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

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ABSTRACT

Lepidopteran stemborers are a serious pest of maize in Africa. While farmers have adopted 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 3-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 with the botanical diversity of hedges. However, the proportion of maize crop in the surrounding landscape was strongly and positively associated with length of tunnelling at 100, 500, 1000 and 1500 m radius, and overrode field level management factors when considered together. Maize grain yield was positively associated with plant density and soil phosphorus content, and not negatively associated with the length of tunnelling. Our findings highlight the need to consider a landscape approach for stemborer pest management, but 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 tonnes of maize were produced in 2016 (FAOSTAT, 2016), maize production is constrained by pests, diseases, 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%–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 scale. 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 9 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 little 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., 2018a,b). 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

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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 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 host finding success and oviposition preference (Kfir et al., 2002). Nitrogen fertilisation may on the one hand enhance maize attractiveness and therefore accelarate stemborer development rates, but 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., 2018a,b), or, depending on the species composition of hedgerows, provide alternative host plants for maize stemborers. It is likely that management practices aimed at increasing 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 plant is associated with higher pest densities (O'rourke et al., 2011), while habitat that support natural enemies of pests may result in increased top-down suppression of pests (Rusch et al., 2016). Therefore, the composition of a landscape, in particular host plant availability and habitat 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 3-year study was to assess the effect and interactions of management practices at the field scale 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 scale 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 characterized by 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). *Busseola 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 characterized 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 and considered the land use within a radius of 100 m, 500 m, 1000 m, 1500 m, 2000 m of each of the 33 focal fields (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 following the Zig-Zag method by Overholt et al., (1994). The same fields were assessed during the three years. 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 dry matter per hectare. Maize stems and leaves were weighted *in situ*, and a sub-sample was oven dried during 48 h at 70 °C to assess the dry matter content.

2.3. Factors at the field level

The owner of each of the 33 maize fields was interviewed on his/her management practices during three consecutive maize growing seasons. We recorded the planting date, the variety of maize and the quantity of fertilizer applied. Since all farmers used urea and diammonium phosphate (DAP) as fertilizers 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 quadrats of 2 m^2 at three locations in each maize field. We assessed the perimeter area ratio of the maize fields and recorded the plant species composition of hedgerows surrounding each field in 2 m sections at 10 m intervals (Miller and Ambrose, 2000), and 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 depth at three points on a diagonal transect across each of the 33 fields. Fresh composite samples were weighted and dried at air temperature, sieved (< 2 mm) and 50 g sub-samples were collected for chemical analysis. The remaining soil subsample was oven dried for 48 h 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 to 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 30 by 30 m (Kebede et al., 2018a,b). 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 m, 500 m, 1000 m, 1500 m, 2000 m around each focal maize field. Percentages 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

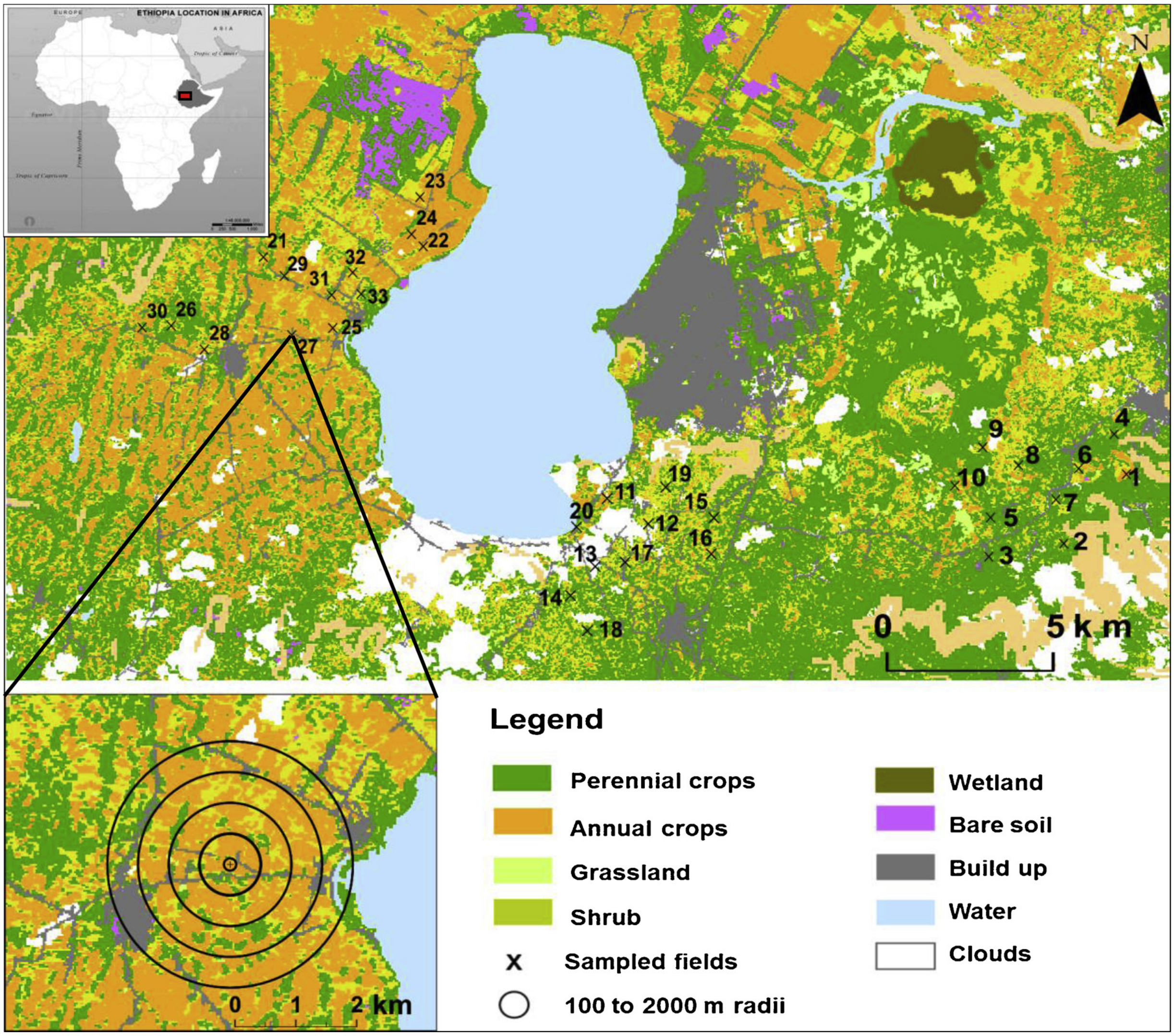

Fig. 1. Location of the study landscape and the sampled fields (numbered from 1 to 33) around Lake Hawassa in the Rift Valley region of Ethiopia, and overview of the five radii considered around each of the 33 maize fields to generate the percentage of maize and perennial crops (100 to 2000 m).

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).

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 plot-level 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 radius 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 100–2000 m and cropping system and planting date were not significant and not further considered. 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 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

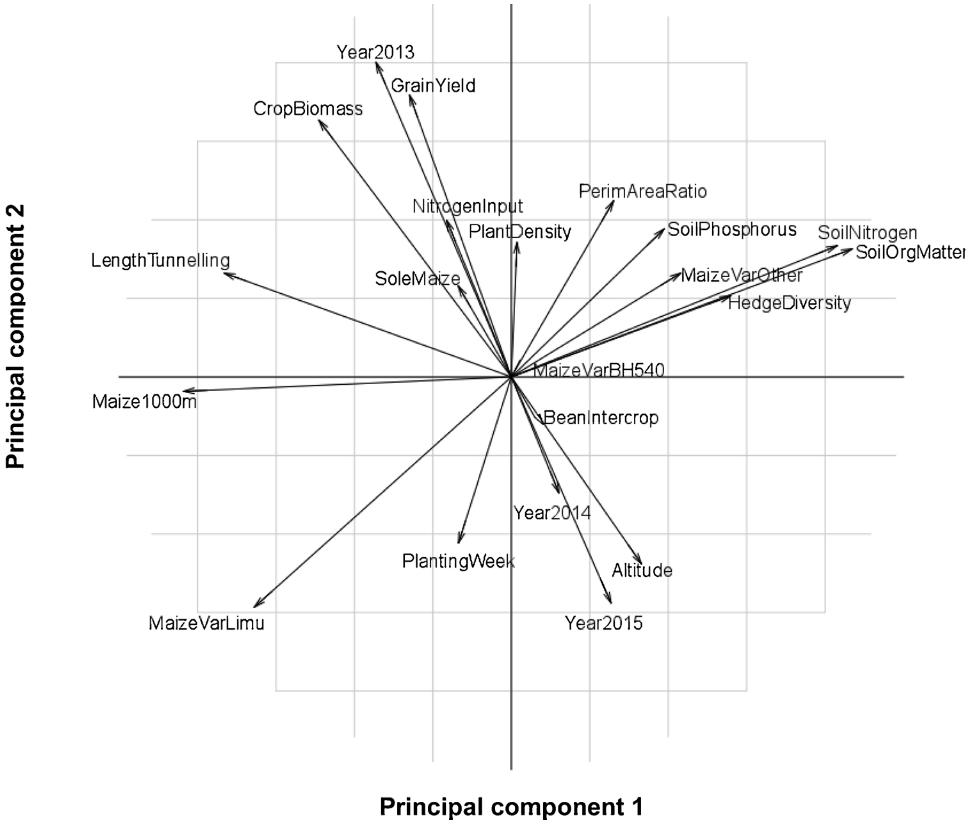

Fig. 2. Plot of Principal Component Analysis (PCA) of response and explanatory variables at the field and landscape level. Since the proportion of maize at 100, 500, 1000, 1500 and 2000 m were highly correlated, we only present the proportion of maize at 1000 m because this had the highest PCA loading.

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 analysis were conducted in R (R Core Team, 2012) using ‘ade4’ package (Dray and Dufour, 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 (Eigen value = 1.39).

Table 1
Overview of a selection of response and explanatory variables (mean ± standard error of mean for the 33 maize fields) 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 (% of cob surface)	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
Larvae density 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 ($P < 0.05$; Table 2). This effect was most pronounced at high infestation levels (Fig. 3A). Other management variables had no significant effect on stemborer infestation level. Yet, quantile regressions analysis revealed that stemborer infestation was

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

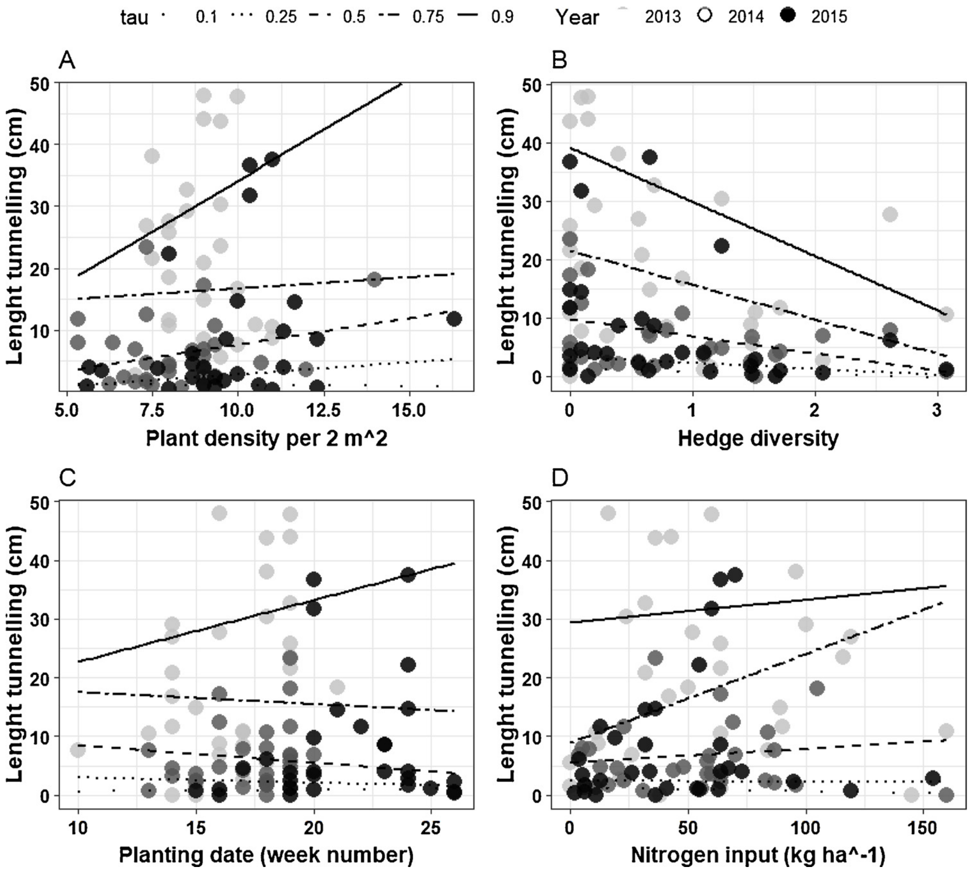

Fig. 3. Quantile regressions at 10, 25, 50, 75 and 90% of the length tunnelling for the field scale variables plant density (A), hedge diversity (B), planting date (C) and nitrogen input (D).

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).

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 not significant ($P < 0.1$). AIC indicated that the models with the proportion of maize at 100 m, 1000 m 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 and positively associated with plant density ($P < 0.001$) and soil phosphorus content ($P < 0.01$; Table 5). In addition, grain yield was not significantly associated with the relative length of tunnelling ($P = 0.060$). Quantile regressions analysis revealed that grain yield was significantly and 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 and significantly associated with plant density ($P < 0.5$).

4. Discussion

In this study, we assessed how factors at the field and landscape scales 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 between 100–1500 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 *Busseola 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 *Busseola fusca* can move up to 50 km in a year (Kruger et al., 2011; Dupas et al., 2014). This suggests that *Busseola fusca* females that laid egg batches in the focal maize fields could have easily crossed 2000 m,

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 date	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

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 *Busseola 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 to 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 factors at the field scale only, plant density was the only factor that was significantly related to stemborer infestation level (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 colonization of maize fields and stemborer supression (Kebede et al., 2018a,b). Although current recommendations for cultural control of maize stemborers promote increasing within-field diversification to stimulate natural enemies, the potential contribution of hedgerows has seldomly been considered (Lawani, 1982; Getu et al., 2001). Therefore, the role of the diversity of plants in hedgerows may be a promising area for futher 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 and for stemborer control in the study area. Previous research in the same area showed that delaying planting after April/early May can result in serious crop losses (Gebre-Amlak et al., 1989). Thus, early planting as soon as the rain starts has been recommended as a practice to reduce crop damage by *Busseola fusca*. Our findings suggest that late planting is associated with higher infestation rates, but 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 and in climate have happened in this period (Kebede et al., 2018a,b).

Nitrogen input did not significantly influence stemborer infestation levels when considering field scale factors alone (Table 2) or in

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 model.

	100m Estimate	Std. Error	p-value	500m Estimate	Std. Error	p-value	1000m Estimate	Std. Error	p-value	1500m Estimate	Std. Error	p-value	2000m 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	0.095
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 ($P < 0.05$), and 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	0.060	−0.423	0.310	0.177

combination with landscape scale factors (Table 4). This finding contrasts with studies that report that NPK fertlisation favors 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, much higher than the rates used in our area (yearly averages ranging between 54 and 70 kg ha^{-1} of nitrogen input) and are 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 the soil texture which affect the mineralisation rate (Kayser et al., 2011), phosphorus deficiency (Nziguheba, 2007) and suboptimal timing of the application or rainfall conditions (rainfall shortage after urea application). While the relationship between nitrogen in plant and its attractiveness to stemborers 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 mediate the effect. In addition, N fertilisation rates reported are on the basis of farmer's recall which could be a source of imprecisions.

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 bean 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 not significantly 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 2 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 *Busseola 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

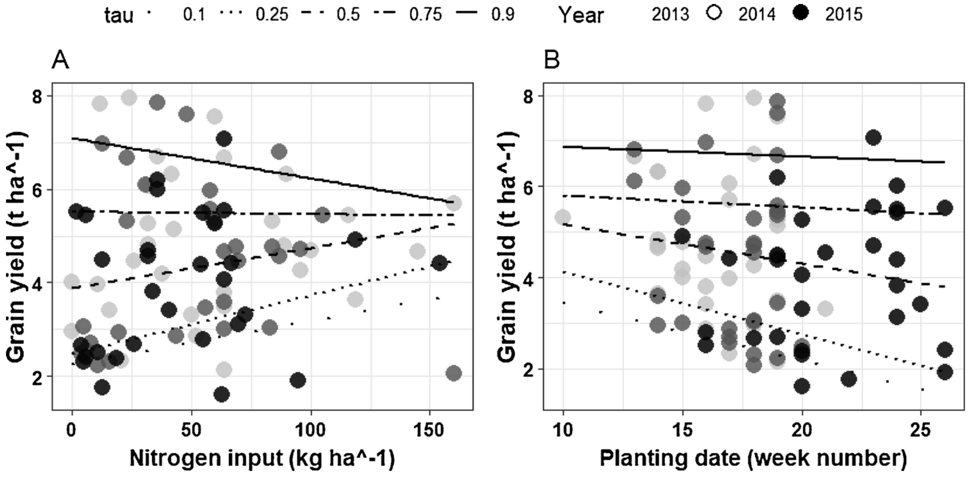

Fig. 4. Quantile regressions at 10, 25, 50, 75 and 90% of the grain yield and nitrogen input (A) and planting date (B).

(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., 2018a,b). Such scenario would be in line with findings of simulation studies that highlight the potential role of changes in agricultuiral 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.

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