Patterns and drivers of crop diversity in the highlands of southwest Ethiopia

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ABSTRACT

Crop diversity plays a major role in underpinning food security. On a global scale it provides the raw materials to meet agricultural challenges such as adaptation to climate change, while locally it enhances productivity, resilience and sustainability. Crop diversity is especially important to smallholder farmers, who often rely on it to stabilise production and avoid harvest failure in increasingly erratic climates. Despite this, the pattens and underlying drivers of crop diversity within regions is not well known. With a novel dataset of over 1000 farms across the highlands of southwest Ethiopia we investigate the presence of distinct farm types, the effect of growing season length and market access on farm-level crop diversity, and of farm size and recently introduced crops on crop diversity of the landscape. We find that farms have spectral variation rather than discrete types, crop diversity increases with market access and decreases with growing season length, landscapes of smaller farms have higher species density, and that recently introduced crops are added to, rather than replacing traditional diversity. Given the rapid climatic, economic and demographic changes occurring in the region and the threats to food security these incur, our results may have important consequences for agricultural policy in southwest Ethiopia and other smallholder agrisystems worldwide.

INTRODUCTION

Crop diversity plays a major role in underpinning food security (Jackson et al., 2007; Kremen et al., 2012). To be food secure an agrisystem must be sufficiently productive, resilient, and sustainable (Fraser, 2007), i.e. it must meet human needs in spite of shocks and stresses, without destroying the natural resources it depends on (Torquebiau, 1992). Crop diversity contributes to these three attributes in agrisystems (see appendix1 for review). However, there is a significant knowledge gap regarding which factors control patterns of regional crop diversity (Ricciardi et al., 2021), especially in smallholder systems (Kumar and Nair, 2004). Understanding the drivers will be essential to anticipate threats to crop diversity, and hence design policy that protects or compensates for it, safeguarding food security. Given the great contemporary losses of crop diversity worldwide (Jacques and Jacques, 2012) coupled with the growing pressure of climate change (Schlenker and Lobell, 2010) there is greater imperative than ever to fill this knowledge gap. Here we use the case study of the highlands of southwest Ethiopia, an area dominated by ancient smallholder agrisystems (Abebe, 2005) to investigate three questions relating to crop diversity. Q1) Do smallholder farms form discrete types? 2) Q2) What are the drivers of farm level crop diversity? 3) What affects the landscape pattern of crop diversity? We study the influence of farm size and the adoption of recently introduced crops.

CROP DIVERSITY IN SOUTHWEST ETHIOPIA

The highlands of southwest Ethiopia are an original hearth of agriculture (Harlan, 1969). Beginning perhaps with the domestication of *Enset ventricosum* over 5000 years ago (Ehret, 1979), the agrisystems today cultivate a great variety of indigenous crops and others introduced over history. The region has long supported a dense rural population (Rahmato, 1995) and today supports one of the highest in Africa (Abebe, 2013), and hosts a great variety of ethno-linguistic groups (Westphal et al., 1975). The agrisystems are characterised by small farms (usually less than one hectare) growing diverse annuals and perennials in mosaics of multi-crop patches, along with livestock pasture and woodlots (Abebe, 2005)(Appendix3). They are an example of intensification in the absence of modern technology, as farmers have developed sophisticated intercropping practices over generations that take advantage of diverse complementary species to maximise use of available resources (Assefa and Bork, 2016; Rahmato, 1995). Enset and coffee are keystone perennials. Enset provides high yields of starch and is resistant to drought (Rahmato, 1995), while coffee is a reliable earner of income (Abebe, 2005). Both species facilitate intercropping arrangements with an average of 13 other species (Abebe et al., 2010).

While Ethiopia has suffered from cyclical famines in the last century (McGuire, 2013) the southwest highlands have almost no record of large scale famine (Rahmato, 1995). Given the minimal levels of imported food, this must be largely due to the integrity of the agrisystems (Fraser, 2007). The region has one of the most favourable agricultural climates in the country (Westphal et al., 1975). However, crop diversity likely contributes to the productivity, resilience, and sustainability of these agrisystems (Abebe, 2005; Tsegaye, 1997). The rich crop diversity, environmental heterogeneity, and heavy reliance on locally produced food (Gezie, 2019) make this region ideal to study patterns of crop diversity, and given the expected climate change, increased market access, population increase, and influx of new international crops (Samberg et al., 2010), an investigation into the impact these changes may have on food security is imperative. In the following section we outline the context and importance of our study questions.

Q1) DO SMALLHOLDER FARMS FORM DISCRETE TYPES?

It is unclear if smallholder farms fall into discrete types with similar crop composition, though this would have strong implications on landscape patterns of crop diversity. Distinct farm types could occur between different ethno-linguistic groups (Perales et al., 2005; Westphal et al., 1975) perhaps associated with different seed exchange networks (Samberg et al., 2013). Alternatively, farm types may be driven by synergistic interactions among particular crop species, providing productivity or sustainability benefits (Abebe et al., 2010; Kumar and Nair, 2004; Subba et al., 2017) creating farm types of specific crop combinations.

Westphal et al., (1975) describe four types of agrisystem in southwest Ethiopia with different balances of staple crops and attributes each to different tribal groups. More recently farm types have been demarcated by the prevalence of cash crops (Abebe et al., 2010; Mellisse et al., 2018), associating types by different subsistence/economic strategies. Whether these types represent discrete crop compositions or sections along a continuum is less clear.

Understanding the presence and nature of farm types is important in guiding policy. Different farm types may react to climate change and market trends in differently, with different capacities to adapt. Additionally, interventions to develop agriculture might need to be sensitive to the different roles of crops across farm types. In this study, we investigate the presence of distinct farm types, and explore key factors for crop composition.

Q2) WHAT ARE THE DRIVERS OF FARM LEVEL CROP DIVERSITY?

Environment

Patterns of wild biodiversity are strongly determined by water-energy dynamics, with diversity of many taxa peaking in areas of high ambient energy and precipitation (Hawkins et al., 2003; Jetz and Fine, 2012). Following these variables, biodiversity generally declines with elevation (Vetaas et al., 2019). Growing season length appears to be a key metric underpinning both wild and linguistic diversity as it correlates to a more predictable climate with greater year round productivity (Hua et al., 2019).

One might expect crop diversity to be driven by the same mechanisms. In some cases this appears true, with low rainfall limiting crop choice in Oromia, Ethiopia (Hailu and Asfaw, 2011) and altitude limiting diversity in southwest Ethiopia (Samberg et al., 2010). However, Abebe (2013) found no effect of altitude in the same region, a finding mirrored in Southern Mexico (Aguilar-Støen et al., 2009). Interestingly, several authors describe the particular advantage of crop diversity under erratic precipitation regimes (Auffhammer and Carleton, 2018; Renard and Tilman, 2019; Ricciardi et al., 2021). As crop diversification is a deliberate strategy used by smallholders to ameliorate risk (Abebe, 2013), there may be an inverse relationship between climatic stability and crop diversity in smallholder agrisystems, contrasting to patterns of wild biodiversity.

Temperature may increase by up to 3.6°C in Ethiopia by 2080 (National Meteorological Agency, 2006) coupled with less predictable rainfall and increased drought, shortening the growing season (Bewket et al., 2015). This may shift crop cultivation ranges to higher altitudes and affect their cultivatable area (Gebresamuel et al., 2021). Understanding the environmental drivers of crop diversity will be vital to anticipate the responses of agrisystems to climate change and inform adaptation measures. Here we investigate how crop diversity in southwest Ethiopia is effected by growing season length.

Market access

Increasing market access underlies transition of small farms from subsistence to commercial orientation, but the effect on crop diversity is unclear (Kumar and Nair, 2004). In Indian (Subba et al., 2017) and southern Mexican (Aguilar-Støen et al., 2009) agrisystems, crop diversity increases with market access, but the pattern in southern Ethiopia is less clear. The expansion of cash crops khat and pineapple associated with market access is replacing traditional perennials (Mellisse et al., 2018), and the multi-crop systems they facilitate (Abebe et al., 2010). Contrarily, Samberg et al, (2013) found crop diversity to increase with frequency of market visits.

Improving road infrastructure is connecting previously isolated farmers to urban markets in southwest Ethiopia (Mushir and Hailemariam, 2015). This process may either homogenise or diversify agrisystems, with differing consequences for policy seeing to maintain food security. Here we investigate the impact of market access on crop diversity.

Q3) WHAT AFFECTS THE LANDSCAPE PATTERN OF CROP DIVERSITY?

Farm size

One would expect larger farms to hold more diversity, but a review found only half of papers to support this in smallholder systems (Ricciardi et al., 2021). The pattern for landscape-level crop diversity is clearer, with an inverse correlation found between species density and farm area across 55 countries (Ricciardi et al., 2018). The authors cite diversification on small farms as a strategy to reduce risk as a cause. However, farms in southwest Ethiopia may be more complicated (Samberg et al., 2010), with species density on some small farms restricted by the necessity to grow only the most productive or profitable crops (Mellisse et al., 2018). However, a comprehensive analysis is lacking.

The rural population of southwest Ethiopia has continually grown over the last century and virtually all available land is under cultivation, leading to declines in farm sizes (Rahmato, 1995). However, rural to urban migration is increasing (Samberg et al., 2010) which may increase farm sizes. Understanding the effect of farm size on crop diversity will allow anticipation of how demographic changes will effect agrisystem integrity and food security. Here we analyse how farm-level and landscape-level crop diversity change with farm area.

Recently introduced crops

Homogenisation of crops in agrisystems worldwide is a distinguishing feature of the Anthropocene (Martin et al., 2019). This has occurred as crop species and varieties have been exchanged with the process of globalisation, and is associated with losses in crop genetic diversity, particularly in centres of domestication (Jacques and Jacques, 2012). Southeast Ethiopia, though historically isolated, is no exception, and has received many new crops in the last century. Genetic erosion of multiple species is occurring (Mekbib, 2008; Mulualem et al., 2020; Wale, 2010). However, whether crops are being replaced on a species level is less clear.

Much of the crop diversity in southwest Ethiopia that underpins food security is made up of traditional species (Abebe, 2013). If contemporary introductions of international crops reduces this diversity it could undermine the integrity of the agrisystems.

Methods

SAMPLING DESIGN

Farms were sampled from seven transects in southwest Ethiopia [Fig1] (n=1170). An eighth transect was removed due to unusual distribution of farm areas around one hectare, suggesting error during fieldwork. In each transect, 150–220 farms were sampled along an altitudinal gradient to capture the full range of environmental variance in each region. Transects encompassed elevational ranges from 918-1804m, and overall sampling points ranged from 1200-3241MASL.

Data on crops present and their area of cultivation was recorded. For some perennials the number of individuals was recorded and converted to area using constants, e.g. 0.002ha for Avocado trees. There were initially 124 species, but those that do not yield edible products were removed. These mainly included trees that may not have been identified consistently across samples as different researchers collected data from each transect. Some species were amalgamated into groups, such as *Musa sp.* because of difficulty to accurately identify them in the field. After quality control we retained 75 species (Appendices). Farms contained up to 29 of these species (mean = 8.28, SD = 3.56). Farm sizes were calculated by summing the area of crops cultivated and varied from 0.004-3.078ha (mean = 0.42ha, SD=0.38ha).

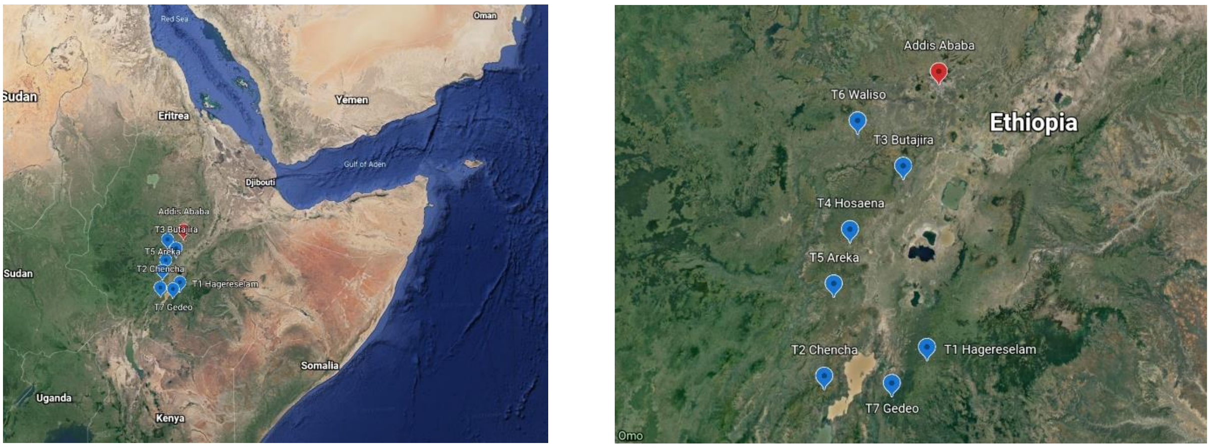


Figure 1

Maps to show transect locations (blue). Addis Ababa is shown in red for location reference only. (“Google Earth,” 2021)

DETERMINING CROP ORIGINS

We sought to determine the origin and period of introduction for each crop into Ethiopia. Data were collected from the literature and used to assign each crop to one of three categories(Appendices3,4): indigenous/ancient are crops that originated in Ethiopia or were introduced before c. 1500AD(n=44); early modern refers to crops introduced during the colonial era(n = 18); recent refers to crops introduced in the last 100 years with little time to naturalise(n=12)[Fig2].

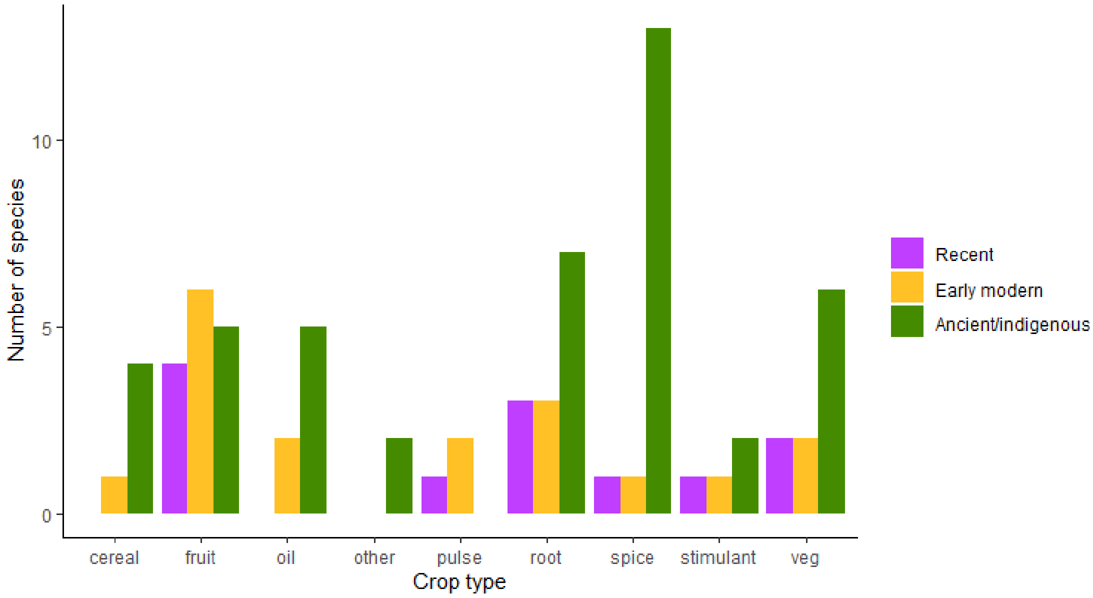


Figure 2

Grouped bar plot showing number of crop species in each functional type, coloured by their period of introduction into Ethiopia. Plot made using ggplot2 (Wickham, 2016).

Q1) DO SMALLHOLDER FARMS FORM DISCRETE TYPES?

To investigate the presence of farm types we used principle component analysis (PCA). The data were transformed to presence/absence of crops on each farm and ggbiplot used to assign PC axes (Vu, 2011). PCA graphs were made using ggplot2 (Wickham, 2016) and RColorBrewer (Neuwirth, 2014) to assign colours corresponding to altitude and area of farms. Factoextra was used to quantify variable loadings and determine the most important crops.

Q2) WHAT ARE THE DRIVERS OF FARM LEVEL CROP DIVERSITY?

We used mixed effects models to investigate drivers of farm-level crop richness, Shannon diversity, and proportion of farm area growing recently introduced crops using nlme (Pinheiro et al, 2020). Shannon diversity was used as it quantifies species evenness (Forman et al., 1995) and calculated using vegan (Oksanen, 2020) and proportion of recent crops gives a measure of the adoption of non-traditional crops, allowing investigation into how this effects diversity patterns.

Fixed effects used were farm area(ha), travel time to nearest main town (TTMT)(minutes), and growing season length (GSL)(days). Transect was assigned as a random effect to control for the influence of different surveyors. GSL data was extracted from Chelsa Climate (chelsa-climate.org) and was used because it is a function of precipitation and temperature, and can be a proxy for climatic regularity (Hua et al, 2019). TTMT data was taken from Ethiogis 3 (www.ethiogis-mapserver.org) and corresponds to market access. Altitude was not used as it does not directly relate to climatic variables (Körner, 2007).

Q3) WHAT AFFECTS THE LANDSCAPE PATTERN OF CROP DIVERSITY?

To investigate the effect of farm size on crop diversity at multiple spatial scales we carried out comparisons between small and large farms while controlling for socioeconomic and environmental variables, thus isolating the effect of farm size. We divided farms into adjacent groups of 10, each representing a small community where we expect socioeconomic and environmental conditions to be very similar. Within each group, the largest and smallest farms were selected and placed in separate groups.

To investigate the diversity of these two groups, species accumulation curves (SACs) were plotted using BiodiversityR (Kindt & Coe, 2005). We plotted curves against number of farms to test how species richness accumulates in equal sized samples of small and large farms. Second, to account for differences in farm size we plotted accumulation of species richness by cultivated area.

We also investigated the effect of the diversity of recent crops on overall crop richness. The farm with the greatest and least diversity of recent crops was selected from each group of 10 adjacent farms, creating groups with a high diversity (mean 2.068), and low diversity (mean 0.179) of recently introduced crops. SACs were similarly plotted for these two groups to test if the effect of recent crops on overall richness.

Results

Q1) DO SMALLHOLDER FARMS FORM DISCRETE TYPES?

In our PCAs we found continuous variation in crop composition among farms, rather than discrete clusters[Fig3a-d]. Banana, coffee, avocado, taro, mango and potato were the most important crops explaining variation in crop presence/absence among farms[table1].

Colouring by altitude shows a strong non-random distribution of farm composition with altitude, as indicated by the light to dark gradient across PC1[Fig3. A] though there is no obvious pattern in PCs 2-4[Fig3. a, b]. Colouring by farm area does not show such a strong pattern, though smaller farms occupy a more restricted space along PCs 2-4 than do larger farms[Fig3. c, d].

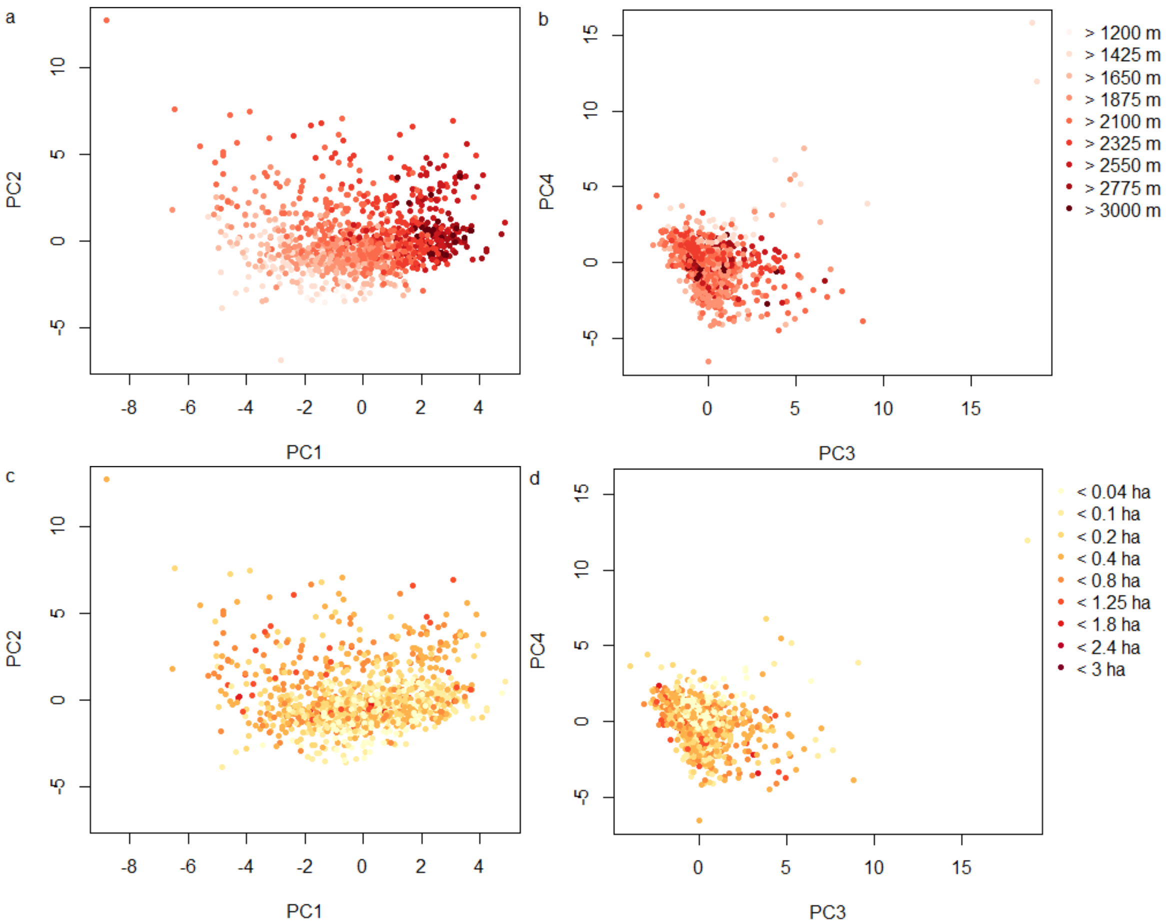


Figure 3

PCAs of farm crop composition. Points correspond to farms, n = 1170, location determined by crop presence or absence.

a, b) coloured by altitude. c, d) coloured by farm area.

Table 1. Main crops contributing to principle components 1-4 in farm crop composition PCA.

Principle component	Variance explained	key species
1	5.4%	banana, coffee, avocado, taro, mango
2	4.2%	potato
3	3.5%	carrot, aerial yam
4	2.9%	khat

Q2) WHAT ARE THE DRIVERS OF FARM LEVEL CROP DIVERSITY?

Our model found farm crop richness to increase with farm area but to decrease with TTMT and GSL[Table2].

Table 2. Mixed effects model of factors effecting farm crop species richness.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	34.2418	7.4843	1160	4.5751	0.0000
Farm area	2.2719	0.2715	1160	8.3683	0.0000
Travel time to main town	-0.0097	0.0024	1160	-4.1266	0.0000
Growing season length	-0.0966	0.0300	1160	-3.2218	0.0013

Shannon diversity decreased with TTMT and GSL. Farm area had no significant effect on Shannon diversity but was included for comparison between models[Table3].

Table 3. Mixed effects model of factors effecting farm crop Shannon diversity.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	7.6413	0.9417	1160	8.1142	0.0000
Farm area	0.0505	0.0343	1160	1.4725	0.1412
Travel time to main town	-0.0008	0.0003	1160	-2.7815	0.0055
Growing season length	-0.0243	0.0038	1160	-6.4327	0.0000

The proportion of farm area used to cultivate recently introduced crops decreased with farm area and TTMT. GSL had no significant effect on the proportion of recently introduced crops but was included for comparison between models[Table4].

Table 4. Mixed effects model of factors effecting proportion of farm area cultivating recently introduced crops.

	Value	Std.Error	DF	t-value	p-value
(Intercept)	-0.0766	0.1553	1160	-0.4933	0.6219
Farm area	-0.0177	0.0066	1160	-2.6672	0.0078
Travel time to main town	-0.0001	0.0000	1160	-2.8085	0.0051
Growing season length	0.0006	0.0006	1160	0.9669	0.3338

Q3) WHAT AFFECTS THE LANDSCAPE PATTERN OF CROP DIVERSITY?

Farm size

The large farm group had significantly greater mean area than the small farm group (0.948ha, SD = 0.507; 0.163ha, SD = 0.137), $t(132.84) = 16.158$, $p = <0.0001$. Larger farms also had significantly higher mean species richness than smaller ones individually (9.436, SD = 3.505; 6.906, SD = 3.283) ,$t(231.01) = 5.6989$, $p < 0.0001$, as indicated by the steeper gradient of the large farm SAC[Fig4. a]. However, both groups had similar total crop diversity (60 in large farms; 61 in small farms).

Controlling for area shows species to accumulate faster on smaller farms[Fig4. b] implying higher species density on smaller farms, and higher species turnover in a landscape of small farms.

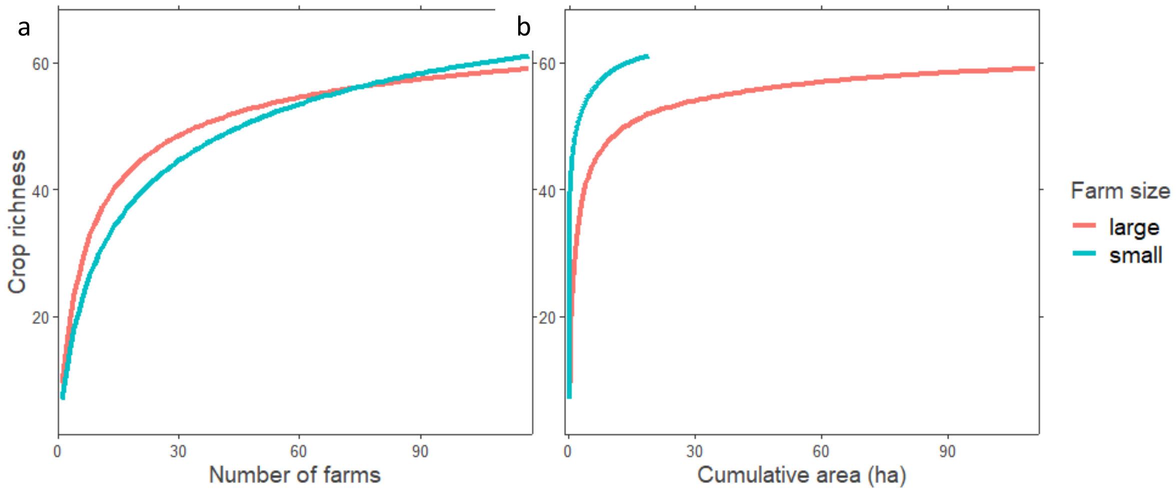


Figure 4

Species accumulation curves for large (red) and small (blue) farm groups (n = 117 in each).

a) species accumulation with number of farms.

b): species accumulation with cumulative area (ha).

Recently introduced crops

The high recent crop diversity group did not differ significantly from the low group in mean farm area (0.456ha, SD = 0.347; 0.401ha, SD = 0.405), $t(226.74) = 1.1211$, $p = 0.2634$. However, the high group had significantly greater mean species richness of all crops (10.179, SD = 3.861; 7.57, SD = 3.407), $t(228.47) = 5.4759$, $p < 0.0001$. This is indicated by the steeper gradient of the high group[Fig. 5]. The high group also has higher total species richness (65 compared to 53).

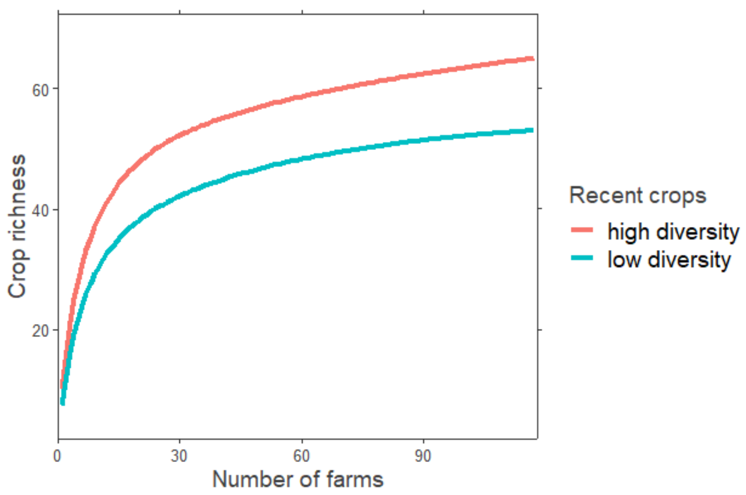


Figure 5

Species accumulation curve (all crop species) for farm groups of high (red) and low (blue) diversity of recently introduced crops (n = 117 in each).

DISCUSSION

Q1) DO SMALLHOLDER FARMS FORM DISCRETE TYPES?

We found no evidence of discrete farm types in our PCAs, indicated by a continual spectrum of variance in farm crop composition. This suggests that if ethno-linguistic structure has an impact on crop choice (Perales et al., 2005; Westphal et al., 1975) it is not strong enough to lead to fully distinct farm types. It may however have an influence on the position of farms along the spectrum of crop composition, but we were unable to explicitly test for this as each transect in our data (and therefore the areas associated with different tribal groups) were sampled by different researchers. Also, the influence of culture may have been stronger in earlier decades when traditional seed networks were more heavily used rather than markets to exchange plant material (Samberg et al., 2013).

Compatible crops combinations undoubtedly benefit agrisystems (Smith et al., 2008) and may be particularly important in smallholder systems where inputs are limited (Rahmato, 1995). However, compatibility between particular species does not seem create discrete farm types. This might suggest that effective combinations do not typically rely on particular species but members of more general guilds, such as shade tolerators with trees (Kumar & Nair, 2004) allowing benefits to be derived from a greater range of species combination.

Policy implications

Our results do not suggest a need to conserve particular species to maintain agrisystem integrity, as might be the case if there were discrete farm types. Instead, attention should be paid to the elevational bands that different species occupy and how these might shift with climate change(Gebresamuel et al., 2021), as altitude had the strongest influence on crop composition in out PCAs.

Q2) WHAT ARE THE DRIVERS OF FARM LEVEL CROP DIVERSITY?

Growing season length

Our models show crop richness and Shannon diversity to decline with GSL. This is contrary to the patterns of wild biodiversity, which increases with temperature and precipitation (Currie et al, 2004), variables which constitute GSL to a large extent (Hua et al, 2019). One reason for our finding may be that farmers in areas of lower GSL purposefully cultivate a greater diversity of crops to buffer food production and reduce risk of crop failure to drought and other disturbances (Auffhammer and

Carleton, 2018; Jackson et al., 2007; Matsushita et al., 2016; Renard and Tilman, 2019; Torquebiau, 1992). Farmers in the region deliberately diversify crops to reduce risk (Abebe, 2013) and may do this more in areas of lower GSL, which can be expected to be climatically riskier for subsistence (Hua et al., 2019).

Another explanation is that areas of lower GSL in the region may have a longer history of agricultural occupation, and accumulated greater crop diversity. The highest GSL sites were areas of previous humid forests recently expanded into for agriculture (Rahmato, 1995) while higher elevation sites have been cultivated for much longer (Samberg et al., 2013) but the relationship between GSL and altitude in the region is not clear(Körner, 2007) Furthermore, there is no clearly defined link between agrisystem age and crop diversity.

Policy implications

Agricultural extension services in southwest Ethiopia typically encourage the cultivation of few elite crops in favour of traditional crop diversity (Abebe et al., 2010). As these crops may be the most vulnerable to climate change (Bewket et al., 2015), their introduction, especially in areas already prone to drought may pose a risk to food security if not accompanied by infrastructural developments such as irrigation (Renard and Tilman, 2019). Instead, there may be potential in promoting a diversity of traditional crops as many of these are hardy (Mercer and Perales, 2010) and contain the genetic potential to adapt to new conditions under climate change (Zimmerer et al., 2019).

Market access

Several authors anticipate a drop in crop diversity with increased access to markets in southern Ethiopia due to replacement of traditional, diverse multi-crop arrangements with homogenous cash crops, particularly khat and pineapple, and annual food crops (Abebe et al., 2010; Hailu and Asfaw, 2011; Mellisse et al., 2018). However, we find that crop richness and Shannon diversity increase with market access.

One possible explanation for this is that market access and associated commercialisation of farms encourages crop diversification. Farmers who become wealthier through trade tend to buy diverse vegetables (Sibhatu et al., 2015), creating a demand for more diverse produce near trade centres. In line with this, sale of diverse vegetables was found to be a profitable strategy in Tanzania (Rajendran et al., 2017). Additionally, commercially oriented farmers may diversify crops to stabilise production and income (Davis et al., 2012) and stagger harvest times (Rahmato, 1995).

Market access may also enable farmers to increase crop diversity by removing the restraint of being completely self-sufficient. Isolated farmers unable to sell produce are limited to growing subsistence species (Subba et al., 2017). When the area is also densely populated, only strict cultivation of the highest yielding species provides adequate food (Abebe, 2005). Markets may also facilitate greater diversity by acting as hubs of seed exchange, exposing farmers to new species (Samberg et al., 2013). This is supported by our finding that recently introduced crops are more prevalent in farms closer to urban centres. Finally, markets may enable the sale of additional crops such as spices, which are difficult for more isolated farmers to make profit from (Agize and Zouwen, 2016).

Policy implications

Improving market access may tend to enhance crop diversity, with co-benefits to nutrition. However, our study only considers crop diversity at the species level. Future research should investigate the effect on within-species crop diversity, as genetic erosion is a serious problem in crop diversity centres worldwide (Jacques and Jacques, 2012). Additionally, Mellisse et al, (2018) believe the only reason khat has not yet become dominant is because farmers perceive the possibility of a ban on sale of the crop. Policy should aim to prevent a heavy transition to khat or other cash crops that would destabilise food security.

Q3) WHAT AFFECTS THE LANDSCAPE PATTERN OF CROP DIVERSITY?

Market access

Our analyses found that crop richness increases with farm size (though Shannon diversity is unaffected), but that small farms have higher species density, agreeing with the recent metanalysis (Ricciardi et al., 2021). Our results suggest landscapes of smaller farms have higher species turnover, and therefore greater crop heterogeneity.

There are multiple reasons why species density might be higher on smaller farms. Firstly, if families grow crops to cover essential needs, such as basic dietary requirements a certain diversity must be grown regardless of area available (Ricciardi et al., 2021). Larger farms may cover these needs and devote excess land to less diverse cash crops (Abebe, 2013).

Another possible reason is that farmers with less land have greater pressure to exploit the benefits of crop diversity such as production stability and risk reduction (Matsushita et al., 2016), and enhanced nutrient cycling (Liebman et al., 2015) as smaller farms are likely to be inherently less food secure than larger ones (Rahmato, 1995). Furthermore, these farmers are likely able to apply more labour per area than those with larger farms, a trend linked to the inverse relationship between farm size and productivity (Ricciardi et al, 2021). If use of diverse crops for increased productivity requires increased labour, occupants of smaller farm will be more able to supply it. Alternatively the benefits of diversifying crops may level off beyond a point (Jackson et al., 2007), reducing the pressure to continually diversify with area.

An alternative explanation is that small farms may replace non-crop components of their land with crops in order to meet their needs (Rahmato, 1995). Loss of trees and livestock could have detrimental effects on the integrity of the agrisystems, as both trees (Abebe, 2013) and livestock (Rahmato, 1995) have important roles maintaining soil quality and providing manure fertiliser respectively.

The higher species turnover associated with smaller farms may have ecosystem service benefits to the agrisystems on the landscape scale, as increased crop heterogeneity can reduce the prevalence of pests and diseases (Letourneau et al., 2011), reducing the need for pesticides (Oerke, 2006), and can increase pollinator abundance (Belfrage et al., 2015; Tscharntke et al., 2012). Landscape heterogeneity can also enhance the agrisystems capacity to resist and recover from environmental shocks and stresses, increasing sustainability (Liebman et al., 2015).

Policy implications

Policies that influence farm size are an avenue to influence landscape level crop diversity. Potentially, smaller farms could yield ecosystem service benefits to the agrisystem. However, if diverse trees and pasture are being replaced with crops, there may in fact be a reduction in wild biodiversity with negative effects on various ecosystem services and on agrisystem sustainability. WE found no significant effect of farm size on the overall crop species pool, and so would not expect changing farm size to cause loss of crop species from the landscape. However smaller farms may be replacing a diversity of traditional crop varieties with less diverse new ones (Samberg et al., 2010). Further research could investigate the effect of changing farm sizes on wild plant diversity and heterogeneity in the region, and additionally on levels of interspecific crop diversity.

Recently introduced crops

There is concern that recently introduced crops are replacing diverse traditional species, and thus damaging agrisystem integrity in southwest Ethiopia (Mellisse et al., 2018). However, we found farm and landscape crop richness to increase with the adoption of recent crops, suggesting they are added to traditional diversity, rather than replacing it.

Policy implications

Adoption of recent crops may enhance the benefits associated with crop species diversity. However, the extent to which recently introduced cultivars replace traditional genetic diversity was beyond the scope of our study and certainly warrants further research.

CONCLUSION

We find farms to vary in composition across a spectrum heavily determined by altitude, rather than forming discrete types. Crop diversity increases with market access, and decreases with growing season length, and species density is higher in smaller farms. Recently introduced crops tend to be added to traditional diversity rather than replacing it. Future research should focus on the effects of climate change on the viable areas of key crops, and on the effect of changing farm size and introduced crops on crop genetic diversity, and the potential of elite introduced vs diverse traditional in adverse environmental conditions.

APPENDICES

1) The importance of crop diversity for food security

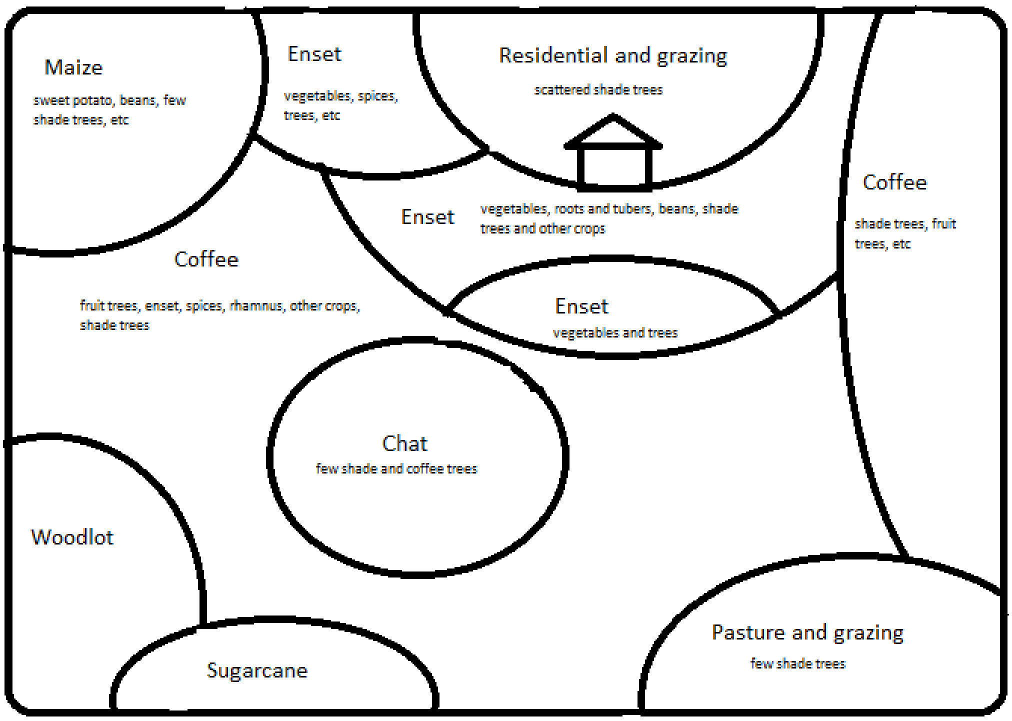
Crop diversity can enhance productivity through beneficial interactions between species (Jackson et al., 2007). Examples include intercropping with legumes and cover crops to enhance N cycling and soil quality (Davis et al., 2012; Liebman et al., 2015), and of species with complementary light requirements and root architectures (Abebe, 2013). Crop diversity can act to suppress weeds, pests and diseases (Letourneau et al., 2011; Ratnadass et al., 2012), offering an alternative to chemical pesticide use (Oerke, 2006). While pesticides often reduce pollinator abundance (Potts et al., 2010), crop diversity can enhance it, greatly benefiting production of many economically and nutritionally valuable crops (Tscharntke et al., 2012). Crop diversity of agrisystems has also been linked to enhanced dietary diversity and dietary quality (Massawe et al., 2016; Rajendran et al., 2017; Sibhatu et al., 2015; Zimmerer et al., 2019) which is of great importance given the still high levels of malnutrition worldwide despite the advances of the green revolution (Haddad et al., 2016).

Crop diversity enhances agrisystem resilience by buffering against environmental and economic stresses (Jackson et al., 2007), stabilising food production and profit under fluctuating conditions (Matsushita et al., 2016). Crop diversity was effective in stabilising production against erratic rainfall in 91 countries, highlighting its particular importance in areas where irrigation is not possible (Renard and Tilman, 2019). Many smallholders throughout the world deliberately diversify crops to reduce the risk of total harvest failure (Torquebiau, 1992), which often also has the benefit of spreading labour and production more constantly over time (Kumar and Nair, 2004).

Agrisystem sustainability is enhanced by crop diversity, as it provides an alternative to agrichemical use(Liebman et al., 2015). Intercropping with nitrogen fixing legumes, perennials and use of cover crops all enhance soil quality or reduce soil erosion, and were found to allow the same or higher yield and profit compared to monocultural corn systems but with far reduced chemical fertiliser input (Lin, 2007; Smith et al., 2008) greatly reducing local environmental toxicity (Davis et al., 2012). These findings have led to suggestions that diversification could be a sustainable way to intensify agriculture in areas in sub-Saharan Africa (Franke et al., 2018).

The traditional crop diversity found in centres of crop domestication provides a service for the whole globe in underpinning long term food security (Khoury et al., 2016) as it contains raw material to create new cultivars with increased productivity, tolerance to adverse environmental conditions and resistance to pests and diseases (Engels et al., 1991; Jackson et al., 2007). This diversity will be of great value in adapting agriculture to climate change (Zimmerer et al., 2019) and species that have so far been largely neglected by breeding programmes may be particularly important because of their strong environmental tolerances (Massawe et al., 2016). Efforts should therefore be made to protect this crop diversity.

3) Farm diagram. Cartoon representation of typical smallholder farm in the highlands of southwest Ethiopia showing mosaic of multi-crop patches. Reproduced from Abebe (2005).



3) Crop list. All crops in the dataset after quality control filtering, with their introduction into Ethiopia category, functional type, number of farms and transects in which they were found, and

Crop name	Introduction	Type	No. farms	No. transects	Total area (ha)
Artemisia afra/abyssinica	Indigenous/naturalised	spice	67	5	0.016
Aframomum corrorima	Indigenous/naturalised	spice	5	1	0.014
Allium cepa	Indigenous/naturalised	root	53	6	0.686
Allium sativum	Early modern	root	30	5	0.221
ananas sp	Recent	fruit	149	7	2.000
Annona sp	Early modern	fruit	112	5	1.221
Arachis hypogaea	Early modern	oil	9	1	0.024
Artocarpus heterophyllus	Early modern	fruit	1	1	0.002
Beta vulgaris cicla	Recent	vegetable	3	2	0.001
Beta vulgaris	Recent	root	40	5	0.941
Brassica carinata	Indigenous/naturalised	vegetable	622	7	10.032
Brassica nigra	Indigenous/naturalised	oil	30	1	0.093
Brassica oleracea	Indigenous/naturalised	vegetable	63	7	1.567
Brassica napus	Indigenous/naturalised	oil	5	1	0.001
Camellia sinensis	Recent	stimulant	1	1	0.001
Canna indica	Early modern	root	22	2	0.017
Capsicum anuum	Early modern	spice	260	7	0.684
Carica papaya	Early modern	fruit	116	7	0.299
Casimiroa edulis	Early modern	fruit	120	7	0.267
Catha edulis	Indigenous/naturalised	stimulant	194	7	12.249
Citrus sp	Unknown	fruit	190	7	0.369
Coffea arabica	Indigenous/naturalised	stimulant	678	7	50.147
Colocasia esculenta	Indigenous/naturalised	root	292	5	26.990
Commelina africana	Indigenous/naturalised	vegetable	5	1	0.005
Coriandrum sativum	Indigenous/naturalised	spice	15	1	0.004
Cucurbita sp	Early modern	vegetable	173	6	0.330
Cymbopogon citratus	Indigenous/naturalised	spice	16	2	0.008
Daucus carota	Recent	root	34	5	0.205
Dioscorea bulbifera	Indigenous/naturalised	root	5	1	0.001
Dioscorea sp	Indigenous/naturalised	root	139	5	1.301
Ensete ventricosum	Indigenous/naturalised	root	1082	7	147.185
Eragrostis tef	Indigenous/naturalised	cereal	145	4	19.028
Ficus sp	Indigenous/naturalised	fruit	104	5	2.030
Foeniculum vulgare	Recent	spice	6	1	0.001
Fragaria ananassa	Recent	fruit	8	1	0.001
Glycine max	Recent	pulse	11	2	0.058
Helianthus annuus	Early modern	oil	4	1	0.004
Hordeum vulgare	Indigenous/naturalised	cereal	180	7	24.152
Ipomoea batatas	Early modern	root	74	6	2.479

Lactuca sativa	Recent	vegetable	22	5	0.042
Linum usitatissimum	Indigenous/naturalised	oil	5	2	0.008
Lippia abyssinica	Indigenous/naturalised	spice	62	2	0.024
Lycopersicon esculentum	Early modern	vegetable	90	7	0.410
Malus sp	Recent	fruit	121	4	1.170
Mangifera sp	Indigenous/naturalised	fruit	326	7	4.218
Manihot esculenta	Indigenous/naturalised	root	7	1	0.006
Moringa sp	Indigenous/naturalised	vegetable	14	2	0.031
Musa sp	Indigenous/naturalised	fruit	365	7	7.906
Nicotiana sp	Early modern	stimulant	48	6	0.141
Ocimum Basilicum	Indigenous/naturalised	spice	117	6	0.112
Ocimum Lamiifolium	Indigenous/naturalised	spice	68	4	0.137
Olea eruopaea	Indigenous/naturalised	other	74	5	0.197
Passiflora edulis	Early modern	fruit	1	1	0.001
Persea americana	Recent	fruit	603	7	5.253
Phaseolus lunatus	Early modern	pulse	6	1	0.007
Phaseolus vulgaris	Early modern	pulse	183	7	10.399
Phoenix sp	Indigenous/naturalised	fruit	9	1	0.012
Plectranthus edulis	Indigenous/naturalised	root	263	6	28.152
Prunus persica Batsch	Indigenous/naturalised	fruit	72	4	0.077
Psidium guajava	Early modern	fruit	52	5	0.075
Rhamnus prioides	Indigenous/naturalised	spice	239	5	2.551
Ricinus communis	Indigenous/naturalised	oil	153	5	0.622
Rosmarinus officinalis	Indigenous/naturalised	spice	62	3	0.018
Ruta chalepenesis	Indigenous/naturalised	spice	274	6	0.091
Saccharum officinarum	Indigenous/naturalised	other	256	7	4.715
Satanocrater somalensis	Indigenous/naturalised	spice	1	1	0.000
Sesamum indicum	Indigenous/naturalised	oil	1	1	0.000
Solanum nigrum	Indigenous/naturalised	vegetable	1	1	0.000
Solanum tarderemotum	Indigenous/naturalised	vegetable	8	1	0.002
Solanum tuberosum	Recent	root	136	3	10.682
Sorghum bicolor	Indigenous/naturalised	cereal	39	5	3.193
Thymus citriodorus	Indigenous/naturalised	spice	4	1	0.000
Triticum aestivum	Indigenous/naturalised	cereal	254	7	35.488
Zea mays	Early modern	cereal	650	7	66.346
Zingiber officinale	Indigenous/naturalised	spice	41	2	4.187

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