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Article

Revisiting the link between cereal diversity and production in Ethiopia

Ben Groom[1,*,†] **and Francisco Pereira Fontes**[2,*]

[1]Dragon Capital Chair in Biodiversity Economics, LEEP Institute, Department of Economics, University of Exeter Business School, Exeter, UK
[2]Monitoring and Analysing Food and Agricultural Policies Programme, Agrifood Economics Division, Food and Agriculture Organization of the United Nations, Rome, Italy

[*]Corresponding author: Ben Groom. Dragon Capital Chair in Biodiversity Economics, LEEP Institute, Department of Economics, University of Exeter Business School, Rennes Drive, Exeter, EX4 4PU, UK.
E-mail: b.d.groom@exeter.ac.uk; Francisco Pereira Fontes. Viale delle terme di Caracalla, 00153 Roma, Italy.
E-mail: francisco.pereirafontes@fao.org
[†]Visiting Professor at the Grantham Research Institute on Climate Change and the Environment, London School of Economics, UK.

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Abstract

Studies show that cereal diversity positively affects mean yields, suggesting increased crop diversity as a means of increasing production (Di Falco and Chavas 2009, Baumgärtner and Quaas 2010). In practice though, agricultural development has relied on nondiverse systems. Using the Ethiopian Rural Household Survey panel, we revisit this paradox and disentangle the effects of agroecological zones and composition of crop diversity. We find a positive effect of greater cereal diversity on cereal production, but mostly in specific agroecological zones and for households who diversify away from a particular low-productivity crop: teff. These results indicate that the scope of cereal diversity to drive increases in output may be limited. Similar to recent studies of biodiversity—ecosystem function relationships (e.g. Jochum et al. 2020), the results suggest that the composition of diverse systems can be more important than the measured *diversity* itself. In the case of cereal crops in Ethiopia, differences in the yields of particular cereals in the crop mix explain the diversity effect, rather than diversity alone. Since some combinations of crops add to productivity but others do not, productivity-related crop choice may not guarantee *in situ* conservation of crop diversity on its own. Alternative conservation solutions may well be needed for that.

Keywords: Agriculture, Biodiversity, Ethiopia, Crop productivity

JEL codes: Q16, Q57

1. Introduction

The effect of crop diversity on agricultural production has been shown to be positive in a variety of contexts via increased mean and often reduced variability of yields (e.g. Di Falco *et al*. 2010; Di Falco and Chavas 2006). Yet this microeconomic evidence is somewhat at odds with historical trends in agricultural development, which has typically relied on nondiverse, even monocropping systems. Understanding the link between crop diversity, productivity, and agricultural development therefore remains important, since it speaks directly to the productivity and development of agricultural systems, and their resilience to weather shocks and even climate change. Crop diversity may have an important role to play in maintaining food security. However, whether increases in crop diversity per se represent a viable development strategy capable of delivering sustained productivity gains, thereby conserving *in situ* crop diversity, remains an open question.

Recently, a number of microeconomic studies seem to suggest a ‘win-win-win’ situation in the form of increased productivity, reduced volatility of output, and greater *in situ* conservation (Di Falco and Perrings 2003; Di Falco and Chavas 2006; Di Falco *et al.* 2007). These findings, however, contrast sharply with historical trends in agricultural development, which appear to be driven by increasingly mechanized, specialized, and input-intensive agriculture. This trend has been epitomized, at different periods in history, by cases such as the USA, Europe, and more recently, by China and India (Borlaug 2000; Evenson and Gollin 2003). As such, a ‘micro–macro’ paradox seems to have emerged. Studies at the farmer level seem to suggest that crop diversity positively affects agricultural productivity. At the macro level, however, increases in productivity in the most recent success stories seem to have been driven by less diverse systems. This current state of affairs is likely to be puzzling for policymakers and is particularly important in the African context. According to Collier and Dercon (2014), the current African experience is unlikely to lead to the radical transformation of the agricultural sector, which could spur broad-based economic development. This implies that alternatives to the current model have to be sought.

In this paper we revisit the link between cereal diversity, productivity, and whether an increase in cereal diversity represents a viable means to achieve sustained productivity gains. Specifically, we focus on two questions. First, we test whether increases in crop diversity lead to productivity increases. Second, we investigate the mechanisms through which any increases may arise, such as whether these productivity effects can be explained solely by regional patterns across agroecological zones, or by the choice of a specific additional and high yielding crop, which would indicate a composition effect, rather than an effect of the pure diversity.

In order to address these questions, we use data from the Ethiopian Rural Household Surveys (ERHS) and use a mix of parametric and semiparametric methods. Addressing this question in the context of Ethiopia using panel data is relevant since (1) agriculture has been selected to be an engine of socioeconomic transformation (World Bank 2007a; Di Falco *et al.* 2010); (2) much of the previous literature on crop diversity has focused on Ethiopia (Di Falco and Chavas 2009; Di Falco *et al.* 2007; Chavas and Di Falco 2012a); and (3) the use of panel data to mitigate concerns of endogeneity via the fixed effects regression surrounding results from previous work.

Overall, two main findings emerge from this paper. First, consistent with previous literature, we find a sizeable average positive effect of crop diversity using both parametric and semiparametric methods. However, unlike previous studies we notice that this overall positive effect seems to be driven by one crop and a restricted set of agroecological zones. Second, because of this, we test whether this relationship could be driven by differences in the potential yield of the cereals in the crop mix. One of the cereals, teff, is notoriously low-productivity crop (Vandercasteelen *et al.* 2013), hence diversification away from teff could be driving the crop diversity-production effect. Our results show that, when teff producers are excluded, the effects of crop diversity on production become noticeably smaller and insignificant at the 5 per cent level in all parametric results. A similar conclusion is drawn from the semiparametric results, which provide a more flexible estimate of the relationship between crop-diversity and production, and clearly illustrate the impact of diversifying from solely producing teff.

Overall, these results suggest that the positive diversity–productivity link is not a clear-cut as previously suggested in the literature. In particular, the scope for production gains from higher levels of crop diversity may be lower than previously thought. Furthermore, our results also indicate that a compositional effect, rather than the traditional ‘complementarity’ and ‘facilitation’ effects often found in the ecological literature, could partly explain the positive relationship found in previous studies. Indeed, similar results have also been found in more ecological studies of the biodiversity–ecosystem function relationships, where clear distinctions are made between the effects of diversity itself and the *functional composition* of the community of species (Jochum *et al.* 2020, p1498). Taken together, the results question the potential of increasing cereal diversity as a means to increase cereal productivity, without first considering the composition of any recommended change.

The rest of this paper is structured as follows. The next section provides a brief overview of the literature on-farm biodiversity. Section three discusses the channels through which crop diversity may impact agricultural productivity. Section four discusses our measurement of crop diversity. Section five describes the data and the methodology used. Section six presents the results and section seven concludes.

2. Agriculture in Africa and Ethiopia

The current African experience promoting smallholder agriculture has not yet led to the productivity increases that will change African agriculture beyond recognition. According to Collier and Dercon (2014), a radical transformation of the agricultural sector is deemed crucial for successful economic development. However, this transformation will have to occur in a very challenging environment defined by rapid demographic pressures as well as the looming threat of climate change. According to the UN world population prospects 2015, over half of the global population increase will occur in Africa. This, allied to potentially large losses arising from climate change (Schlenker and Lobell 2010; Müller *et al.* 2011) will make for a very challenging setting in which increases in productivity will need to happen.

In Ethiopia, the importance of the Agricultural sector for its economic development is well recognized. As explained by Dercon and Zeitlin (2009), since the early 1990s, the Ethiopian Government's growth strategy made the agricultural sector a pillar of its national development strategy under the agricultural development-led industrialization (ADLI). This policy focused primarily on smallholders and, according to Rahmato (2008), sought to increase crop production through the provision and distribution of a number of modern inputs (including seeds and fertilizer) and training.

As a result, our sample period (1994–2009) was characterized by a rapid expansion in cereal area cultivated and strong growth in terms of agricultural output (World Bank 2015). However, the growth in cereal yields was more modest, partly due to land degradation and weather variability, which were found to have nonnegligible effects (World Bank 2007a,b). Since 2008, however, national-level data shows a significant increase in cereal yields from 1.45 tonnes/ha in 2008 to 2.33 tonnes/ha in 2014.

Recently, while the importance of agriculture in the economy has decreased, it remains a vital sector. In 2013, agriculture still accounted for about three quarters of total employment (73 per cent) and 41 per cent of GDP (World Bank 2015). Looking forward, one key debate relates to whether production systems should be geared toward input-intensification or whether systems that are more diverse should be promoted (higher 'Agro-intensification'). This debate hinges directly on the link between increased crop diversity and production.

3. Crop diversity and productivity

In recent years, there has been an increase in the number of studies that have looked at the link between various forms of biodiversity, including cereal diversity, and agricultural outcomes. In general, there are a number of channels for why increased crop diversity may be beneficial for agriculture and development.

From an ecological perspective, higher levels of on-farm crop diversity potentially represent an effective way of conserving plant genetic resources (Di Falco 2012). However, there are also a number of channels through which it may directly affect crop production directly. The first such channel is through a sampling effect: the higher the species richness (i.e. higher number of species), the larger the probability that the key species with the highest effects on the performance are present in the ecosystem (Tilman *et al.* 2005; Di Falco 2012).

A second channel, as explained in Hooper *et al.* (2005) relates to a potential complementarity between crops. Different species use different resources at different times. Therefore, where resources are a limiting factor to growth and productivity combining species with different patterns of resource use may lead to a more efficient use of limited resources. A third channel relates to a facilitation effect. This effect refers to positive interactions between species. An example of this effect can be found if, for example, one species is capable of providing a critical resource for other species or alleviate harsh environmental conditions (Hooper *et al.* 2005; Di Falco 2012). According to Hooper *et al.* (2005), the complementarity and facilitation effects are two of the main reasons leading to overyielding (i.e. yields from a mixture of crops exceeding those of monoculture).

From an economic perspective, there are also a number of reasons why higher levels of agrobiodiversity may be desirable. As argued by Baumgärtner (2007), biodiversity has the potential to act as a natural insurance for risk-averse farmers, thus potentially being a substitute for financial insurance (Baumgärtner 2007; Quaas and Baumgärtner 2008). Moreover, as argued by Di Falco (2012), it allows farmers to produce and market their crops multiple times a year. This has the potential to hedge farmers against crop-price volatility, as well as provide a smoother inflow of income.

Studies of biodiversity and ecosystem function (e.g. biomass production of natural grasslands) suggest that the relationship between biodiversity as measured by species richness, species unevenness, (e.g. Shannon index) or phylogenetic diversity, is context dependent and can be positive, negative, or neutral (Jochum *et al.* 2020; van der Plas 2019)[1]. There is some evidence that including areas of high noncrop plant diversity within arable farmland can increase the productivity of certain monocrops via processes like pollination (Carvalheiro *et al.* 2011). Yet, in the specific context of crop diversity, empirical evidence supporting increased crop diversity as a key source of productivity typically comes from studies performed in an experimental setting. While in certain circumstances, experimental results on the role of biodiversity appear to be generalisable to the real-world settings of natural assemblages and communities (see e.g. Jochum *et al.* 2020), this may not always be the case. Where crops are concerned, experimental results need not translate to nonexperimental settings where natural conditions and the choices of individual farmers are likely to differ substantially (See also Sandau *et al.* 2019; Eisenhauer *et al.*, 2016). Consequently, the importance of crop diversity for productivity in agriculture is typically studied in nonexperimental settings, which have real-world policy relevance. Nevertheless, the overarching results of nonexperimental analyses seems to broadly corroborate the overall findings from the agroecology literature. The vast majority of studies focusing at the household level tend to find nonnegligible economic or production gains from more diverse cropping systems, both in the form of increased mean yields and reduced output volatility[2].

Evidence from Asia (Smale *et al.* 1998; Smale *et al.* 2008) as well as Europe (Di Falco and Chavas 2006; Di Falco and Perrings 2003; Di Falco and Perrings 2005) all seem to suggest that higher levels of crop diversity are generally correlated with higher yields and lower variance in yields and/or reduced probability of crop failure. An additional study by Omer *et al.* (2007), which uses a stochastic frontier model approach, finds that higher levels of biodiversity are associated with a higher frontier and reduced inefficiency in the case of the UK.

In Africa, Ethiopia has probably been the most studied country and most of the research has focused on the Highlands of Ethiopia. In Tigray, Di Falco and Chavas (2009); Di Falco *et al.* (2007); Chavas and Di Falco (2012a) all find that, on average, higher levels of crop diversity have a net positive effect on productivity. However, Chavas and Di Falco (2012a) highlight that there may be different sources of value for diversity. In particular, they find a positive complementarity effect (positive synergies between crops) and a negative convexity effect (scale effect). The latter provides an incentive to specialize. However, overall, the authors still find a positive value of crop diversity. In the Amhara region, Di Falco *et al.* (2010); Chavas and Di Falco (2012b), and BangwayoSkeete *et al.* (2012) all find a positive effect of crop diversity on mean yield. In addition to this, Di Falco *et al.* (2010) also find that this effect tends to be stronger when rainfall is lower.

In sum, most studies seem to suggest a positive effect of greater crop diversity on production, productivity, and reduced variability. Moreover, the estimated effects also tend to be large, with Chavas and Di Falco 2012b), for example, finding an estimated effect of crop diversification amounting to approximately 17 per cent of revenue for an average farm.

However, despite recent empirical evidence, a number of gaps remain in this literature. First, the majority of the literature focusing on Ethiopia has focused on the Ethiopian Highlands. As a result, findings may not be transposable to other areas of Ethiopia. Since the Ethiopian Highlands tend to be quite moisture strained, it may be the case that this reduces the effectiveness of other inputs,[3] thus favouring increasing crop diversity as an alternative. As a result, whether crop diversity yields similar gains across agroecological settings is still an open question. Second, previous research studying the cereal diversity–productivity link in agricultural economics does not convincingly answer why a positive relationship exists. Beyond the marginal effects, authors have not questioned which underlying channel was likely to explain this link. This is not a trivial question since policy implications will differ depending on whether the result is driven by one specific crop (a sampling effect) or whether it is driven by interactions between cereals (complementarity and facilitation effects). Previous research does not even address the possibility that results could be driven by the inclusion of particular high- or low-performing crop/subspecies of a crop. Our empirical specification, explained in Section 5, addresses some of these concerns.

4. Defining cereal diversity

Quantifying diversity is complicated and, so far, no universal definition has been agreed upon. A number of different definitions have been proposed (Baumgärtner 2006) but different definitions are used in different contexts, not least because different professions value biodiversity for different reasons (see Baumgärtner (2006) for a review of the debate). For our purpose, the most common indices used include a simple count measure (as used in Di Falco *et al.* 2010), the Simpson index and the Shannon index (used by Di Falco and Chavas (2008)). In this paper, we opt for the use of the Shannon index of cereal diversity for three reasons.

First, as argued by Di Falco and Chavas (2008), it is possible that a simple index of species richness, which fails to control for evenness, will lead to a sampling effect whereby the diversity index may capture the performance of a single species (crop in our case), rather than the effect of diversity. However, since the Shannon index controls for both richness and evenness, this problem becomes less severe. Second, the Shannon index is likely to be more suitable than the Simpson index in this context, as it has been found in the literature that the Simpson index could be biased toward the dominant species (Magurran 1988; Di Falco and Chavas 2008). Finally, it is important to mention that other measures could have been used to construct an index of cereal diversity. For instance, the index proposed by Weitzman (1992), a measure of genetic distance, would probably be suitable in our context. However, the data required for the construction of such an index is simply not available in this dataset.

Nevertheless, there are three limitations of the Shannon index in our application. First, while we observe different cereals, we do not observe different subspecies of the same crop[4]. This was shown to be important in Di Falco and Chavas (2008) and it is an issue we are not able to address, given our data. A second limitation is that our Shannon index is built at the household level. As a result, it is possible that, in some cases, a nonnegative Shannon index captures two monocultures in separate plots.[5] Finally, a third limitation is that we look at the Shannon index for cereals only. This has certainly been the most common type of crop diversity explored in the agricultural economics literature. However, measuring other types of crop diversity could lead to different effects on crop production. The following sections explain our empirical approach and how it attempts to ameliorate some of these concerns.

With these caveats noted, we build on previous work in this area, which also typically used household rather than plot-level data to study the impact of diversity on production using the Shannon index. We calculate the cereal Shannon index as follows:

$$SI = -\sum_{i} p_i * \log(p_i) \tag{1}$$

Where p_i represents the proportion (of cereal area) allocated to cereal crop i. Given that we include six cereals in the analysis, the Shannon index in our study has a theoretical range between 0–1.86.[6] The Shannon index is a special case of a more general family of diversity measures represented by $v_a = (\sum_i p_i^2)^{\frac{1}{1-\alpha}}$, where a larger value of α represents a larger penalty on the diversity measure due to unevenness in the relative abundance of each species i. For the Shannon index $\alpha = 1$, leading to Equation 1. To test the robustness of our results to the choice of diversity measure, we also undertake the analysis under the assumption that $\alpha = 2$, which has a larger penalty for unevenness and is known as the Simpson index.[7]

5. Data and methodology

5.1 Data

The dataset used is the ERHS (ERHS 2011)[8] and all waves since 1994 are used. The 1994 wave is composed of 1,470 households from 18 different peasant associations (15 different villages), spread over four regions. The location, characteristics and the agroecological zone breakdown of these peasant associations can be found in Figs A1 and A2 and Table A1 of the Online Appendix A, respectively.[9] However, it is important to mention that this sample is not nationally representative (Dercon and Hoddinott 2004).

As mentioned in Dercon and Hoddinott (2004), attrition between 1994–2004 is estimated at 13 per cent. In addition, only observations that cultivate cereals in at least two consecutive periods were used in our sample. This choice was driven by the needs of the semiparametric model.

As a result, the sample in this paper consists of 1,280 individuals (5,806 observations), for which a table of summary statistics (Table 1) is presented below.

Table 1 highlights stark differences in terms of the use of inputs across different agroecological zones. Overall, farmers in the Central Highlands and in the Arusi/Bale (‘Other’) agroecological zones allocate higher proportions of land to cereals, use more fertilizer, have higher average levels of cereal diversity, and display the highest yields compared to the average household in the Northern Highlands or in the enset agroecological zones.

Our choice of dependent variable in this study reflects our desire to investigate the drivers of the crop diversity—productivity relationship found in the previous literature in agricultural and environmental economics. We use total production of cereals as the dependent variable following Di Falco and Chavas (2008, 2009), Di Falco *et al.* (2010), and Omer *et al.* (2007). Total production of cereals sums the production (in kilograms) of each cultivated cereal. The explanatory variables included consist of cereal area (measured in ha), number of oxen, household size (to proxy for labour), the quantity of fertilizer,[10] the number of hoes, and ploughs. In addition to this, the crop diversity variable, the cereal Shannon index, is included. A detailed explanation of how these variables were constructed is available in Online Appendix C.

Table 1. Summary statistics

	All		N. Highlands		C. Highlands		Other		Enset	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Cereal production (kg)	810.12	988.32	343.69	414.28	1073.79	946.29	1260.72	1300.63	256.18	385.94
Cereal yield (kg/ha)	806.22	753.13	518.14	518.58	922.89	766.19	972.23	799.23	714.35	795.18
Cereal area (ha)	1.20	1.09	0.87	0.95	1.43	1.01	1.64	1.25	0.53	0.65
Shannon index	0.49	0.41	0.45	0.43	0.50	0.34	0.77	0.37	0.13	0.26
Number of oxen	0.87	1.10	0.64	0.83	1.20	1.13	0.95	1.28	0.41	0.84
Household size	6.02	2.72	5.21	2.39	5.84	2.65	6.30	2.58	7.04	3.04
Quantity fertilizer (kg)	51.12	86.78	2.90	10.99	76.32	84.90	82.94	120.68	18.88	31.88
Number of ploughs (units)	1.78	2.98	1.76	3.05	2.31	3.32	1.66	2.99	0.94	1.69
Number of hoes (units)	1.12	1.59	0.82	1.40	1.41	1.80	1.07	1.56	1.00	1.30
Tigray	0.13	0.33	0.56	0.50	0.00	0.00	0.00	0.00	0.00	0.00
Amhara	0.37	0.48	0.44	0.50	0.78	0.42	0.00	0.00	0.00	0.00
Oromia	0.33	0.47	0.00	0.00	0.22	0.42	1.00	0.00	0.00	0.00
SSN	0.18	0.38	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Northern Highlands	0.23	0.42	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Central Highlands	0.34	0.48	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Other	0.25	0.43	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
Enset	0.18	0.38	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Number of observations	5,806	1,324	2,003	1,456	1,023					

5.2 Methodology

5.2.1 Fixed effects model

Our analysis of the productive effects of crop diversity is concerned with agricultural productivity and the role of crop diversity. We use a flexible translog functional form for the production function, which includes the natural logarithm of land, labour, fertilizer, oxen, hoes, their squares, and their interactions. In order to capture local level trends in output as well as aspects such as weather shocks which are common to households in a given peasant association, we also include a dummy variable for each peasant–association–year.[11] We prefer to include peasant–association–year dummy variables rather than a time trend since we do not want to impose a specific linear time trend at the peasant–association level.

Identification comes from a fixed effects model, which accounts for potential endogeneity running through unobserved heterogeneity at the household level by using within-household variation over time in all variables to identify the impact of crop diversity on production. The estimated regression equation is as follows:

$$\ln(y_{it}) = \alpha_i + \sum_{n=1}^{n=N} \beta_k \ln(x_{nit}) + 0.5 \sum_{n=1}^{n=N} \sum_{n=1}^{n=N} \beta_{nm} \ln x_{nit} * lnx_{mit} + \sum_{t=1}^{t=T} \sum_{p=1}^{p=P} d_t * d_p + e_{it} \quad (2)$$

Equation 2 can be interpreted in four parts. First, α_i captures household-specific, time-invariant features. Importantly, household-level fixed effects and the use of within-household variation that this implies mean that the variation in the Shannon index captures changes over time for each household, rather than structural differences in crop diversity between households, such as intercropping versus cultivation separate plots, or even different levels of household risk aversion. This is a partial, yet by no means complete, remedy to the issues raised above concerning plot versus household level data.[12] The second part refers to the inclusion of the natural logarithms of all the explanatory variables, their squares and their interactions. The third part of this equation refers to the year–peasant–association dummy variables ($d_t * d_p$), which absorbs common shocks at the peasant–association level for different years.[13] Finally, the last component is the error term, e_{it}. We note that a number of our variables (oxen, fertilizer) have a large proportion of zero values. This has been shown to potentially lead to biased estimates of the marginal effects if not dealt with properly (Battese 1997). In our case, however, the correction proposed by Battese (1997) would conflict with the fixed effects, as many of the input-use dummies are time invariant. Nevertheless, we show (in Online Appendix A) that using the Battese correction does not alter the main conclusions of the paper, though the magnitudes become different. We also explain the Battese correction, its rationale, and how it is implemented in practice in Online Appendix C.

5.3 Semiparametric estimator

In addition to the parametric results, since there is little theoretical guidance on the likely shape of the relationship between cereal diversity and production, we also conduct a series of semiparametric regressions. This specification allows for greater flexibility in the relationship, since it makes it easier to investigate a possible nonlinear effect of crop diversity on production. The basic cross section model proposed by Robinson (1988) can be summarized using the following equation:

$$\ln(y_{it}) = \boldsymbol{\beta}_x \mathbf{X}_{it} + f\left(sh_{it}\right) + e_{it} \quad (3)$$

Where **X** is a set of explanatory variables which includes all inputs except the Shannon index. For the parametric component of the model, we use the two sets of variables detailed in the previous section, but exclude the Shannon index. The latter is captured in the component $f(sh_{it})$, which represents the nonparametric smooth function of the Shannon index, which we believe may be nonlinear.

This model has subsequently been extended to include fixed effects in a panel data setting (Baltagi and Li 2002). The Baltagi and Li (2002) model differs from the original model by taking the first differences of Equation (3). We implement this procedure using the *xtsemipar* command in STATA 14 (Libois and Verardi 2012). For all sets of results, we use a kernel regression with the rule-of-thumb bandwidth. In all cases, we use a degree 4 local weighted polynomial fit using the Epanechnikov kernel.[14]

5.4 Limitations of the empirical approach

The first and most important limitation of our approach, as with other papers in this literature, relates to the issue of the endogeneity. Given that the choice of the level of cereal diversity is likely to be endogenous and that we were unable to find a suitable instrument, we are not able to claim the estimation of a causal relationship between cereal diversity and production. However, our empirical specification is more stringent than the norm in similar studies, thereby potentially attenuating concerns related to endogeneity. Specifically, we take two steps that make for a more convincing approach to the estimation of this relationship than what has traditionally been the case in the literature. First, we use panel data and, as a result, this allows us to control for household fixed effects, which are likely to control for household-specific, time-invariant characteristics. Second, all of our specifications use peasant–association–year fixed effects, which are likely to control for common, time-varying unobservable heterogeneity at the peasant–association level.

A second limitation relates to the narrow focus on the effect of cereal diversity on cereal production. While estimating the impacts on production has been the most common approach in agricultural economics to date, the approach could neglect other important aspects of crop diversity choice. For instance, Baumgärtner and Quaas (2009) discuss the impact of crop diversity on revenues, rather than profits. Furthermore, we focus only on the productive implications of the diversity of systems of cereal production. We do not discuss the relationship between crop diversity and other production or environmental variables, such as volatility or erosion, which, although controlled for in our empirical approach, may also be important in their own right. Finally, it is also possible that other types of diversity, such as mixing a cereal with a legume, for instance, or the proximity of areas containing noncrop biodiversity (e.g. Massaloux *et al.* 2020), may have a very different effects on production. These aspects of the biodiversity–productivity relationship are important but are not the focus of our study. Our focus on production allows us to point to potential oversights in the previous literature, and highlight not just the importance of crop diversity, but also the composition of this diversity. In broader welfare terms, the focus on production can also be motivated by the low level of market engagement in the population in question, meaning that the pure production effects we analyse are potentially more relevant to the livelihoods of the population sampled.[15]

6. Results

6.1. Parametric results

The full set of estimates from the translog production function are shown in Table A2 in Appendix A. Table 2 shows that coefficients of the estimated production functions have the expected signs for all inputs, illustrating the importance of inputs like land, draft power (oxen), and fertilizer, and how these effects vary across agroecological zones. Focusing in on the impact of crop diversity in this production function, Table 2 assembles all of the coefficients related to the Shannon index, from which a number of observations can be

Table 2. Main results: Parametric translog

	All	N. Highlands	C. Highlands	Other	Enset
Shannon index	0.047	0.03	0.024	0.122	0.021
	(0.029)	(0.054)	(0.046)	(0.077)	(0.066)
Shannon index (square)	0.006	0.005	0.003	0.015	0
	(0.004)	(0.007)	(0.006)	(0.010)	(0.008)
Area*Shannon index	−0.006**	−0.008	−0.005	0.008	−0.015**
	(0.003)	(0.005)	(0.004)	(0.008)	(0.007)
Household size*Shannon index	0.003	0.007	0.001	−0.007	−0.008
	(0.004)	(0.007)	(0.006)	(0.011)	(0.011)
Oxen*Shannon index	0.000	0.000	0.000	−0.001	0.000
	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)
Fertilizer*Shannon index	0.000	0.000	0.000	0.001	−0.001
	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)
Hoes*Shannon index	0.000	0.001***	0.000	0.000	−0.002**
	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)
Ploughs*Shannon index	0.000	−0.001*	0.000	−0.001	0.002***
	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)
Constant	6.335***	4.991***	6.449***	5.929***	5.577***
	(0.110)	(0.355)	(0.167)	(0.234)	(0.404)
Elasticity of Shannon index	0.022**	0.012	0.013	0.098*	0.022
p-value	0.013	0.159	0.566	0.075	0.500
Fixed effects	✓	✓	✓	✓	✓
Village-year fixed effects	✓	✓	✓	✓	✓
Linear variables	✓	✓	✓	✓	✓
Squares	✓	✓	✓	✓	✓
Interactions	✓	✓	✓	✓	✓
Number of households	1,281	289	429	299	264
Number of observations	5,804	1,323	2,003	1,456	1,023
Average obs. per household	4.531	4.578	4.669	4.87	3.875
R-squared a	0.546	0.658	0.556	0.509	0.453
R-squared w	0.555	0.671	0.571	0.526	0.481

Notes: N. Highlands refers to Northern Highlands. C. Highlands refers to Central Highlands. Numbers in parentheses represent clustered standard errors at the household level. The specification in the regression is a translog specification and the full list of coefficients can be seen in Table A2 in the Online Appendix. As explained in the methodology section, this specification does not include the adjustment proposed by Battese since many of these dummies are time invariant, which would be incompatible with the fixed effects. Instead, 0 values are assigned the value of 0.000001. *, **, *** denote statistical significance at the 10%, 5% and 1% level, respectively.

made. First, the estimated coefficients associated with the Shannon index differ substantially from one agroecological zone to another. Concerning the overall productive effect of cereal diversity on production, similar to previous results in the literature, we find a positive and statistically significant effect between cereal diversity and cereal production for the full sample (column 1, Table 2). However, running the regressions separately by agroecological zone reveals stark differences. Although we find a positive elasticity in every agroecological zone (columns 2–5, Table 2), this elasticity is only large and statistically significant in the 'Other' agroecological zones (Arusi/Bale). Additional heterogeneity of the effect of cereal diversity on production can be seen in some of the interaction effects. One that consistently appears with a negative sign, and is sometimes statistically significant, is the interaction with land size. This suggests that the returns to a more diverse system may be higher in smaller land holdings, with more intensive use of modern inputs and/or mechanization becoming the main driver of productivity increases in larger land holdings.

Turning back to the heterogeneity by agroecological zone, an interesting finding is that the ordering of the magnitude mirrors closely the proportion of households who cultivate teff, known to be a lower-productivity crop.[16] In other words, the two agroecological zones displaying higher coefficients are also the agroecological zones where teff is most prevalent.

Table 3. Main results: Parametric translog (teff only)

	All	N. Highlands	C. Highlands	Other	Enset
Shannon index	0.184***	0.129	0.061	0.303***	0.215*
	(0.047)	(0.086)	(0.067)	(0.076)	(0.128)
Shannon index (square)	0.023***	0.029**	0.006	0.036***	0.015
	(0.006)	(0.012)	(0.009)	(0.010)	(0.017)
Area*Shannon index	−0.019***	−0.035***	−0.018**	−0.006	−0.021**
	(0.005)	(0.012)	(0.009)	(0.017)	(0.009)
Household size*Shannon index	−0.001	0.028	−0.005	−0.018	−0.043***
	(0.006)	(0.018)	(0.011)	(0.015)	(0.016)
Oxen*Shannon index	0.000	−0.001	0.000	0.001	0.001
	(0.000)	(0.002)	(0.001)	(0.001)	(0.001)
Fertilizer*Shannon index	0.000	−0.002	0.000	0.000	−0.001
	(0.000)	(0.002)	(0.001)	(0.001)	(0.001)
Hoes*Shannon index	0.001	0.002	0.002**	0.002*	−0.002
	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)
Ploughs*Shannon index	0.001**	−0.002	0.001	−0.003**	0.004***
	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)
Constant	6.347***	5.472***	6.791***	5.747***	5.801***
	(0.146)	(0.558)	(0.338)	(0.230)	(0.575)
Elasticity of Shannon index	0.105***	0.154**	0.024	0.235***	0.001
p-value	0.000	0.019	0.607	0.000	0.981
Fixed effects	√	√	√	√	√
Village-year fixed effects	√	√	√	√	√
Linear variables	√	√	√	√	√
Squares	√	√	√	√	√
Interactions	√	√	√	√	√
Number of households	782	152	217	211	202
Number of observations	2,799	544	679	960	616
Average obs. per household	3.579	3.579	3.129	4.55	3.05
R-squared a	0.511	0.358	0.557	0.597	0.535
R-squared w	0.526	0.412	0.59	0.616	0.573

Notes: N. Highlands refers to Northern Highlands. C. Highlands refers to Central Highlands. Numbers in parentheses represent clustered standard errors at the household level. The specification in the regression is a translog specification and the full list of coefficients can be seen in Table A3 in the Online Appendix. As explained in the methodology section, this specification does not include the adjustment proposed by Battese since many of these dummies are time invariant, which would be incompatible with the fixed effects. Instead, 0 values are assigned the value of 0.000001. *, **, *** denote statistical significance at the 10%, 5% and 1% level, respectively.

For this reason, we test whether the effect we capture could be attributed to the cultivation of teff and separate the sample into households that cultivate teff and those who do not. The results can be seen in Tables 3 and 4.[17] Overall, the results in Table 3, which only include households who cultivate teff, seem to suggest a positive significant elasticity of cereal diversity in two out of four agroecological zones. However, once households that cultivate teff are removed, none of the elasticities are statistically significant at the 5 per cent level, though in one case the coefficient increases. These results do not prove beyond doubt that the full effect is attributable to a compositional effect. For one, sample sizes decrease substantially in a number of agroecological zones, which makes it harder to ascertain statistical significance. Nevertheless, these results are indicative that, perhaps, a compositional effect, whereby crops (or subspecies of specific crops) with different productive potential are mixed, could be part of the explanation behind the result found in the crop diversity literature. Perhaps, what is being captured in these results is that, as cereal diversity increases, the relative contribution of the low-productivity cereal gradually fades, thereby leading to higher levels of production and productivity.

Table 4. Main results: Parametric translog (no teff)

	All	N. Highlands	C. Highlands	Other	Enset
Shannon index	−0.004	−0.088	0.098	−0.079	0.04
	(0.051)	(0.070)	(0.080)	(0.148)	(0.129)
Shannon index (square)	−0.002	−0.013	0.012	−0.022	−0.003
	(0.007)	(0.009)	(0.011)	(0.021)	(0.015)
Area*Shannon index	−0.002	0.004	−0.001	0.014	−0.013
	(0.004)	(0.009)	(0.005)	(0.010)	(0.016)
Household size*Shannon index	−0.001	0.004	−0.004	−0.035**	−0.023
	(0.005)	(0.009)	(0.008)	(0.016)	(0.036)
Oxen*Shannon index	0.000	0.000	0.000	−0.001	0.000
	(0.000)	(0.001)	(0.001)	(0.001)	(0.002)
Fertilizer*Shannon index	0.000	0.000	−0.001	0.001	0.002
	(0.000)	(0.001)	(0.000)	(0.001)	(0.002)
Hoes*Shannon index	0.000	0.001	−0.001	0.000	0.000
	(0.000)	(0.001)	(0.001)	(0.001)	(0.002)
Ploughs*Shannon index	0.000	0.000	0.000	0.000	0.003
	(0.000)	(0.001)	(0.001)	(0.001)	(0.003)
Constant	6.324***	5.039***	6.357***	6.300***	6.501***
	(0.174)	(0.541)	(0.214)	(0.698)	(1.303)
Elasticity of Shannon index	0.007*	0.0354*	0.038	−0.0689	0.011
p-value	0.090	0.066	0.229	0.369	0.897
Fixed effects	✓	✓	✓	✓	✓
Village-year fixed effects	✓	✓	✓	✓	✓
Linear variables	✓	✓	✓	✓	✓
Squares	✓	✓	✓	✓	✓
Interactions	✓	✓	✓	✓	✓
Number of households	894	211	345	128	210
Number of observations	3,006	779	1,324	496	407
Average obs. per household	3.362	3.692	3.838	3.875	1.938
R-squared a	0.593	0.752	0.564	0.332	0.486
R-squared w	0.607	0.768	0.584	0.394	0.548

Notes: N. Highlands refers to Northern Highlands. C. Highlands refers to Central Highlands. Numbers in parentheses represent clustered standard errors at the household level. The specification in the regression is a translog specification and the full list of coefficients can be seen in Table A4 in the Online Appendix. As explained in the methodology section, this specification does not include the adjustment proposed by Battese since many of these dummies are time invariant, which would be incompatible with the fixed effects. Instead, 0 values are assigned the value of 0.000001. *, **, *** denote statistical significance at the 10%, 5% and 1% level, respectively.

We also carry out four sets of robustness checks, which are available in Online Appendix B. Tables B1–B6 summarize the results when the regression is estimated by OLS and the Battese (1997) correction is applied. Tables B8–B13 show the results when we only consider households for which there is no imputed data for fertilizer, ploughs, and hoes. Tables B15–B20 summarize the results when only the households for which we have six observations are considered (i.e. a balanced panel).[18] We also test the robustness of the results to an alternative functional form (quadratic), as shown in Tables B22–B26. Finally, the robustness of the results to an alternative diversity measure (the Simpson index) was tested and these results are shown in Tables B27–B32. Though the magnitudes of the coefficients certainly differ, the overarching conclusions remain the same in all three robustness checks. Beyond the effects on productivity, we also tested for potential effects on the variance of production, following the method proposed by Just and Pope (1979). As shown in Table B33, an insignificant result was found in all agroecological zones, implying management of production risk was unlikely to be an outcome of crop diversity after controlling for inputs, household-level fixed effects, and peasant–association trends.

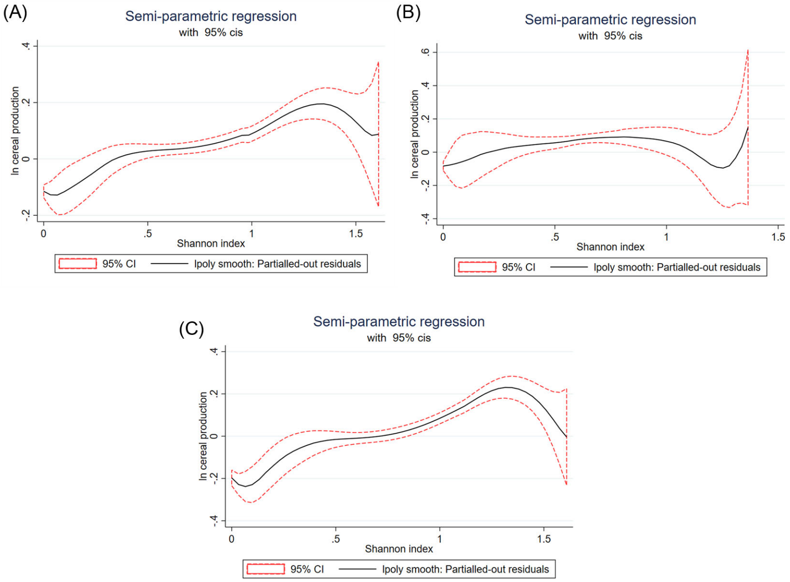

Figure 1. Effect of Shannon index—Semiparametric full sample. (A) Full sample. (B) Non-teff-producing households. (C) Teff-producing households.

6.2. Semiparametric results

Given that there is no proven underlying theory informing the expected shape and magnitude of the production–diversity relationship, the statistically insignificant results displayed in the previous section may be masking a nonlinear relationship. In other words, it is possible that the insignificant results in parametric models are a result of not taking into account nonlinearities in an appropriate way. Alternatively, it could be that there may be a positive effect of crop diversity, but that this effect is confined to a subset of diversity values. Additionally, it is possible that, while a stark relationship exists in a number of subsamples, the statistical significance may be hampered by the small sample sizes of the subsamples. It is for these reasons that we also run a set of semiparametric regressions, which allow for a more flexible characterization of the relationship between crop diversity and production, and tend to be less sensitive to sample size.

The parametric part of the results are summarized in Tables A5–A9 and the smooth functions of the crop diversity result in the partialled-out residuals are available in Figs 1–5.[19] For each figure, corresponding to a given geographical region, we have three subfigures. Subfigure (a) summarizes the results when all the households in a given region are included, subfigure (b) summarizes the results when teff producers are excluded, and subfigure (c) shows the results when only teff producers are included.

The semiparametric results, to a certain extent, confirm the findings of the parametric results. We find a clear positive correlation between the Shannon index for panel (a) of the full sample (Fig. 1) and in the Arusi/Bale/Hararghe agroecological zones (Fig. 4), with the Northern Highlands (Fig. 2) also displaying a positive but noisy relationship. Also similar to our findings from the parametric models, these results appear to be largely driven by the inclusion of teff producers, with none of the panels (b) displaying a large, clear, and positive relationship, though panel (b) of Fig. 4 seems to suggest a somewhat positive relationship.[20] Conversely, most panels (c), with the exception of panel (c) in Fig. 3, suggest a positive relationship, suggesting that the inclusion of teff producers seems to

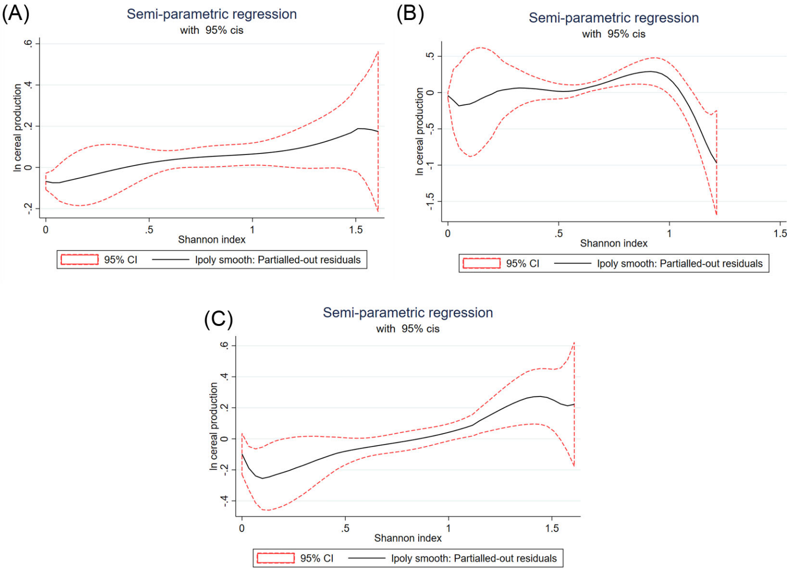

Figure 2. Effect of Shannon index—Semiparametric Northern Highlands. (A) Full sample. (B) Non-teff-producing households. (C) Teff-producing households.

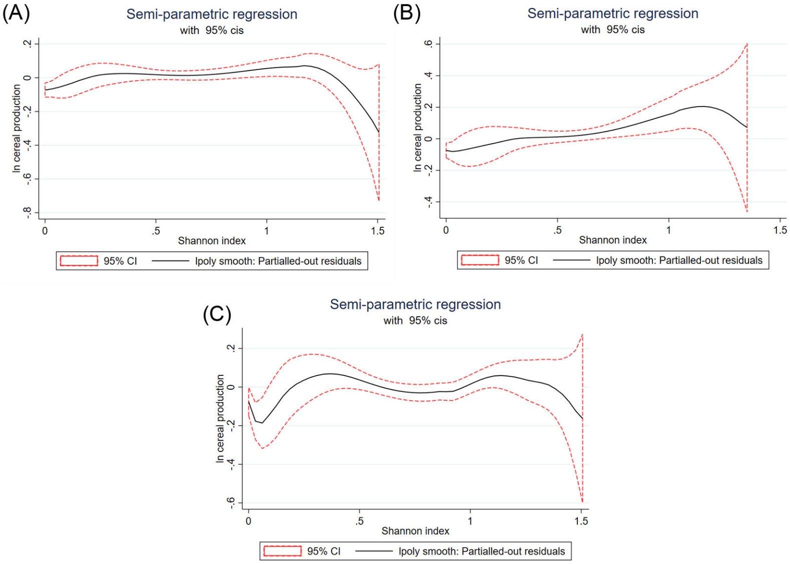

Figure 3. Effect of Shannon index—Semiparametric Central Highlands. (A) Full sample. (B) Non-teff-producing households. (C) Teff-producing households.

drive our results. This provides some support for the existence of a potential compositional effect.

However, the semiparametric results also shed some light on additional aspects of this relationship. First, when we find a clear positive relationship, we tend to also find a large, statistically significant negative intercept of the estimated function. For the

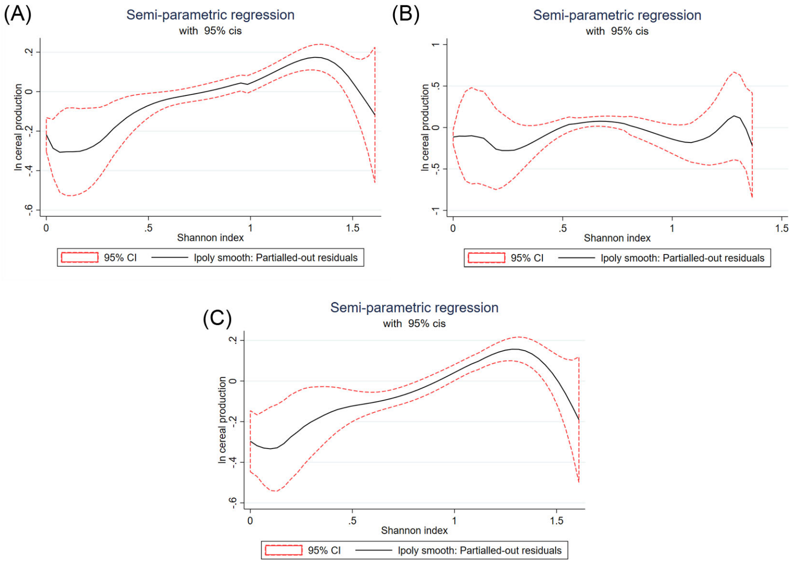

Figure 4. Effect of Shannon index—Semiparametric Arussi/Bale. (A) Full sample. (B) Non-teff-producing households. (C) Teff-producing households.

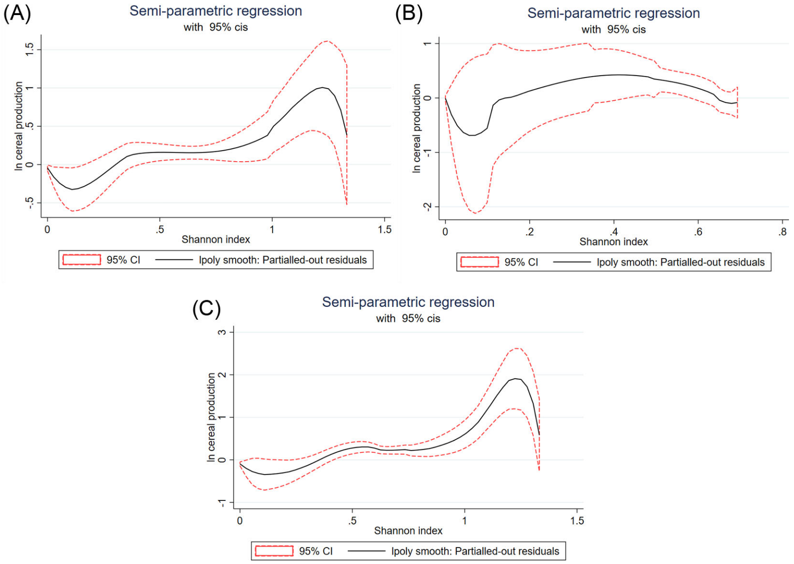

Figure 5. Effect of Shannon index—Semiparametric enset. (A) Full sample. (B) Non-teff-producing households. (C) Teff-producing households.

Arusi/Bale/Hararghe (‘Other’) agroecological zones, this can be explained by the large proportion of farmers cultivating teff (64 per cent of the total) and the fact that these farmers tend to cultivate teff together with crops that have higher average yields.[21] As a result, an increase in the impact of the crop diversity index could simply indicate a shift away from a low productivity cereal. A similar mechanism may be at play in the Northern Highlands for the case of Barley, which is the second lowest productivity crop in our sample.[22] Second, the semiparametric results highlight the shape of the relationship. Partly as a result of the negative intercept, in some cases (Figs 2, 3, and 5) the strongest positive relationship occurs between low to medium values of the Shannon index. We also find a sharp (but very noisy) decrease in the relationship at large levels of cereal diversity in three out of four agroecological zones (Fig. 2 being the exception). Taken together, these results suggest rather limited benefits of pursuing very diverse systems in terms of cereal production.

7. Conclusion

This paper revisited the link between cereal diversity and cereal production using a panel representative of a larger geographical area in Ethiopia than what has typically been the case. Doing this allows us to understand whether *in situ* conservation may yet deliver a promising solution in terms of conservation of plant genetic material alongside sustained productivity gains.

In some cases, our results corroborate a number of previous results in the literature. For instance, we find large positive gains of cereal diversity on cereal production for the full sample. However, unlike previous studies, we find that these effects are very heterogeneous across agroecological zones. Specifically, specific agroecological zones (Arusi/Bale/Hararghe) and one crop (teff) seem to be driving these results in both parametric and semiparametric specifications. This suggests that, at least in our case, the 'biodiversity' effect seems to be capturing a decreasing share of a low-productivity crop in the crop mix.

These results highlight the importance for practitioners in the literature to attempt to understand what is driving the results between diversity and productivity. It is important to at least consider the possibility that this effect could partly reflect different potential yields for cereals in the crop mix. As a result, increases in the diversity index could be capturing a move away or toward a particularly high- or low-performing cereal. In our case, given that we do not have data on subspecies, the results seem to be partly driven by one crop (teff). However, a similar mechanism could be at play with particular high- or low-performing subspecies of a given crop. The results are similar in nature to those recently found in the ecological literature where the importance of separating out the effects of diversity from composition were found to be important in explaining the biodiversity–ecosystem function and biomass relationships (Jochum *et al.* 2020). The development of empirical methods and/or experiments to cleanly separate these effects in the context of crop diversity and productivity remains for future work.

From a policy perspective, however, the results highlight two main points. First, while diversity, in itself, may be desirable for a number of reasons, its positive productive implications are not clear once farmers who cultivate low-yield crops are removed from the sample. As a result, it seems that increases in diversity only seem to have a positive effect in one direction (from high proportion of low-yield crop to diverse mix of low- and high-yield crops). Second, the shape revealed in the semiparametric method suggest that these effects are not linear and that, beyond a certain point, the associated gains of increased diversity seem tenuous, at best.

Taken together, these results suggest that cereal diversity is unlikely to be a panacea for cereal productivity. Lack of clear production gains from increasing cereal diversity allied to the development of alternative sources of insurance and the modernization of agriculture, which tends to lead to a reduction of cereal diversity, highlights the need to focus on alternative means of conserving crop genetic diversity.

In addition to this, our paper highlights a number of possible directions for future research. First, this paper focuses on a very narrow type of crop diversity (cereal diversity) and these results are not necessarily transposable to other types of crop diversity, for which the relationship may be very different. Second, while we believe our empirical specification improves on previous literature focusing on this question, endogeneity remains a concern. Consequently, our results do not settle this debate and we cannot and do not claim a perfect causal relationship. Further research regarding potential instruments or alternative research designs (e.g. field experiments) would be useful. A third aspect that was absent from this analysis relates to the relationship between land degradation-crop diversity. As argued by Taddese 2001, land degradation is a serious issue in Ethiopia and crop diversity may well have an important effect on land quality, which we do not capture or investigate in this paper. Finally, our analysis leaves aside the links between cereal diversity and income, nutrition as well as production, and income volatility, all of which could be valid reasons to pursue a diversification strategy, despite limited gains in output. In our specific case, while teff typically displays lower yields, it has a very high market value compared to other cereals. As a result, it could still make economic sense to cultivate teff, despite its productive implications.

Supplementary material

Supplementary data are available at *Q Open* online.

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Data availability

The data used in this paper is publicly available at: https://dataverse.harvard.edu/dataset.xhtml?persistentId=hdl:1902.1/15646.

End Notes

1. There is a rich literature investigating biodiversity–ecosystem relationships in ecological communities. For instance, in trees (van der Plas *et al.* 2016), at different scales (Gonzalez *et al.* 2020), and in agricultural landscapes (Tscharntke *et al.* 2005).
2. See, for example, Di Falco *et al.* (2010) for a review of the evidence.

Gebregziabher and Holden (2011) find that in the Tigray region, the yield response to chemical fertilizer is poor under rain-fed conditions since it is a moisture-strained environment.

4. With the exception of teff, where we observe both white and black teff.
5. However, in our data we do not have information about the location of different plots. As such, while it could be that the two monocultures are in plots very far away from each other, it could also be that they are located in plots adjacent to each other. It is not clear, therefore, whether constructing the Shannon index at the plot level would be preferable. While plot level data would be better in principle, in practice it has been shown that production and productivity measures in small areas are often unreliable (Desiere and Joliffe, 2018). Therefore, a Shannon index at the plot and subplot (e.g. field) level could introduce a bias if plot/field size is correlated with measurement error which itself drives the relationship between production and observed biodiversity. Household-level data is less prone to such relationships.
6. A household cultivating two cereals in equal proportions will have a Shannon index of 0.69. If three cereals are cultivated in equal proportions, the Shannon index will take a value of approximately 1.1.

7. See, for example, Baumgärtner 2006 for a discussion of the relative merits of different measures.
8. These data have been made available by the Economics Department, Addis Ababa University, the Centre for the Study of African Economies, University of Oxford, and the International Food Policy Research Institute. Funding for data collection was provided by the Economic and Social Research Council (ESRC), the Swedish International Development Agency (SIDA), and the United States Agency for International Development (USAID); the preparation of the public release version of these data was supported, in part, by the World Bank. AAU, CSAE, IFPRI, ESRC, SIDA, USAID, and the World Bank are not responsible for any errors in these data or for their use or interpretation.
9. The agroecological zone breakdown was adapted from Nisrane *et al.* 2011. Dercon and Hoddinott (2004) is the source for the map and site characteristics.
10. In the case of fertilizer, whenever there was data on the application of fertilizer directly on cereal, this data was used. When only the total amount of fertilizer was available, the total amount was apportioned to cereal area (i.e. we assumed that the household uses fertilizer evenly in his land).
11. That is, for each peasant association we include a dummy for each year.
12. For instance, if a farmer grows only single crops on the same plots over time, this household will not contribute to the effect that we identify.
13. Year–peasant fixed effects are likely to include aspects such as rainfall, temperature, as well as peasant–association specific trends in production over time, such as the effects of degradation or technological change.
14. We also test the sensitivity of our results to a degree one local polynomial fit.
15. Kim *et al.* (2016) note that in the 2009 wave of the ERHS only 37 per cent of farmers sold any crops to the market, and average sales were worth only 20 per cent of the total value of production.
16. Although low in terms of production, teff has other qualities such as resistence to storage pests (Fikadu *et al.* 2019; Bekkering and Tian 2019), is a reasonable cash crop if sold (Fikadu *et al.* 2019), and is strongly associated with Ethiopian culinary traditions (Injera).
17. The full set of estimates can be found in Appendix A in Tables A3 and A4.
18. Balanced subsample refers to the subsample of households for which we have observations for each period. However, the 'teff only' and 'no-teff' regression are not necessarily balanced since some households switch in and out of teff during the sample period. Also, as can be seen in Tables B21–B26, using the balanced sample leads to a sharp decrease in sample size. This is very severe in the enset area for the no-teff subsample, where there are very few observations with a Shannon index above zero. As a result, for this subsample, we do not have a high degree of confidence in the results presented.
19. Figures with scatter plots are available in the Online Appendix TablesA3–A7. Both sets of figures (1–5 and A3–A7) use a degree 4 polynomial (the default) and the rule-of-thumb bandwidth. The rule-of-thumb bandwidth is summarized in the Appendix in Table A10.
20. Panel (b) in Fig. 5 is not particularly informative as there are very few observations of non-teff producer with a nonzero Shannon index (less than 5 per cent of the values). This is made more clear in Table A7.
21. In terms of combinations in the 'Other' zone: In terms of combinations: teff-maize (25 per cent), teff–barley–wheat-maize (14.9 per cent), teff–barley–maize (14.1 per cent), teff–wheat (14.1 per cent), and teff–barley–wheat (12.9 per cent), represent the most common combinations and account for of 80 per cent of the observed crop combinations in this subsample. Wheat and maize, in particular, tend to have much higher yields than teff.
22. In the full sample of teff growers, just under a quarter of teff producers cultivate teff as a monoculture. An additional 69 per cent of the sample grow teff alongside one or two crops. Finally, 247 households (8.8 per cent) grow teff alongside three or four crops. In terms of combinations, together with teff as a monoculture (22 per cent), the teff–maize (16.0 per cent), teff–wheat (10.1 per cent), teff–sorghum (8.5 per cent), and teff–wheat–maize (7.7 per cent) jointly account for two-thirds of the observations for teff growers.

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