la parcelle, et la nature du contexte paysager affectent les niveaux d'infestation par les foreurs de maïs ; et quelle est l'impact sur la productivité du maïs. Les niveaux d'infestation de maïs, le rendement et la production de biomasse ont été évalués dans 33 champs de maïs des producteurs. Lorsqu'on ne tenait compte que des facteurs à l'échelle de la parcelle, il existait une corrélation positive entre la densité des plantes de maïs et le niveau d'infestation par les foreurs. Dans le cas de fortes infestations, la longueur du tunnels formés par les foreurs dans la tige de maïs, un moyen d'estimation du niveau d'infestation et de dommages causés aux plantes, était positivement associée à la date de plantation et négativement à la diversité botanique des haies. Cependant, la proportion de maïs dans le paysage environnant était fortement liée au niveau d'infestation à des échelles allant de 100, 500, 1 000 et 1 500 m de rayons. Ces résultats révèlent que les effets contexte du paysage priment sur les pratiques de gestion des agriculteurs pour expliquer les niveaux d'infestation de maïs ; et indique également que le maïs est tolérant aux niveaux d'infestation faibles et moyens des stemborers.

Le système push-pull, appelé aussi système de répulsion-attraction est une stratégie de culture biologique consistant à intercaler des céréales avec des légumineuses et entourée de graminées fourragères. C'est une stratégie de diversification des cultures prometteuse pour les petits exploitants agricoles en Afrique, car il peut contribuer à contrôler le niveau d'infestation du maïs par *Busseola fusca* (Fuller) tout en améliorant la fertilité des sols et en fournissant de l'aliment pour le bétail. Au chapitre 5, j'ai étudié les performances de différents systèmes de push-pull en termes de suppression des foreurs, d'abondance des prédateurs et de productivité du maïs dans un gradient de complexité du paysages. Dans chaque paysage (simple, intermédiaire et complexe), des parcelles expérimentales ont été établies sur quatre exploitations agricoles. Dans chaque ferme, nous avons eu recours à une conception factorielle en deux blocs et trois parcelles par bloc. Les blocs étaient entourés ou non d'herbe de Napier et les parcelles secondaires contenaient trois traitement: monoculture de maïs, une culture intercalaire maïs-haricot et une culture intercalaire maïs-Desmodium. J'ai évalué les niveaux d'infestation par les foreurs et les rendements en grain et en fourrage de maïs pendant deux ans; J'ai aussi évalué l'abondance d'ennemi naturel et prédation des œufs à deux stades de développement du maïs au cours de la deuxième année. J'ai démontré que le système push-pull était efficace pour réduire l'infestation par les foreurs uniquement dans le paysage de complexité intermédiaire ; en effet les parcelles de monoculture de maïs présentaient des niveaux d'infestation plus élevés que ceux des cultures intercalaire maïs-haricot ou maïs-Desmodium. Dans le paysage simple, dominé par le maïs, tous les traitements présentaient des niveaux d'infestation élevés, indépendamment des traitements; la présence de Napier était associée à une plus grande abondance de prédateurs, tandis que les taux de prédation des œufs étaient les plus élevés dans la culture intercalaire maïs-haricot. Dans le paysage complexe, les niveaux d'infestation étaient faibles dans tous les traitements. Je n'ai trouvé aucune différence significative entre les deux cultures intercalaires testées - Desmodium ou haricot - ce qui suggère que les haricots peuvent être utilisés comme «push » dans les systèmes push-pull avec l'avantage supplémentaire d'augmenter le taux de prédation des œufs et d'être une pratique courante des producteurs. Cependant, il n'y avait pas de différences de rendement significatives entre les sous-systèmes ni entre les trois paysages. Ainsi, les avantages du système push-pull proviennent principalement des cultures associées (haricot, Desmodium et Napier) plutôt que de la suppression des foreurs en soi.

Les paysages agricoles de la région de Hawassa ont subi d'importantes transformations au cours des 40 dernières années en raison des effets combinés de facteurs nationaux, régionaux et locaux (politiques agricoles, prix des produits de base et infrastructures) et de facteurs régionaux et locaux (densité de population et urbanisation), les moyens de subsistance des agriculteurs et les événements climatiques imprévus. La superficie des monocultures de maïs a diminué et a été progressivement remplacée par des cultures pérennes, telles que l'enset (culture vivrière) et le khat (culture marchande). En outre, la croissance démographique et l'expansion des zones urbanisées ont réduit la disponibilité de terres et conduit à une plus grande fragmentation des terres cultivées, avec un bénéfice potentiellement positif pour le contrôle biologique des foreurs de maïs. Bien que le système push-pull soit une stratégie de diversification des cultures prometteuse pour les petits exploitants agricoles en Afrique, son adoption peut être limitée par le manque de terre agricole, probablement en raison de la réticence des agriculteurs à remplacer les cultures vivrières, telles que le haricot , par des cultures fourragères. De plus, le développement de Napier peut être entravé lorsque l'azote est un facteur limitant. Par conséquent, il est nécessaire de développer des systèmes push-pull qui utilisent des plantes disponibles localement. Le Napier pourrait être planté dans les haies vives pour ne pas gêner le travail mécanique des champs. En général, la diversité végétale croissante des haies vives et leur densité peuvent contribuer à accroître l'abondance des ennemis naturels et à réduire les niveaux d'infestation par le maïs.

En outre, la gestion intentionnelle des haies vives pourrait également envisager l'ajout de plantes et d'arbres multifonctionnels (plantes médicinales, aliments pour le bétail, contrôle de l'érosion des sols, stockage de carbone, bienfaits pour la faune du sol, etc.). Avant tout, étant donné l'influence prépondérante du contexte paysager et la nature multifonctionnelle des systèmes agricoles de petites exploitations, la conception d'agroécosystèmes durables nécessite une approche spécifique au contexte et fortement intégrée (objectifs sociaux, économiques et environnementaux). En prenant la pression des foreurs de maïs comme point d'entrée de cette étude, j'ai montré que l'infestation ne pouvait pas être expliquée uniquement par des facteurs à l'échelle de la parcelle. S'attaquer aux problèmes d'infestation du maïs nécessite une approche paysagère pour une gestion durable des nuisibles. La composition du paysage, en particulier, pourrait avoir un impact direct sur l'abondance de ravageurs de cultures et influencer sa dispersion, sa mortalité ou sa reproduction ; ou indirectement en affectant ses ennemis naturels. Cependant, un aménagement paysager qui vise non seulement le contrôle écologique des planteurs de maïs, mais également d'autres contraintes agricoles (fertilité du sol, disponibilité du fourrage) doit également viser à maintenir la fertilité et l'humidité du sol et viser des systèmes agricoles diversifiés pour accroître la diversité de la nutrition et des revenus des petits exploitants. Les systèmes agricoles diversifiés qui favorisent la conservation des ennemis naturels semblent être une solution écologiquement rationnelle, mais des recherches supplémentaires sont nécessaires pour comprendre et optimiser l'efficacité des systèmes de cultures mixtes existants. Une approche systémique de la production agricole telle que l'agroécologie pourrait être la meilleure option pour répondre aux exigences de la petite agriculture de subsistance multifonctionnelle en Afrique.

Resumen

En todo el mundo, la cubierta terrestre y el uso de la tierra están cambiando rápidamente debido a factores biofísicos y complejos causas socioeconómicos y políticos. Estos cambios afectan directamente la biodiversidad local y global y obstaculizan la capacidad de los paisajes agrícolas para proporcionar servicios ecosistémicos esenciales. Estos cambios son particularmente evidentes en África Subsahariana, que está experimentando una transformación rápida en zonas rurales y urbanas como consecuencia de la urbanización y el crecimiento de la población y, al mismo tiempo, es el continente con mayor necesidad de aumentar su producción agrícola y el más amenazado por el cambio climático y los brotes de plagas. Hay una creciente necesidad de prácticas agrícolas alternativas que conserven la biodiversidad y los procesos reguladores naturales para satisfacer una creciente demanda de diversidad alimentaria y dietética, para mitigar el cambio climático, y para restaurar los ecosistemas degradados. Para comprender mejor el potencial de servicios ecosistémicos esenciales en paisajes agrícolas actuales, se requiere información sobre las trayectorias históricas de los sistemas agrícolas, sus causas y cómo estas causas dieron forma a los paisajes actuales en cuanto a la composición y la estructura, así como el impacto que tienen en los servicios ecosistémicos. Estas ideas pueden contribuir al diseño informado de agroecosistemas basados en la producción de cereales más sostenibles para la agricultura de subsistencia multifuncional de los pequeños productores.

Etiopía es ahora el segundo país más poblado de África con más de 100 millones de personas y una tasa de crecimiento poblacional del 3% por año. En Etiopía, los cereales son los principales cultivos básicos, con el maíz en segundo lugar después del teff (*Eragrostis tef*) en superficie y primero en producción y productividad total. En el área de Hawassa, en el valle del Rift de Etiopía, la productividad del maíz (*Zea mays*) fluctúa ampliamente, y esto se debe en parte a la infestación por barrenadores del tallo del maíz. Los adultos barrenadores son polillas nocturnas que se dispersan en vuelo, mientras que las etapas larvales tienen una amplia gama de plantas hospedadoras. Las prácticas actuales de manejo de plagas recomendadas para los barrenadores del tallo del maíz solo se centran en el nivel de la parcela y no tienen en cuenta todo el sistema de cultivo o la composición del contexto del paisaje circundante. Sin embargo, los sistemas agrícolas y las prácticas de manejo y los contextos de paisaje asociados son cruciales para comprender la dinámica de la población de los barrenadores, sus enemigos naturales y la presión de plagas resultante. En Hawassa, hay una transformación continua de los sistemas agrícolas, y estos cambios están influenciados por factores institucionales y socioeconómicos, como la regulación de

la tenencia de la tierra, el acceso a los mercados y el crecimiento de la población. No está claro cómo estos factores influyen en la dinámica de los sistemas agrícolas y, en última instancia, configuran los paisajes agrícolas y su potencial para la provisión de alimentos, piensos y energía. El objetivo general de mi trabajo fue identificar estrategias de manejo de los barrenadores del tallo del maíz en los campos, la granja y el paisaje para una intensificación más sostenible de los sistemas de producción basados en el maíz que (i) limitarían la incidencia del barrenador, (ii) mantendrían o mejorarían la fertilidad del suelo, y (iii) mejorarían la producción de forraje para el ganado. En particular, estudié cómo las trayectorias de los sistemas agrícolas han dado forma a los paisajes agrícolas actuales y evalué las implicaciones en la presión de las plagas del barrenador del tallo del maíz y el potencial de control biológico. Cuantifiqué las relaciones entre la abundancia de barrenadores, las prácticas agrícolas y los rendimientos de maíz a nivel de parcela y analicé el impacto de los factores del paisaje en los barrenadores y la abundancia de su enemigo natural. Esto aporta una nueva perspectiva que puede informar las prácticas agrícolas efectivas para aumentar la producción de maíz y la supresión del barrenador en múltiples escalas espaciales.

En el Capítulo 2, evalué cómo la expansión en curso de las tierras cultivables y las áreas urbanas está afectando la disponibilidad de recursos comunes, como los bosques y las tierras de pastoreo, y la disponibilidad de biomasa para alimentos, piensos y energía. Al combinar datos de (i) encuestas de hogares agrícolas, (ii) discusiones de grupos focales con agricultores, (iii) tipología estadística de las trayectorias de cambio en los sistemas agrícolas, (iv) sensores remotos y (v) análisis de datos secundarios, demostré que los sistemas agrícolas actuales en Hawassa son el resultado de los efectos combinados de políticas pasadas, el crecimiento de la población, el acceso al mercado, la urbanización y las características biofísicas. Este trabajo ha revelado, entre otras cosas, que el tamaño de las fincas disminuyó rápidamente en las últimas cuatro décadas y que los agricultores respondieron a esta restricción mediante la adopción de tres estrategias principales de subsistencia: consolidación, diversificación y especialización. Estas trayectorias combinadas con la urbanización llevaron a paisajes más fragmentados y complejos.

En el Capítulo 3, evalué cómo los cambios en el uso de la tierra y la composición y estructura del paisaje en la región de Hawassa influyeron en la capacidad del paisaje para apoyar a las comunidades del enemigo natural de los barrenadores de maíz. *Busseola fusca* (Fuller). Se tomaron muestras de enemigos naturales en campos de maíz adyacentes a setos simples, setos complejos, campos de ensetes (*Ensete ventricosum*) y campos de khat (*Catha edulis*) a 1, 10 y 30 m con escollos y trampas amarillas en 2014 y 2015. El análisis indicó que los paisajes en el área de estudio han cambiado con el tiempo de a) dominados por el maíz a b) agroecosistemas fragmentados a pequeña escala más diversos, con una mayor proporción de cultivos perennes. En campos de maíz adyacentes a ensets y en setos complejos encontré una mayor abundancia de depredadores (principalmente hormigas y escarabajos estafilínidos) que en los campos de maíz adyacentes a khat y setos simples, y la influencia del tipo de borde disminuye con la distancia desde el borde. La abundancia de parasitoides y moscas parasitarias no fue influenciada por el tipo de borde. Concluí que, en términos del servicio de biocontrol, los cambios observados en la composición y estructura del paisaje pueden haber influido en la capacidad del paisaje para apoyar a las poblaciones de enemigos naturales de los barrenadores de diferentes maneras. Por un lado, los tamaños de campo más pequeños han resultado en más bordes de campo que pueden soportar densidades de depredadores relativamente altas; por otro lado, el área de khat aumentó, y el área de enset disminuyó, lo que pudo haber tenido un efecto negativo en las densidades de depredadores.

En el Capítulo 4, investigué cómo las prácticas de manejo de los agricultores a escala de campo y en el contexto del paisaje afectan los niveles de infestación de los sembradores de maíz y la productividad del maíz. Los niveles de infestación de maíz, el rendimiento y la producción de biomasa se evaluaron en 33 campos de agricultores manejados de acuerdo con las prácticas locales. Cuando se consideraron sólo los factores de nivel de campo, la densidad de la planta se relacionó positivamente con el nivel de infestación del barrenador. Durante los eventos de infestación alta, la duración de la tunelización, un indicador de la infestación y el daño a las plantas, se asoció positivamente con la fecha de plantación y se asoció negativamente con la diversidad botánica de los setos. Sin embargo, la proporción de cultivos de maíz en el paisaje circundante estuvo fuertemente asociada positivamente con la longitud de los túneles a 100, 500, 1000 y 1500 m de radio. Los hallazgos revelan que el contexto del paisaje anula las prácticas de manejo de los agricultores como explicación a los niveles de infestación de maíz. También indican que el maíz es tolerante a los niveles de infestación bajos y medios de los barrenadores.

El sistema *push-pull*, una estrategia de cultivo de estímulo-disuasión consistente en cultivos intercalados de cereales con leguminosas y rodeados de pastos forrajeros, se considera una estrategia prometedora para la diversificación de cultivos para los pequeños agricultores de África, ya que puede contribuir a la supresión del barrenador del maíz *Busseola fusca* (Fuller), mejorando la fertilidad del suelo y proporcionando alimento para el ganado. En el Capítulo 5, investigué el rendimiento de diferentes sistemas *push-pull* en términos de supresión de barrenadores, abundancia de depredadores y productividad de maíz en diferentes entornos paisajísticos. Dentro de cada paisaje (simple, intermedio y complejo), se establecieron parcelas experimentales en cuatro granjas representativas de pequeños agricultores. En cada granja utilizamos un diseño factorial de parcelas divididas con parcelas principales rodeadas o no por pasto de Napier y parcelas consistentes de maíz único, maíz-frijol o maíz-Desmodium. Evalué los niveles de infestación del barrenador y los rendimientos de grano y rastrojo de maíz durante dos años. También evalué la abundancia del enemigo natural y la depredación de huevos en dos etapas de desarrollo del maíz en el segundo año. Demostré que el sistema *push-pull* fue efectivo para reducir la infestación del barrenador solo en el paisaje de complejidad intermedia, donde las parcelas secundarias con maíz único tenían niveles más altos de infestación del barrenador en comparación con maíz-frijol o maíz-Desmodium. En el paisaje simple, que estaba dominado por el maíz, todos los tratamientos tenían altos niveles de infestación de barrenadores, independientemente de la diversidad de cultivos dentro del campo; la presencia de pasto Napier se asoció con una mayor abundancia de depredadores, mientras que las tasas de depredación de huevos fueron las más altas en el cultivo de maíz y frijol. En el paisaje complejo, los niveles de infestación fueron bajos en todos los tratamientos. No encontré una diferencia significativa entre los dos cultivos de empuje probados (Desmodium o frijol), lo que sugiere que los frijoles se pueden usar como cultivos de empuje en los sistemas de *push-pull* con la ventaja adicional de aumentar la tasa de depredación de huevos y ser una práctica común de los agricultores de maíz y frijol. Sin embargo, no hubo diferencias significativas de rendimiento entre los subsistemas ni entre los tres paisajes. Por lo tanto, los beneficios del sistema *push-pull* provienen principalmente de los cultivos acompañantes (frijol, Desmodium y Napier) más que de la supresión del barrenador en sí.

Los paisajes agrícolas en el área de Hawassa sufrieron importantes transformaciones en los últimos 40 años debido a los efectos combinados de los impulsores a nivel nacional, regional y local (políticas agrícolas, precios de productos básicos e infraestructura), factores a nivel regional/local (densidad de población y urbanización), activos de subsistencia de los agricultores y eventos climáticos inesperados. El área de monocultivos de maíz disminuyó y fue reemplazada progresivamente por cultivos perennes, tales como ensets (cultivos alimentarios) y khat (cultivos comerciales). Además, el crecimiento de la población y la expansión de las áreas urbanizadas han reducido la disponibilidad de tierra y han llevado a una mayor fragmentación de las tierras de cultivo, con un posible beneficio positivo para el control biológico de los cultivadores de maíz. Si bien el sistema *push-pull* es una estrategia prometedora para la diversificación de cultivos para los pequeños agricultores en África, su adopción puede ser limitada en sistemas agrícolas con limitaciones de tierras, probablemente debido a la reticencia de los agricultores a reemplazar los cultivos alimentarios, como el frijol común, con cultivos forrajeros. Además, el desarrollo del pasto Napier puede verse obstaculizado cuando el nitrógeno es un factor limitante. Por lo tanto, existe la necesidad de desarrollar sistemas *push-pull* que usen plantas disponibles localmente. El pasto Napier podría plantarse como parte de setos para evitar obstaculizar el trabajo mecánico de los campos. En general, el aumento de la diversidad de plantas de setos y su densidad puede contribuir a aumentar la abundancia del enemigo natural y disminuir los niveles de infestación de maíz. Además, el manejo intencional de los setos también podría considerar agregar plantas y árboles que sean multifuncionales (por ejemplo, productos botánicos, alimentos para el ganado, control de la erosión, almacenamiento de carbono, beneficios para la fauna del suelo). Sobre todo, dada la influencia predominante del contexto paisajístico sobre las prácticas de gestión a nivel de campo y la naturaleza multifuncional de los sistemas de pequeños agricultores, el diseño de agroecosistemas sostenibles requiere un enfoque específico del contexto (objetivos sociales, económicos y ambientales). Tomando la presión del barrenador de maíz como punto de entrada, mostré que la infestación no se puede explicar sólo por factores de nivel de campo. Abordar los problemas de infestación de maíz requiere un enfoque de paisaje para el manejo sostenible de plagas. La composición del paisaje, en particular, podría impactar la abundancia de la plaga directamente al afectar su dispersión, mortalidad o reproducción, o indirectamente al afectar a sus enemigos naturales. Sin embargo, un diseño de paisaje que apunte no sólo al control ecológico de los barrenadores de maíz, sino que también aborde otras restricciones de la agricultura (es decir, la fertilidad del suelo, la disponibilidad de forraje) también debería apuntar a mantener la fertilidad y la humedad del suelo para evitar el fracaso de los cultivos (utilizando cultivos de cobertura, aumentando la infiltración pluvial) y apuntar a diversos sistemas agrícolas para aumentar la nutrición y la diversidad de ingresos para los pequeños agricultores. Los sistemas agrícolas diversificados que promueven la conservación de los enemigos naturales parecen ser una solución ecológica, pero se necesita más investigación para comprender y maximizar la eficiencia de los sistemas de cultivos mixtos existentes. Un enfoque de sistemas para la producción agrícola, como la agroecología, podría ser la mejor opción para responder a los requisitos de la agricultura de subsistencia multifuncional a pequeña escala en África.

ማጠቃለያ

በአለም አቀፍ ደረጃ የመሬት ሽፋንና መሬት አጠቃቀም በማህበራዊ ኢኮኖሚያዊ እና ፖለቲካዊ ምክንያቶች በፍጥነት እየተቀየረ ነው ፡፡ እነዚህ ለውጦች በቀጥታ ለሀገርና ለአለም አቀፍ ስነ-ሕይዎት ላይ ተጽኖ እያሳደሩ ያሉ ለውጦችና በግብርና የስነ መሬት አስተዳደር ላይ አሉታዊ ተጽኖ ያላቸውና ይህም አስፈላጊ የከባቢያዊ አገልግሎት ለማቅረብ ይረዳል፡፡ እነዚህ ለውጦች በተለየ ሁኔታ በከፊል ሰብ-ሰሀራ አፍሪካ ውስጥ የሚስተዋሉና በከተማና በገጠር ፈጣን ሽግግር ላይ ከፍተኛ ተጽኖ ያሳደረና የከተማ አመሰራረትና የህዝብ ብዛት ከፍተኛ የግብርና ምርት እድገትና በአየር ንብረት የተጎዳና የተለያዩ ፀረ ሰብል ነፍሳት ተጽኖ አድሮበታል፡፡ ይህም አማራጭ በግብርና ምርት ዘይቤ በመታገዝ የስነ መሬት ይዘትን መጠበቅና ተፈጥሮአዊ የመቆጣጠሪያ ሂደቶችን በመጠቀም እያደገ የመጣው የግብርና ፍላጎት አቅምና የአመጋገብ ስርዓት ልዩነቶች የአየር ንብረት ለውጥ መቋቋምና የታጠበውን የስነ መሬት ገጽታ እንዲያንሰራራ ማስቻል ይቻላል፡፡ ወቅታዊ የግብርና ስነ መሬት ገጽታ በተሻለ ሁኔታ አስፈላጊውን የከባቢአዊ ስርዓት አገልግሎት እንዲያገግም ለማስቻል የተለመደውን የግብርና ስርዓት መቀየር አስፈላጊ ሆኗል፡፡ እነዚህ ግፊት ፈጣሪዎች ወቅታዊ የስነ መሬት አቀማመጥ ከማደራጀትና አደረጃጀት አንፃር እንዴት መቀረጽ እንዳለባቸው እንዲሁም ለከባቢያዊ ስርዓት አገልግሎት ያላቸውን ተጽኖ በተሻለ ሁኔታ መገንዘቡ ተገቢ ነው፡፡ እነዚህ ጉዳዮች የተሻለ ቀጣይነት ያለው የሰብል ተኮር የግብርና ስርዐት እንዲኖር ማስቻልና ዲዛይኑ ትናንሽ የተቆራረጠ የግብርና መሬት ያላቸው ከእጅ ወደ አፍ አምራች የሆኑ ገበሬዎችን መረጃ ተደራሽነት ማረጋገጥ ያስፈልጋል፡፡

ኢትዮጵያ በአሁኑ ሰዓት ሁለተኛዋ ብዙ ህዝብ የሚኖርባት የአፍሪካ ቀንድ ሀገር ነች፡፡ የህዝቦች ብዛት ከአንድ መቶ ሚሊዮን በላይ ሲሆን፣ ይህም በየአመቱ ሶስት በመቶ ጭማሪ ያሳያል፡፡ በኢትዮጵያ ውስጥ በዋና የተለመዱ ሰብሎች በቆሎና ጤፍ ሲሆኑ፣ በሄክታር ሰፊውን ድርሻ ሽፍነው የያዙ ናቸው፡፡ ሃዋሳ አካባቢ ባለው ስምጥ ሸለቆ በቆሎ ይዘራል፣ ይህም ሰብል በፀረ ሰብል ነፍሳትና የበቆሎ አገዳ ሰርሳሪ ትሎች ጉዳት ይደርስበታል፡፡ ጎልማሳ የአገዳ ትሎች እሾህማ አፍ ያላቸውና በመብረር የሚሰራጩ፣ ሲራቡም (በእንቁላል ደረጃ) መጠጊያቸው ተክሎቹ ናቸው፡፡ በአሁኑ ሰዓት የፀረ እጽዋት ቁጥጥር ተግባራት በአገዳ ሰርሳሪ ትሎች ላይ የማሳን ደረጃና እንክብካቤና የመሬት አቀማመጡን ከግንዛቤ ያስገባ አይደለም፡፡ በአሁኑ ሰዓት የግብርና ስርዐትና ተያያዥነት ያላቸው ተግባራትና የስነ መሬት አቀማመጥ ይዘቶች ስለ አገዳ ሰርሳሪ ትሎች ግንዛቤ እና ብዛታቸው ስለ አገዳ ሰርሳሪና የፀረ ሰብል ግፊት አካላት ሆኖ ይስተዋላሉ፡፡ በሀዋሳ ውስጥ ቀጣይነት ያለው የግብርና ስርዓት ሽግግር አለ፡፡ ይህ ለውጥ በከፍተኛ ደረጃ በተቋማዊ፣ ማህበራዊና ኢኮኖሚያዊ አሳላጮች ማለትም የመሬት አስተዳደር መመሪያ ማርኬት፣ የገበያ አቀማምጥና የህዝብ ብዛት እድገት ዋነኞቹ ታሳቢዎች ናቸው፡፡ በተጨማሪም የመሬት አቀማመጥ፣ የምግብ አቅርቦት፣ አመጋገብ እና የጉልበት ፍሰት ታሳቢዎች ናቸው፡፡ የስራዬ አጠቃላይ አላማ የአገዳ ትሎችና የአገዳ ሰርሳሪ ትሎች ለመለየት የሚያስችል፣ የግብርና እና የመሬት አቀማምጥ ከፍተኛ ሰፊ የበቆሎ ምርት እድገት እንዲኖር ማስቻልና ይህ የምርት ስርዓት የበቆሎ አገዳ ሰርሳሪ ትሎች ገጠመኝ፣ የአፈር ለምነትን መጠበቅና ማሻሻል፣ የከብቶች ምርት ማሻሻል ነው፡፡ በተለያየ ሁኔታ የግብርና ስርዓት በወቅቱ ያለውን ግብርና የስነ መሬት አቀማምጥ እና ወቅታዊ የበቆሎ አገዳ ትል ቁጥጥርና ህይወት የሚያግዝ ይሆናል፡፡ በአገዳ ትሎች እና ሌሎች ተያያዥነት ያላቸው ግንኙነቶች የግብርና ተግባራትና የበቆሎ ምርቶች በማሳ ደረጃ እና የስነ መሬት አቀማመጥ ተጽኖ በበቆሎ አገዳ ሰርሳሪ ትሎች ላይ ከፍተኛ እና ቁጥራዊ መገለጫዎች ትስስር ለመፍጠር ያግዛል፡ ፡ ይህም ለውጥ ወቅታዊ የምግብ ሰንሰለት እና የጉልበት ፍሰት ለመቆጣጠር የሚያስችል ነው፡፡

በክፍል ሁለት ውስጥ የሰብል መሬት እና የከተማ መስፋፋት የጋራ የሆነ ሀብት ላይ ተጽኖ እየፈጠረ ይገኛል፡፡ ይህም ማለት ጫካና የግጦሽ መሬት የምግብ መጠን አመጋገብና የጉልበት ፍሰት ላይ ተስኖ ያሳድራል፡፡ ከአርሶአደር አባወራዎች ከአርሶአደር አባወራዎች ከአርሶ አደር ጋር ያለ ውይይት ሌላም ስታስቲካዊ የአረሶአደር አስተራረስ ስርዐት እና ለውጥ፣ ወደ ፊት ሊያጋጥም የሚችለውን አደጋ ማሰብ እና የሁለተኛ ወገን ቋት ምርመራ በመመልከት አሁን ያለው የአስተራረስ ዘይቤ ስመለከት በሀዋሳ ውስጥ ቀድሞ የነበሩ ፖሊሲዎች፣ የህዝብ ብዛት እድገት፣ የገበያ ቀረቤታ፣ የከተማ መስፋፋት እና ሌሎች አካላዊ ገጽታዎች ለማየት ችያለሁ፡፡ ይህ ስራ እንዳመላከተው ከሌሎች ተደማሪ ጉዳዮች ጋር የአርሶ አደር የእርሻ መሬት ላለፉት አራት ዓመታት በፍጥነት እየቀነሰ የመጣና አርሶአደሮችን ለዚህ የሚሰጡት መልስ እና የሚጠቀሙት ዘዴ፤ አዝርእት መቀያየር፣ የተለያዩ አዝዕርቶችን አብሮ መዝራት እና የተለዩ ሰብሎችን ማኖር የሚሉት ካሉት ዘይቤዎች የሚጠቀሙበት ነው፡፡ ከከተማ መስፋፋት ጋር ተያይዞ ያለው ችግር የበለጠ የተበጣጠሰ የመሬት ይዞታ እና ከፍተኛ ውስብስብ የመሬት አቀማመጥ እንዲኖር ያደርጋል፡፡ በአንቀጽ 3 ውስጥ በሀዋሳ ከተማ ውስጥ የመሬት አጠቃቀምና የመሬት ማልማት ተግበራትና አደረጃጀት ስንመለከት የሀዋሳ ክልል ከመሬት አቀማመጡ አንፃር የበቆሎ አገዳ ተፈጥሮአዊ ጠላት የሆነው የበቆሎ አገዳ ሰርሳሪ ትል ላይ ተጽኖ ያሳድራል፡፡ ቡሲዎላ ፉስካ (አሚይ) ካሉት የሰብል ዓይነቶች ተፈጥሮአዊ ጠላት

ስለመሆናቸው በበቆሎ አገዳ ሰርሳሪዎች ላይ ማስተዋል ተችሏል፡፡ ይህም ክስተት ውስብስብ የእንሰት (ቬንትሪኮዞም) እና የጫት (ካታይዱሊስ) የግብርና ቦታዎች ላይ በአንድ አስር እና ሰላሳ ሜትር ርቀት ላይ የተለያዩ ቅጠላቸው የመሸርሸርና ቢጫ የመሆን ችግር በ2014 እና 2015 ላይ ተስተውሏል፡፡ የመሬት አቀማመጥ ዳሰሳ እንደሚያመላክተው የመሬቱ አቀማመጥ ከረዥም ጊዜ በኋላ እየተቀየረ የመጣና ከቆሎ ተኮር ምርት እና የተበጣጠሰ የግብርና ስራ ትስስር እና ወቅታዊ ሰብሎች ብቻ የታገዘ እየሆነ መጥቷል፡፡ በበቆሎ ማምረቻ ቦታ ከእንሰት ጎን ለጎን እና ውስብስብ ብዙ ተመጋቢዎችን (አምበጣ ትላትል እና በራሪ ነብሳት) ከጫት ጎን ካለው የበለጠ ይስተዋላል፡፡ ከወገብ ወይም ጫፍ እየራቅን በሄድን ቁጥር ይህ ችግር እየሰፋ የሚሄድ ነው፡፡

የጥገኛ ነፍሳት እና ሌሎች ጸረ ሰብል ከጫፍ ባሉት ላይ ያን ያህል ተጽኖ አላሳደረም፡፡ በማጠቃለያ ልገነዘበው እንደቻልኩት የስነመሬት ቁጥጥር አገልግሎት ላይ የተስተዋለው ለውጥ የመሬት አቀማምጥ ይዘት እና አደረጃጀት የመሬቱን አቀማመጥና አቅም የህዝብ ብዛት ድጋፍ የጋራ የአገዳ ሰርሳሪ ናቸው፡፡ በአንድ በኩል በሌላው መንገድ ጥቃቅን የተበጣጠሱ የግብርና መሬቶች ብዙ ድንበሮችን እንዲኖሩ በማድረግ በአካባቢው ላይ እነዚህ ፀረ ሰብል እንዲኖሩ አስችሏል፡፡ በሌላ በኩል የጫት መኖር የእንሰቱ መጠን እንዲቀንስ በማድረግ በአካባቢው ላይ ባሉት ተመጋቢ ነፍሳቶች አሉታዊ ተጽኖ አሳድሯል፡፡ በአንቀጽ አራት ውስጥ የአርሶአደሮች የአሰራር ተግባራት እና ማሳዎቻቸው እንደየመሬቱ አቀማመጥ በቆሎ አገዳ ሰርሳሪ ትሎች እና የመራባት ደረጃቸው ላይ ተጽኖ አሳዳሪ ነው:: የበቆሎ የምርት ደረጃ እና የስነህይወት ተጽኖ በ33 የአርሶ አደሮች እርሻ ቦታ በአገሪቱ ልማዳዊ ተግባር ቁጥጥር ይደረግ ነበር፡፡ የእርሻ ቦታ ደረጃ ሁኔታ ስንመለከት የእጽዋት ብዛት ከአገዳ ትል ብዛት ጋር አውንታዊ ግንኙነት አለው፡፡ በከፍተኛ የአገዳ ትል ክስተት ጊዜ የሚወድሙ እጽዋቶች ከመጠን በላይ የመርዘም እና የመሰበር ችግሮች ከእጽዋቱ የመትከያ ቀን እና ከመሬቱ የአቀማመጥ ሁኔታ አሉታዊ ትስስር አላቸው፡፡ ይሁን እንጂ የበቆሎ ሰብል መጠን ከአካባቢው የስነ መሬት አቀማማጥ ጋር በከፍተኛ ደረጃ 100፣500፣ 1000 እና 1500 ሜትር ከፊል የወገብ መስመር (ራዲ)ድረስ ከፍተኛ አዎንታዊ ትስስር አላቸው፡፡ ግኝቱ እንደሚያመላክተው ከመሬቱ አቀማመጥ አንፃር ጠንካራ አዎንታዊ ትስስር አለው፡፡ ግኙቱ እንደሚያሳየው የበቆሎ የጥቃት ደረጃ እና የአርሶአደሮቹ ዘልማዳዊ አሰራርን ያካተተ እና በተጨማሪም ዝቅተኛ እና መካከለኛ የአገዳ ትል ተጠቃሾች ናቸው፡፡

የፑሽ ፑል ስርዓት /ግፊት/፣ የተለያዩ ሰብሎችን አንድ ላይ መዝራትና በዚህም አዝእርት ውስጥ የቅባት እህሎችና የሳርነት ባህሪ ያላቸውን እጽዋቶች አብሮ መዝራት ተስፋ ሰጪ የተለያዩ ሰብሎችን አብሮ መዝራት በአፍሪካ ውስጥ እንደ አንድ ዘዴ ተወስዶ በአርሶ አደር አባወራዎች የሚዘወተር ነው፡፡ ይህም ለአገዳ ትል ቡሲዮላ ፉስካ እንዲፈጠር በማድረግ የአፈር ለምነትና ለከብቶች የመኖ አቅርቦት እንዲፈጠር ማስቻል ነው፡፡ በአንቀጽ አምስት ውስጥ የተለያዩ የፑሽ ፑል ስርዓት በመጠቀም የአገዳ ትል እንዳይስፋፋ ማድረግ እና የተመጋቢዎች ሙብዛት እና የተለያዩ የበቆሎ ምርት በተለያየ የመሬት አቀማማጥ ላይ ይስተዋል የነበረ ሲሆን በእያንዳንዱ የመሬት አቀማመጥ ፣ መጠነኛ መካከለኛና ውስብስብ ፣ የእርሻ ቦታ ቤተ ሙከራ የተመሰረተው በአራት የአርሶአደር አባወራዎች እርሻ ቦታ ላይ ተስተውሏል፡፡ በእያንዳንዱ የግብርና ቦታ ማሳውን በተለያዩ ዲዛይኖች በመከፋፈል በአርሶአደሩ የግብርና ቦታ ማእከላዊ ፓርት ላይ እንዲኖር ማድረግ እና ናፒል ሳር እና ከፊል የበቆሎ ማሳ፣ በቆሎ እና አተር ወይም በቆሎ እና ሌሎች ተያያዥነት ያላቸው ስራዎች እንዲሰሩ፣ ያስችላል፡፡ ይህንን የአገዳ ሰርሳሪ ትሎች የጥቃት ደረጃና ዋና ሰብል ለሁለት ዓመታት ያሉ የሰብል ውጤቶችን የሚያካትት ነው:: በተጨማሪም የተፈጥሮ ጠላት ብዛትና የነዚህ ጸረ ሰብል ነፍሳት በሁለት የበቆሎ ልማት ደረጃ በሁለተኛው ዓመት ላይ የሚከናወን ሲሆን በተጨማሪም የፑሽ ቡል ዘይቤ የአገዳ ሰርሳሪ ትል የጥቃት ደረጃ ከፍተኛ የሚሆነው መካከለኛ ውስብስብ የመሬት አቀማመጥ ላይ ሲሆን ይህም በቆሎ ብቻ በሚዘራበት ጊዜ ከፍተኛ የአገዳ ትል ጥቃት ደረጃ የሚኖረው አተር በቆሎ ወይም በቆሎ ሌሎች ሰብሎች ጋር ሲነፃፀር ከፍተኛ የአገዳ ስር አለው፡፡ በትንሹ በበቆሎ የተዋጠ እርሻ ለከፍተኛ የትል ተጋላጭነት ስላለው ይህ ችግር ሊወገድ የሚችለው በእርሻ ቦታው ላይ የተለያዩ ሰብሎችን በመዝራት ነው፤ የናፒር ሳር ብዙ ተመጋቢዎችን እንዲፈጠሩ ሁኔታ ያመቻቻል፡፡ የእንቁላል መራባት ደረጃ በበቆሎና አተር እርሻ ላይ ከፍተኛ ነው። ይሁን እንጂ በቂ የምርት ልዩነቶች በንዑስ ስርአቶች ውስጥም ሆነ በሶስቱ የስነ መሬት አቀማመጥ ላይ ከፍተኛ ተጽኖ ያለው ነው፡፡ ስለዚህ የፑሽ ፑል ስርዐት ጥቅም በብዛት የሚመጣው ተያያዥነት ካላቸው አዝርእቶች (አተር፣ ባቄላ እና የናፒር ሳር/ ተጠቃሾች ናቸው፡፡ የግብርና የስነ መሬት አቀማመጥ በሀዋሳ አካባቢ ባለፉት አርባ አመታት ውስጥ በጥምር ብሄራዊ፣ ክልላዊ እና በአካባቢ ደረጃ ያሉ ግፊት ፈጣሪዎች (የግብርና ፖሊሲ) የግባት ዋጋና መሰረተ ልማቶች፣ ክልላዊና አካባቢያዊ ሁኔታዎች (የህዝብ ብዛትና የከተማ መሰፋፋት) የገበሬዎች ሀብትና ያልተጠበቀ የአየር ንብረት ክስተቶች በዋናነት

ተጠቃሽ ናቸው፡፡ የበቆሎ አዝእርት ብቻ የሚዘራበት አካባቢ የረዥም ጊዜ ሰብሎች በቀጣይነት እየተተካ የመጣ ሲሆን፣ እነዚህም ሰብሎች እንሰትና ጫትን ያካትታል፡፡ በተጨማሪም የህዝብ ብዛት እድገትና የከተማ መስፋፋት የመሬት አቀማመጥና አቅርቦትን በማሳነስ የተበጣጠሰ የእርሻ ሰብል እንዲኖር አድርጓል፤ አውንታዊ የሆነ ጥቅም የበቆሎ አደጋ ሰርሳሪ ትል ከፍተኛ ተጽኖ ፈጥሯል፡፡ በተጨማሪ የፑሽ ፑል ስርዓት የተለያዩ ስርዓትን በአንድ ቦታ የመዝራአት አካሄድ በአፍሪካ ትናንሽ የእርሻ ቦታ ያላቸው አርሶ አደሮች ጋር የተለመደ ነው፡፡

ይህም የመሬት እጥረት ባለበት የአርሶአደር ስርዓት እና የአርሶደሩ የምግብ ሰብሎችን ለመቀየር ካለው ስጋት አንፃር የተለመደ አተር እና ሌሎች ሰብሎችን ባለመተካት ችግሩ ሊባባስ ይችላል:: በተጨማሪም የናፒር ሳር እድገት በመሬት ውስጥ ያለው የናይትሮጅን አናሳነትን በከፍተኛ ደረጃ ተጽኖ ያሳድራል፡፡ ስለዚህ ይህንን የፑሽ ፑል ስርዓት ለመዘርጋት በአካባቢው ያሉትን እጽዋቶች የናፒር ሳር በእርሻ ቦታው ያሉትን የጉልበት ስራዎች እና አላስፋጊ የሆኑ እንቅፋቶች ያስቀራል፡፡ በአጠቃላይ እጽዋትን ማፈራረቅ እና ብዛታቸው በአካባቢው ላይ ሊፈጠሩ ስለሚችሉ ፀረ ሰብል ችግሮች እንዲጨምሩ ማድረግ እና የበቆሎ የጥቃት ደረጃ እንዲቀንስ ይሆናል፡፡ በተጨማሪ አለማቀፍ የጸረ እጽዋት አስተዳደር ዘርፈ ብዙ የሆኑ እጽዋቶችን እና ተክሎችን፣ ለምሳሌ ኀታኒካሎች፣የእንስሳት መኖ፣ የጎርፍ ቁጥጥር፣ የካርቦን ክምችት፣ የአፈር ውስጥ ነፍሳት ጥቅም የመሳሰሉት ላይ ግንዛቤን ማስጨበጡ አስፈላጊ ነው፡፡ ከሁሉም በላይ የስነ መሬት አቀማመጥና ከፍታ ያለውን የመሬት አስተዳደር አተገባበሮችና ዘርፈ ብዙ ተፈጥሮአዊ አገልግሎትና ጥቃቅን የማሳ ባለቤት የሆኑ አባወራዎችና የተፈጥሮአዊ የግብርና ስነ አካባቢያዊ ስርዐት ጠንካራና አካባቢውን ያገናዘበ የተናበበ ማህበረሰባዊ ኢኮኖሚያዊና አካባቢያዊ አላማዎችና የጥናት ዘዴዎች መኖራቸው ተገቢ ነው፡፡ የበቆሎ አገዳ ሰርሳሪ ትሎች ተጽኖ እንደመግቢያ ተጠቅሜ ይህ ተጽኖ በእርሻ ቦታ ውስጥ የሚገለጽ አይደለም፡፡ የመሬት አቀማመጥ ይዘት በተለይም የጸረ እጽዋት ብዛት እና ቀጥተኛ ተጽኖዋቸው ስርጭት፣ የመባዛት ወይም ምርት እና በተዘዋዋሪ የተፈጥሮ ጠላቶቹ ላይ ተጽኖ ያሳድራል፡፡ በአሁኑ ሰዐት የመሬት አቀማመጥ ዲዛይን የበቆሎ አገዳ ሰርሳሪ ትሎች የአካባቢያዊ ቁጥጥር ችግር ብቻ ሳይሆን ሌላ የግብርና ቦታ ውስንነቶች /ይህ ማለት የአፈር ለምነት፣ የተለያዩ ችግሮች/ የአፈር ለምነት አቅዶ እና ያለውን የውርጭ ደረጃ ለማዘጋጀት የሰብል ችግርን የሚያስገወድ ይሆናል፡፡ መሬት ሊሸፍኑ የሚችሉ የዝናብ መጠን ሊቀንሱ የሚችሉ የእጽዋት አይነቶችን መጠቀም፣ በተጨማሪም በተለያዩ የግብርና ስርዓት ላይ የአፈር ለምነት እንዲጨምር የሚያስችሉና ለጥቃቅን መሬት ባለቤት የሆኑ የአርሶአደር አባወራዎች ገቢ ምንጭ ለማስፋት እንዲቻል ሆኖ መታሰብ ይኖርበታል፡፡ ዘርፈብዙ የግብርና ስርኣት እና የተፈጥሮ የእጽዋት ጠላት የሆኑ ነፍሳትን እንደ ስነ አካባቢያዊ መፍትሄ ማሰቡ ትልቅ መፍትሄ ነው፡፡ ነገር ግን በአሁኑ ሰዓት ያለውን ድብልቅ የአዘራር ዘይቤ በመረዳት ከፍተኛ አስተዋጽኦ ያለው ስለመሆኑ የበለጠ ጥናት ያስፈልገዋል፡፡ የግብርና ምርት አቀራረብ ዘይቤ ማለትም የግብርና ኢኮሎጂ በአፍሪካ ውስጥ ያለውን ከእጅ ወደ አፍ የሆነ የተበጣጠሰ የግብርና የመሬት አጠቃቀም ለማሻሻል እና ከተሻለ ደረጃ ለማድረስ የተሻለ አማራጭ ነው፡፡

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The journey which conducted to the this PhD thesis started several years before the actual moment I enrolled at Wageningen University in 2013. While working as research assistant for the Catholic University of Louvain-la-Neuve in Belgium, I wrote two PhD proposals and applied for fellowships which did not work out. When my contract finished at Louvain-la-Neuve; I was unemployed for several months, I doubted about my aim of conducting a PhD and started to look for jobs outside of academia. I went for an interview at the Technical Centre for Agricultural and Rural Cooperation ACP/UE (CTA, Wageningen), I was in the final round very close to get the position. Michael Hailu, Director of CTA, called me in his office and said: Yodit, you left CTA in 2010 to conduct a PhD, go and do it. Michael, I am very thankful for these words, which encouraged me to keep holding on my dream. Two months after this conversation, I started this PhD thesis, which not only was the best subject I could dream working on but also had the field work in Ethiopia, my country of origin. A double research journey started then, a scientific one and the other about my identity.

All along the scientific journey, I have been accompanied by a very complementary and committed supervisory team: Pablo Tittonell, Felix Bianchi, Frédéric Baudron. First of all, thanks to the three of you for having giving me the opportunity to work together on this project. Now that it is finished, I realise how much you made me grow scientifically and personally. Pablo, thanks for giving me trust and making me believe in myself. You gave me a number of opportunities to build my self-confidence, and even if I do not like this word, you definitely “empowered” me. I learned a lot from your inspiring and inclusive leadership style. Felix, thanks for not only reconciling me with statistics but also making me love them. I learned a lot from your rigorous, precise and concise scientific writing style and your pedagogical skills. Thanks also for your patience with my “franglish”. Frédéric, you did not only accompanied me in this journey, you were present in every step, every doubt, every silence. Thanks for constantly challenging and pushing me and bringing me much further than I would have ever thought (and maybe that you would have ever thought…). I learned a lot from your creative, passionate and hard-working mind set.

A large part of this PhD journey was in Hawassa, Ethiopia where I conducted the field work with the precious help of three dedicated field assistants: Dawit Kassahun, Tamet Tesfaye and Abraham Kifle. They shared with me all the challenges and disappointments of the field work: the maize of an experimental plots being eaten by hippopotamus, yellow pan traps destroyed by hyenas, mature maize cobs being attacked by baboons requiring two guards day and night! Thanks so much for your precious help and for making the field work enjoyable. Other people were also involved in making the field work possible: the staff of the Ethiopian Institute of Agricultural Research (EIAR-Hawassa sub-office), in particular Goshime and Mesele who helped me with logistical and institutional challenges. I am also very grateful to the farmers involved in this research; for their time, for sharing their knowledge, for the numerous meals and coffee they offered me. I am really touched by their generosity.

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Every PhD is a personal journey. Mine, was not only metaphorically but also latterly. It brought me back to my country of birth, Ethiopia. It allowed me to see and spend time with my family back there. It gave me the opportunity to laugh daily. It revealed me the values of Ethiopian culture. And above all, this PhD journey had been the realisation of the beautiful path travelled since I left this country as a child. And to walk back as an adult, was a pure blessing.

Va, vis et reviens.

About the author

Yodit Kebede was born in Ethiopia in 1983. At 9 years old she left the small town of Agaro (Western Ethiopia) and moved to La Défense, a major business district located in Paris. After only one year in La Défense where she learned French and enrolled in French education system, she moved to Madagascar and lived in Tamatave for 6 years followed by 2 years in Conakry, Guinea with frequent travels back to France. After completing high school in the French High School of Conakry, she enrolled at the University of Paris-Sud and followed a general scientific section program with a strong biology and chemistry components to prepare for a competitive national contest for entering French state-run schools of agronomy.

In 2003, she joined the formerly called "École nationale d'ingénieurs des travaux agricoles (ENITA)" in Clermont-Ferrand, France; now renamed VetAgro sup. After obtaining a master degree in agricultural engineering with a specialisation in marketing and agricultural economics, she moved to Wageningen, The Netherlands in 2006. There, she conducted another master degree: international land and water management with a specialisation in erosion and soil and water conservation and a minor in GIS and remote sensing.

After completion in 2008, she worked for two years as junior consultant assisting a senior programme coordinator at the Technical Centre for Agricultural and Rural Cooperation ACP/UE (CTA, Wageningen). In 2010 she moved to Brussels, Belgium and worked as research assistant for the Catholic University of Louvain la Neuve. In 2013 she moved back to Wageningen and was enrolled as research assistant and conducted this PhD thesis with frequent and long stays in Hawassa, Ethiopia for the field work. Since the end of the PhD contract in 2017, she has been working as an international consultant for the Food and Agriculture Organisation of the United Nations, in Rome, Italy within the ecosystem services and agroecology unit.

Publication list

Peer reviewed journal articles

Kebede, Y., Baudron, F., Bianchi, FJJA. and Tittonell, P., 2018. Unpacking the push-pull system: Assessing the contribution of companion crops along a gradient of landscape complexity. *Agriculture, Ecosystems & Environment*, *268*, pp.115-123. https://doi.org/10.1016/j.agee.2018.09.012

Video abstract: https://www.youtube.com/watch?v=LAPPJYs0oF0&t=40s

Kebede, Y., Bianchi, F., Baudron, FJJA., Abraham, K., de Valença, A. and Tittonell, P., 2018. Implications of changes in land cover and landscape structure for the biocontrol potential of stemborers in Ethiopia. Biological Control, 122, pp.1-10. https://doi.org/10.1016/j.biocontrol.2018.03.012

Video Abstract: https://www.youtube.com/watch?v=5becsq1QZxo

Kearsley, E., De Haulleville, T., Hufkens, K., Kidimbu, A., Toirambe, B., Baert, G., Huygens, D., **Kebede, Y**., Defourny, P., Bogaert, J. and Beeckman, H., 2013. Conventional tree height–diameter relationships significantly overestimate aboveground carbon stocks in the Central Congo Basin. *Nature communications*, *4*, p.2269. https://doi.org/10.1038/ncomms3269

Accepted

Kebede, Y., Bianchi, F.J.J.A., Baudron, F., and Tittonell, P. Landscape composition overrides field level management effects on maize stemborer control in Ethiopia. Agriculture, Ecosystems & Environment.

Submitted

Kebede, Y., Baudron, F., Bianchi, F.J.J.A., and Tittonell, P., 2018. Drivers, farmer responses and landscape consequences of smallholder farming systems changes in southern Ethiopia

Conference/Symposium Proceedings

Kebede, Y., Baudron, F., Bianchi, F.J.J.A., Abraham, K., Woyessa, K.L., Tittonell, P.A., Kooistra, L., 2015. Trajectories of farming systems and land use changes in Southern Ethiopia.

Kebede, Y., Baudron, F., Bianchi, F.J.J.A., Tittonell, P.A., 2014. A multi-scale analysis (plot, farm, landscape) of the factors controlling maize stemborer (*Busseola fusca*) infestation in Southern Ethiopia. Towards a multi-scale push-pull approach.

Chavarría, J.Y.D., Baudron, F., **Kebede, Y**., Groot, J. 2014. Energy flows in the farming systems of Southern Ethiopia: implications for sustainable intensification.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)

- Landscape composition, pest pressure and sustainable intensification: stem borers in maize-based systems in Ethiopia

Writing of project proposal (4.5 ECTS)

- Landscape composition, pest pressure and sustainable intensification: stem borers in maize-based systems in Ethiopia

Post-graduate courses (6.8 ECTS)

- Sampling in space and time for survey and monitoring of natural resources; PE&RC (2013)
- Farming systems and rural livelihoods: vulnerability and adaptation, Ethiopia; PE&RC, WASS, WIAS (2013)
- Linear models; PE&RC (2013)
- Bugs at your service; PE&RC (2014)

Laboratory training and working visits (1.5 ECTS)

- Field training about stem borers identification and sampling; ICIPE Kenya (2013)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Agronomy for Sustainable Development: advantages of intercropping maize and alfafa
- Wageningen Journal for Life Sciences: adaptation to climate change of maize-producing smallholder farmers in Ethiopia.

Deficiency, refresh, brush-up courses (1.5 ECTS)

- Basic statistics; PE&RC (2013)

Competence strengthening / skills courses (4.9 ECTS)

- Competence assessment; WGS (2015)
- Project and Time Management (P&TM); Wageningen University, Valley Consult
- Data management; PE&RC
- Techniques for writing and presenting a scientific paper; PE&RC,WIAS, VLAG, WASS
- Teaching and supervising MSc thesis; Educational staff development of Wageningen University

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)

- PE&RC Weekend for the first years (2013)
- PE&RC Day or one-day symposium WGS PhD workshop (2016, 2018)

Discussion groups / local seminars / other scientific meetings (5.5 ECTS)

- Sustainable intensification of agricultural systems (2013-2016)
- R Group meetings (2014-2016)

International symposia, workshops and conferences (5.7 ECTS)

- SIMLESA annual meeting; poster presentation; Ethiopia (2014)
- International Symposium for Farming Systems Design; oral presentation; Montpellier (2015)
- Netherlands Annual Ecology Meeting; poster presentation; the Netherlands (2015)

Lecturing / Supervision of practicals / tutorials (3 ECTS)

- Analysis and design of organic farming systems (2013)

Supervision of MSc students (12 ECTS)

- Kassahun Lemi Woyessa: analysing the trajectories of maize-based farming systems using participatory methods in Hawassa area, Ethiopia

- Jean-Yves Duriaux Chavarría : energy flows in the farming systems of Sothern Ethiopia: implication for sustainable intensification

- Anne de Valença: perennial landscape elements as reservoir for natural enemies: assessment of maize stemborer natural enemies in maize fields along perennial landscape elements in Hawassa area, Southern Ethiopia

- Kristin Abraham : detecting shifts in agricultural landscape patterns in Hawassa area, Southern Ethiopia

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