Putting biodiversity into context: Cereal biodiversity, production potential and technical efficiency in Ethiopia.

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Abstract

Recently, a number studies suggest that, at the micro level, cereal diversity positively affects mean yields and decreases the variability of yield. However, most analyses tend to focus on very specific sub-regions and tend to ignore the potential dynamic effects of more diverse systems. We empirically estimate a True Fixed Effects Stochastic Frontier model using data from the Ethiopian Rural Household Survey[1] and set out to investigate the static and dynamic effects of cereal diversity on the production frontier for a broader set of agro-ecological subregions in Ethiopia.

In general we find a positive, but very heterogeneous static effect of greater cereal diversity on cereal production, which seems to be specific to the agro-ecological zone in which the farming occurs. We also find some support for a convergence hypothesis with positive dynamic effects of crop diversity found only in agro-ecological zones with lower levels of initial crop diversity. These findings indicate that 1) the scope cereal diversity to drive long-term increases in output may be limited; and 2) alternative conservation solutions may be needed.

JEL classification: Q16, Q57

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1 Introduction

The effect of crop diversity on agricultural production remains somewhat of a conundrum in the Agricultural Economics literature. However, the importance of understanding this link should not be underestimated, as it speaks directly to the productivity of agricultural systems and their resilience to climate and weather. This implies that crop diversity may have an important role to play in terms of food security. But, whether increases in crop diversity represent a viable development strategy capable of delivering sustained productivity gains over time 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 and Di Falco et al. 2007). These findings, however, contrast sharply with historical trends in agricultural development, which appears 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 United States, 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 policy-makers 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 alternatives to the current model have to be sought.

Consequently, this paper looks at cereal diversity and seeks to understand whether an increase in cereal diversity represents a potential alternative. Specifically, we focus on two questions. First, we seek to understand whether increases in crop diversity can deliver sustained productivity increases over time. Second, we want to understand whether the effects of crop diversity are homogeneous or whether they fundamentally depend on context.

In this paper we argue that the relation between crop diversity and productivity is a complex one. Conceptually, we argue that crop diversity is likely to have effects on both the production frontier (maximum production achievable for a given set of inputs) and efficiency (how far a farmer is from the frontier). We further argue that these effects could be both static (average gains over all time periods) or dynamic (change over time). Static gains are likely to depend on aspects such as the level of crop diversity and interactions between crop diversity, the environment and the technology used. Dynamic gains, on the other hand, may be driven by a convergence pattern towards an optimal level of crop diversity as well as by technological changes which affect the effectiveness of inputs over time.

The implications from understanding these different effects are twofold. First, if increases in crop diversity were to provide a credible alternative to the current model, then we would expect sizeable static and dynamic gains associated with crop diversity. Second, understanding whether there are discernible patterns driving the effects of crop diversity is important in order to understand where this approach is likely to be more successful.

In order to address these questions, we estimate a fixed effects stochastic frontier model Greene (2005) we apply this model to data from the Ethiopian Rural Household Survey (ERHS). Addressing this question in the context of Ethiopia is relevant since 1) agriculture has been selected to be an engine of socio-economic transformation (World Bank (2007a), Di Falco and Bezabih (2012)); and 2) much of the previous literature on crop diversity has focused on Ethiopia (Di Falco and Chavas 2009 and Di Falco et al. 2007 and Di Falco and Chavas 2012a).

Overall, three main findings emerge from this paper. First, consistent with previous literature, we find a sizeable average positive effect of crop diversity on agricultural production and technical efficiency. However, we notice that these effects vary substantially across agro-ecological zones and are not always linear.

Second, while we find a large static effect of crop diversity on production, the magnitude and significance of the dynamic effect depends seems to be related to initial conditions. In other words, in agro-ecological zones with low levels of initial crop diversity we find a positive or insignificant dynamic effect. The opposite pattern tends to apply in agro-ecological zones with high initial levels of crop diversity. These results support, to some extent, a convergence hypothesis towards an optimal level of crop diversity.

Overall, these results suggest that increases in crop diversity are associated with production gains but that the scope for large production gains over time are limited. This is especially true in areas that already have high initial levels of average crop diversity. As a result, it is unlikely that increases in crop diversity represent a *panacea* for the future of agricultural development. In addition, low dynamic effects may make intensification and/or specialization more attractive in the long-run raising questions over whether *in situ* conservation is the more suitable strategy of conservation of plant genetic material.

The rest of this paper is structured as follows. The next section provides a brief overview of the literature on farm biodiversity. Section three introduces the theoretical model. Section four describes the data and the methodology employed. Section five presents the results and section six concludes.

2 Background

2.1 Agriculture in Africa and Ethiopia

The current African experience promoting smallholder agriculture has, so far, not led to the productivity increases that will change African Agriculture beyond recognition (Collier and Dercon 2014). According to the authors, 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 Lobbel 2010) will make for a very challenging setting in which increases in productivity will need to happen.

As a result, it could be said that the African agriculture is now at a crossroad and a number of choices will have to be made. One, the main focus of Collier and Dercon 2014, relates to a choice between policies geared towards smallholders vs. larger-scale commercial producers. A second choice, more related to this paper, concerns that of pursuing a more traditional pattern of input-intensification vs. moving towards more diverse systems (higher Agro-intensification).

In Ethiopia the importance of the Agricultural sector for its economic development is well recognized. As explained by Dercon and Zetlin (2009), since the early 1990s, the Ethiopian Governments 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 (World Bank 2015) and a strong growth in terms of agricultural output. However, the growth in cereal yields was more modest (World Bank 2007a and World Bank 2007b) and this was partly attributable to both land degradation and weather variability, which were found to have non-negligible effects.

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 there has been a decreasing trend in the importance of Agriculture in the economy. However, in 2013 agriculture still accounted for about three quarters of total employment (73%) and 41% of GDP (World Bank 2015).

As such, given the preponderance of the agricultural sector in Ethiopia, it is important to understand whether 1) cereal diversity constitute a source of sustained productivity increase over time; and 2) whether these effects are relatively homogeneous or context-specific.

2.2 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 preserving 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 the sampling effect. In essence, the sampling effects implies that, 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, combining species which have different resource patterns may allow for such a complementarity effect, which is likely to result in a more efficient use of resources over time. As a result, in cases where resources are a limiting factor to growth and productivity, increasing the richness of the ecosystem could lead to greater productivity. 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 exceed those of monoculture).

From an economic perspective, there are also a number of reasons why higher levels of agro-biodiversity 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, Baumgärtner and Quaas 2008, 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.

Nevertheless, it should be noted that most evidence for the channels which explain why crop diversity may be a key source of productivity come from studies in ecology performed in an experimental setting. Consequently, the experimental results need not translate to non-experimental settings where conditions are likely to differ substantially. This has led to the productive importance of biodiversity in agriculture being increasingly studied in non-experimental settings. The overarching results of this literature, however, seem to broadly corroborate the overall findings from the agroecology literature. The vast majority of studies focusing at the household level tend to find non-negligible economic gains from more diverse systems, both in the form of increased mean yields and reduced output volatility.

Evidence from Asia (Smale et al. 1998, Smale 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 uses a stochastic frontier model approach and find that higher levels of biodiversity are associated with 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 and Di Falco and Chavas 2012a all find that, on average, higher levels of crop diversity have a net positive effect on productivity. However, Di Falco and Chavas 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 resulting in 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, Di Falco and Chavas 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 finds 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 and Chavas 2012b, for example, finding an estimated effect of crop diversification amounting to approximately 17% of revenue for an average farm.

However, despite the empirical evidence there are a number of gaps that 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 some of these study areas 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 agro-ecologies is still an open question.

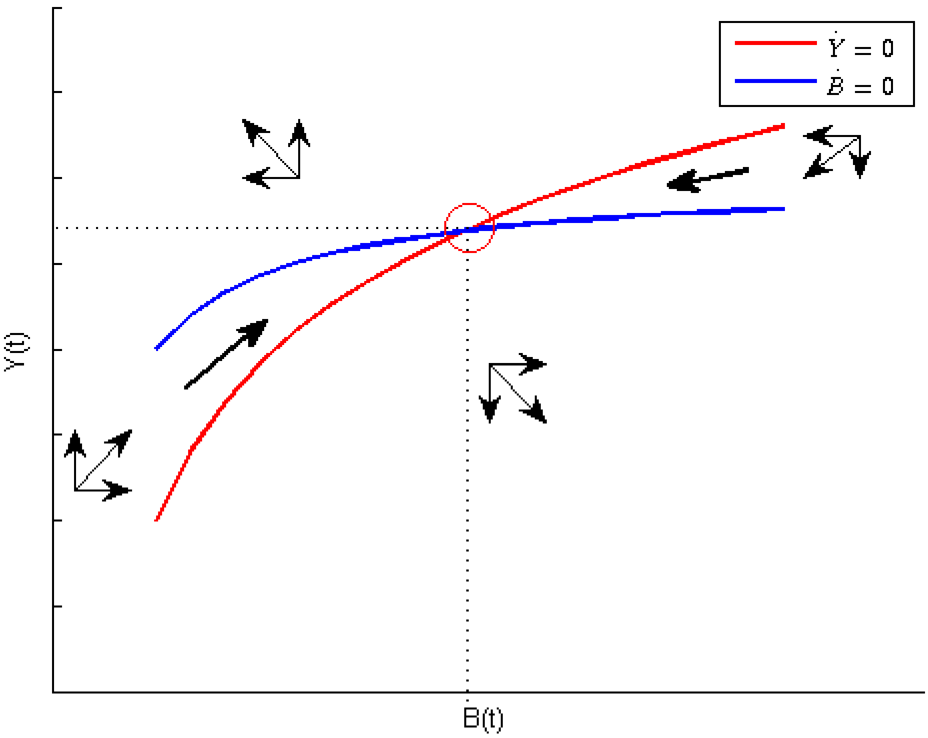
[3]Gebregziabher et al. 2012 find that in the Tigray region, the yield response to chemical fertilizer is poor under rain-fed conditions since it is a moisture-strained environment

Secondly, while studies focusing on Ethiopia seem to show that crop diversity may be associated with higher productivity, dynamic effects have not been widely studied, partly because most studies rely on cross-sectional data. This implies that estimates tend to highlight average effects over the sample period and do not look at how these effects evolve across time. However, we argue that this is an important question. If the effects of crop diversity are fixed over time, this suggests that, while they may be able to lead to average increases in productivity, the scope for such increases over time may be limited. In such a scenario, this would suggest that the scope for crop diversity, on its own, to significantly affect productivity over time may be limited. The next section provides discusses our research hypothesis based on a number of stylized facts from the Omer et al. 2007 bio-economic model.

3 Research Hypotheses and Bio-economic models

This section discusses our research hypothesis in light of a number of stylized facts from Bio-economic models. In particular, the discussion follows quite closely the theoretical results derived in Omer et al. 2007 and Omer et al. 2010 (the mathematics relating to a slightly modified version of this model can be found in the Appendix A). We used this model as a basis for the discussion of our hypothesis because it analyzes some of the interactions between biodiversity (crop diversity in our case) and output in a flexible way and captures a number of stylized facts that have emerged from the literature. In these models, the Omer et al. 2007 model the relationship between crop diversity and production as a dynamic optimization problem and the overall relationship can be summarized by the following phase diagram (conditions are shown in Appendix A.):

Figure 1: Dynamics in the Biodiversity-Output space



Such models shed some light on three features of the crop diversity production link which are relevant for the purposes of this paper. The first aspect is that, under some conditions (shown in the Appendix[4]), there exists an optimal (equilibrium) level of crop diversity. As such, we would expect increases in crop diversity to lead to increases in output. However, these increases are likely to diminish with the level of diversity as it approaches the equilibrium (optimal) level. The idea of an optimum level of crop diversity from a productive perspective is not new. As mentioned in Hooper et al. 2005, higher crop diversity is often associated to increased productivity through the "sampling" , complementarity and facilitation effects and it is often hypothesized that there is a saturating response of ecosystem properties to increased species richness. This implies that, beyond a certain point the effects of increased species richness is likely to have a decreasing marginal effect on productivity[5]. Empirically, there also seems to be some support for this shape in the economics literature (see, for example,Di Falco et al. 2007 [6]). As such one of our research questions is to assess whether there seem to be positive effects of crop diversity on production and, if so, whether they seem to highlight a saturating response.

[4]In the Appendix we present a simplified and slightly modified version of Omer et al. 2007

[5]It should be noted that the type of species also has been shown to matter widely, although our index does not capture this.

[6]In this paper the authors find a positive effect of diversity on production but a negative coefficient on the quadratic term

A second important implication of this model relates to the equilibrium level. In this model, the equilibrium level depends on a number of factors, including the marginal effects of crop diversity on production and its effects on the damage function (which we do not address in this paper). Ethiopia being a very diverse country (Rahmato 2008), it is conceivable that the effects of crop diversity may differ considerably, as these effects may differ according to the context. As a result, our second research question is to assess whether there seems to be evidence suggesting that the effects of higher crop diversity on production differ considerably, depending on the agro-ecological zone.

A third implication relates to the dynamic effects. Assuming the existence of an optimal level of crop diversity, if a given household starts below its given optimal level of crop diversity and increases its level of crop diversity, we would expect average gains on production to increase over time. In the case where households are already at, or close to, their optimal level, however, we would expect small or no dynamic effects. As such our third research hypothesis is to understand whether there seems to be support for a "convergence hypothesis, whereby dynamic gains are higher in areas starting at low levels of crop diversity.

4 Defining cereal diversity, data and methodology

4.1 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 (see Baumgartner 2006 for a review) but different definitions are used in different contexts, not least because different professions value biodiversity for different reasons (see Baumgrtner 2006 for a review of the debate). For our purpose, the most common indices used are 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, may lead to a "sampling effect". As a result the diversity index may capture the performance of a single species (crops 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.

Secondly, 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 may well be biased towards 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 our index of cereal diversity. For instance, the index proposed by Weitzman 1992 which is a measure of genetic distance, would probably be suitable for our context. However, the amount of data and detail required for such an index is simply not available in this dataset.

There are two limitations of the Shannon index in this applications. First, while we observe different cereals, we do not observe different sub-species of the same crop[7]. This was shown to be important in Di Falco and Chavas 2008 but 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 non-negative Shannon index actually captures two monocultures in separate plots.

As shown in Di Falco and Chavas 2008, the cereal Shannon index can be algebraically represented 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.

4.2 Data

The dataset used is the Ethiopian Rural Household Survey (ERHS 2011) and all waves post-1994 were used. The 1994 wave is composed of 1,470 households from 18 different peasant associations (15 different villages), spread over 4 regions. The location, characteristics and the Agroecological zone breakdown of these peasant associations can be found in figures B.1 and B.2 and Table B.1 (Appendix B)[8]. However, it is important to mention that this sample is not nationally representative (Dercon and Hoddinott 2004).

[7]with the exception of Teff, where we observe white and black teff

[8]The agro-ecological zone breakdown was adapted from Hoddinott et al. 2011. Dercon and Hoddinott 2004 is the source for the map and site characteristics

As mentioned in Dercon and Hoddinnot 2004, attrition between 1994-2004 is estimated at 13%. In addition, only farmers which report cultivating cereals in every wave of the panel are included in our sample. As a result, the sample in this paper consists of a balanced panel of 839 individuals, for which a table of summary statistics (Table 1) is presented below.

Table 1: Summary statistics by Region

	Tigray		Amhara		Oromia		SSN	
Variable	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Cereal Production (kg)	220.507	255.227	938.802	850.355	1337.154	1295.447	224.057	270.743
Cereal Area (ha)	0.428	0.358	1.64	1.098	1.482	1.228	0.429	0.559
Number of Oxen (units)	0.63	0.758	1.252	1.126	0.998	1.224	0.387	0.813
Household Size	5.575	2.65	5.578	2.194	6.548	2.866	6.856	2.943
Quantity of Fertilizer on Cereals (kg)	4.527	13.821	65.601	87.423	81.400	99.856	19.885	28.577
Number of hoes	0.526	0.653	1.449	1.774	1.223	1.673	1.112	1.325
Number of Ploughs	1.354	2.06	2.586	3.701	1.729	2.776	0.861	1.678
Cereal Shannon Index	0.269	0.346	0.538	0.345	0.712	0.425	0.102	0.239
Northern Highlands	1	0	0.243	0.429	0	0	0	0
Central Highlands	0	0	0.757	0.429	0.324	0.468	0	0
Others	0	0	0	0	0.676	0.468	0	0
Enset	0	0	0	0	0	0	1	0
Number of Households	104		292		259		184	

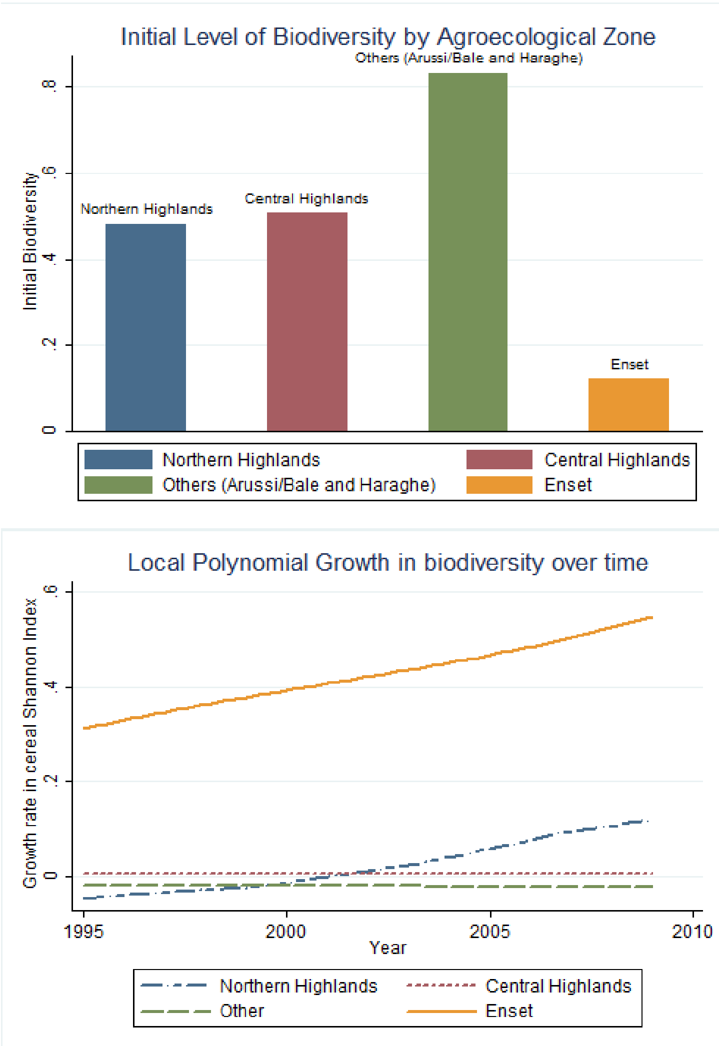
As is made clear in Table 1, the four different regions included in the analysis differ substantially from each other in terms of the all the inputs. On average, farmers in Amhara and Oromia, which make up the majority of the sample, allocate larger areas to cereals, have higher levels of production of cereals, use more fertilizer and have higher levels of cereal diversity than the average farmer in Tigray and SSN.

In terms of the variables used in this paper, the dependent variable in this study is the total quantity of cereals produced, which consists of the unweighed sum (in kilos) of the production of all cereals. The explanatory variables included consist of cereal area (measured in ha), number of oxen, household size (to proxy for labour), the quantity of fertilizer[9], the number of hoes and ploughs. In addition to this, the crop diversity variable, the cereal Shannon Index, will be included.

[9]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 the household uses fertilizer evenly in his land)

Given that this relates directly to our hypotheses, we summarize in Figure 2 he initial of cereal diversity by agro-ecological zone and its growth rate over time. As Figure 2 shows, the initial level of the cereal Shannon index in 1994 differed substantially by agro-ecological zone. While there was a high initial average level of crop diversity in the Arussi/Bale agro-ecological zone, the households in the Enset agro-ecological zone had a comparatively lower average level of crop diversity. The growth rate of the Shannon index over time also reveals a heterogeneous pattern, with the average faster average growth in the Shannon index occurring in the Enset and Northern highlands agro-ecological zones (also the areas with lowest initial diversity). In the Central Highlands and the Arussi/Bale agro-ecological zones, we note a relatively steady level of the Shannon index across time.

Figure 2: Initial level of Biodiversity and Growth rate by Agro-ecological Zone



4.3 Methodology

4.3.1 Stochastic Frontier Analysis and the True Fixed Effects model

Our analysis of the productive effects of crop diversity is concerned with several aspects of agricultural productivity, development and the role of crop diversity. Our general interest in re-evaluating previous work is also informed by the stylized facts emerging from bio-economic theoretical models. Overall, it is clear that to answer these questions we need to evaluate static, dynamic as well as technical efficiency dimensions of farm productivity and the extent to which these are determined by choices over crop diversity. To this end Stochastic Frontier Analysis is a particularly suitable empirical method.

The objective of efficiency analysis is to measure the efficiency of a decision-making unit (household in our case) against the (unobserved) maximum potential value possibly achieved by the unit of observation, given its inputs (Fried et al. 2008). Stochastic Frontier Models were first introduced simultaneously and independently by *Aigner et al. 1977* and Meeusen and van den Broeck (1977) and the basic model can be algebraically represented by equation 2:

$$y_{it} = exp\{f(x_{it};\beta)\} * exp\{\varepsilon_{it}\}; \quad \varepsilon_{it} = v_{it} - u_i \tag{2}$$

Therefore, the output of given household i at time t, is a function of a deterministic component $f(x_{it};\beta)$ and an error term ε_{it}, composed of a noise term v_{it}, which can be both positive and negative (normally distributed) and accounts for factors such as shocks due to variations in the performance of inputs, and an inefficiency term, and u_i, which is non-negative (following a half-normal distribution) and is the inefficiency term (Coelli et al. 2005).

The degree of technical efficiency of a given unit can then be computed as the ratio given in equation 3, below:

$$TE = \frac{y_{it}}{exp\{f(x_{it};\beta + v_{it})\}} = \frac{exp\{f(x_{it};\beta) + v_{it} - u_i\}}{exp\{f(x_{it};\beta) + v_{it}\}} = exp\{-u_i\} \tag{3}$$

Essentially, equation 3 states that the level of technical efficiency of household i is determined by the ratio of its output to the output of a predicted output of a fully-efficient household using the same input vector (Coelli et al. 2005).

In this paper, we will use a True Fixed effects model (Greene 2005) which extends the Aigner et al. 1977 model to include fixed effects. By doing this, it allows us to capture some individual heterogeneity through the inclusion of fixed effects. While we believe this is a better model for our purposes, it should be noted that, conceptually, there is potentially one drawback from using this model. In this model, the inefficiency term in does not distinguish between time-invariant inefficiency and time-invariant heterogeneity (Kumbhakar et al. 2015 p. 263 Chapter 10).

In this paper we use a translog specification for our production function for all the inputs except crop diversity. This means that natural logarithm of land, labour, fertilizer, oxen, hoes, their squares and respective interactions will be included. In the case of the Shannon index, we opt for adding it separately using dummies for different ranges of the Shannon index. The main reason for this is that, while a non-saturating response is hypothesized (and a quadratic relationship could be assumed), we prefer to remain agnostic regarding the functional form. As a result we construct three dummy variables. The first dummy variable takes the value of 1 if a household has a Shannon index above 0 and below 0.5 and takes a value of 0 otherwise. The second dummy takes the value of one if the household has a Shannon index between 0.5 and 1. Finally, the last dummy variable takes the value of one if the household has a Shannon index above 1. In order to provide an idea of what these values mean in terms of the crop mix, the following hypothetical examples may be helpful. A household who allocates all of his area to one crop (monoculture) will have a Shannon index of 0. If 90% of the land is allocated to one crop and the remaining 10% to another, this will result in a Shannon index of approximately 0.32. The value of the index increases to approximately 0.68 if two crops are distributed evenly and raises further to about 1.1 if three crops are cultivated evenly. The chosen ranges also loosely correspond to the first quartile, the two middle quartiles and the last quartile of all households with a non-zero value for the Shannon index.

Another important methodological points relates to the treatment of independent variables where a large proportion of the values are zero. In our sample, variables such as number of oxen, quantity of fertilizer, number of ploughs and number of hoes all have a non-negligible number of 0 values since not all household will use each input in every period. To deal with this, we follow the the procedure suggested by Battese (1997), namely to include an input-use dummy variable[10] for all variables which have 0 as a potential value (fertilizer, number of oxen, number of hoes and number of ploughs). This dummy variable takes a value of 1 when the input is 0, and takes the value of 1 otherwise. In addition to the inclusion of the dummy variable, the method proposed by Battese 1997 requires to transform the input variables such that all 0 values are replaced by a 1.

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 association-year [11]. We prefer to include peasant-association-year dummy variables rather than a time trend since we want to allow for potential non-linearities in the frontier over time. Finally, in order to capture non-neutral component of technical change, we interact a time trend with all the inputs in our production function (Shiu and Heshmati 2006). The non-neutral component of technological change captures whether the contribution of a certain number of inputs to the production frontier changes over time (Heshmati and Kumbhakar 2011b, Heshmati and Kumbhakar 2011a).

Algebraically, we can then represent the equations used by equation 4

$$\begin{aligned} ln\, y_{it} = \alpha_i + \sum_{k=1}^{k=m} \beta_k d_{kit} + \sum_{j=1}^{j=n} \beta_j \, ln\, x_{jit} + 0.5 \sum_{j=1}^{j=n} \sum_{m=1}^{m=n} \beta_{jm}\, lnx_{jit} * lnx_{mit} + \sum_{b=1}^{b=3} \beta_b \, db_{bit} \\ + \beta_{tb}\, ln\, bd_{it} T + \sum_{j=1}^{j=n} \beta_{jt}\, ln\, x_{jit} T + \sum_{t=1}^{t=n} \sum_{p=1}^{p=n} d_t * d_p + v_{it} - u_i \end{aligned} \tag{4}$$

[10]Conider an input k for which some farmers have a 0 value. Battese (1997) shows that in this case, simply adding a small number may not be the most appropriate solution. Instead, Battese (1997) proposes the inclusion of a dummy variable, d_k which takes a value of 1 when the input is not used (i.e. $d_k = 1$ if $k = 0$ and, conversely, $d_k = 0$ when $k > 0$). Additionally, for these variables, $k = \max(k, d_k)$.

[11]i.e. For each peasant association we include a dummy for each year

This equation can be interpreted in four parts. First, α_i captures household-specific, time-invariant features. The second part refers to a static component where db_{bit} refers to the crop diversity band, b, in which a household i is at time t. The term x_{jit} refers to the value of inputs used (including the transformed inputs using the Battese method). d_{kit} indicates whether a zero or positive quantity of input k is used ($d_k = 1$ if there is a 0 quantity of a given input). The third component is the dynamic component where we capture the neutral component of technological change by including year-peasant association dummy variables ($d_t * d_p$). We capture non-neutral technical change by interacting a time trend T (whose values range from 1 in 1994 to 16 in 2009) with all the inputs as well as the logarithm of the Shannon index $ln\, bd_{it}$. Finally, the last component is the error term which is composed of a stochastic component, v_{it} and an inefficiency term u_i. The estimation will be carried separately by agro-ecological zone[12].

4.4 Empirical Strategy and limitations

Given our stated hypotheses in section 3, we can divide our results in two main parts. The fist part relies directly on the interpretation of the crop diversity coefficients from the True fixed effects model. The second part is more descriptive and uses the estimated frontiers and efficiency scores to try and understand the efficiency-diversity link.

Given the stylized facts presented earlier we would expect two patterns to emerge from the output of the True Fixed effects model. First, we would expect the coefficients on the biodiversity dummies to 1)be increasing in the level of crop diversity (at least up to a certain point)[13]; and 2) vary significantly according to the agro-ecological zone analysed. As with the previous literature on this topic, our estimation of these effects may suffer from issues associated with endogeneity. However, we believe that the inclusion of fixed effects, together with year-peasant-association time dummies is likely to attenuate some of these concerns.

[12] A table detailing which peasant associations are in which Agro-ecological Zone can be found in the Appendix.

[13] e.g. we would expect the coefficient corresponding to low levels of crop diversity to be lower than the dummy for medium-high levels.

Secondly, we are also interested in the sign, magnitude and significance of the coefficient β_{tb}. This coefficients reveals whether, over time, the effects of crop diversity have been increasing. According to the stylized facts presented in section 3, we would expect a more positive relationship in agro-ecological zones with lower initial levels of the Shannon index. Our interpretation is that, if this pattern is found, it seems to provide some support for a convergence hypothesis. However, there are at least two potential issues with this interpretation. First, the optimal level of crop diversity cannot be observed by the researcher. As a result we do not know how far from the optimal level a given household is. Nevertheless, if we observe both low initial average levels of the Shannon index and a steady increase of the value of the index over time, it may provide some evidence that a large number of farmers in that given agro-ecological zone may be below the equilibrium. A second potential weakness of this interpretation is that this coefficient does not distinguish between dynamic effects arising from (a potential) convergence from dynamic changes arising from changes in the farming technology. It is possible that this coefficient captures a mix of these two effects.

The third aspect we are interested in is the relationship between crop diversity and efficiency. Here we are particularly interested in finding out whether, as found by Omer et al. 2007, this relationship is positive. Regarding the efficiency-diversity link, we use a more descriptive approach. We first summarize the efficiency scores results by different strata (quartiles of the average Shannon index over the sample period). Then we also run a local polynomial regression between the efficiency scores and the level of diversity to try and understand the shape of the relationship.

5 Results

5.1 Stochastic frontier model - Static and dynamic effects of biodiversity on frontier yield

As can be seen, from Table 2, the production coefficients estimated differ from one agro-ecological zone to another. These differences reflect the different production strategies undertaken by farmers in each area in response to local environmental conditions, constraints and also agricultural development policies in recent years and it applies to conventional inputs as well as to the choice of on-farm crop diversity. Therefore, as would be expected, the coefficients estimated for different areas differ substantially for most inputs, including crop diversity.

In the Northern Highlands, crop diversity has a positive and significant effect on production (at medium and high levels of crop diversity). At the same time, the coefficient on the interaction of the time trend and our crop diversity measure is positive but insignificant. The estimated coefficients on the static effect of crop diversity for this agro-ecological zone are also the largest of any agro-ecological zone for all the strata of crop diversity[14]. Moreover, we also find a positive and insignificant interaction between the time trend and the cereal Shannon index. The sign of the coefficient may be explained by the starting levels of crop diversity. As made clear by Figure 2 and by the descriptive statistics, the Northern Highlands have the second lowest starting level of average on-farm crop diversity and the Shannon index has grown over time. This presumably suggests that the households in this area may be yet converging towards an optimal level of crop diversity(Figure 2).

In the Central Highlands, the results seem to clearly indicate decreasing returns to crop diversity, in accordance with empirical results found in other studies of Ethiopian agriculture. The largest impacts of crop diversity on productivity are found at medium levels of diversity (the coefficient on *biodiversity2* is the largest). However, it is important to notice that the coefficients of two of the three crop diversitty indicator variables are positive and significant (except for low levels of cereal diversity).

[14] The one exception relates to the coefficient on high levels of crop diversity (biodiversity 3), which is the largest for the Enset agro-ecological zone. However, the latter coefficient is based on observations from 6 households and as such it is likely to be unreliable

In terms of the dynamic effect we notice that it is significant, large and negative. The initial levels of crop diversity in this agro-ecological zone offer a plausible explanation for this pattern. A large proportion of households are already at the band with highest returns to production. In addition, as can be seen from Figure 2, the average level of crop diversity has not grown substantially over the sample period. This is perhaps an indication that, on average, the farmers in this agro-ecologcal zone, on average, are likely to be close to their "optimal level" of crop diversity, which explains the negative dynamic effect. Therefore, in this agro-ecological zone, while cereal diversity is playing an important static role in production, this role seems to have been decreasing over time.

In the "Other" Agro-ecological zones (which comprises the peasant associations in the Arussi/Bale and Hararghe Agro-ecological zones (Nisrane et al. 2011)) the results indicate a different pattern of the effects of cereal diversity on production. The results suggest a positive and increasing marginal effect, but the effect of crop diversity on production is only positive and significant at medium and high levels of crop diversity (the coefficients of *biodiversity 2* and *biodiversity 3* are positive and significant). At lower levels of crop diversity, we find a positive (but insignificant) coefficient. Therefore, in this agro-ecological zone, it would seem that higher gains exist at higher levels of crop diversity.

However, the dynamic effect is insignificant and negative. Again, by inspecting figure (Figure 2) and looking at the descriptive statistics, we notice that this area had the highest level of initial on-farm cereal diversity and this level has remained fairly constant over time. Therefore, this is potentially an indication that, on average, farmers in this area are already close to their optimal level of functional on-farm crop diversity.

Finally, in the Enset Agro-ecological zone, the static relationship is somewhat similar to the "Northern Higlands" agro-ecological zone: a positive and increasing relationship between crop diversity and production. We notice, that the coefficient of crop diversity at high levels of crop diversity ("biodiversity 3") is extremely large. However, in this case, this coefficient is unlikely to provide an accurate estimate and should be interpreted with caution as it is estimated based solely on the observations from six households over the sample period. As such, we also report the results while omitting the households which make up this strata (last column of the table 2).

In terms of the dynamic effect, however, we notice that, over time, crop diversity seems to have a very large significant positive effect on the frontier production in this agro-ecological zone. This results can once again be rationalized by the fact that this region has started with the lowest levels of on-farm cereal diversity and has had the fastest growth in the average level of cereal Shannon index over the sample period.

This pattern of heterogeneous agro-ecological zones leading to heterogeneous technological solutions and consequent roles for crop diversity, reveals an interesting pattern. In the agro-ecological zones with lowest initial levels of cereal diversity, over time, cereal diversity has had the greatest positive dynamic effect on frontier output, which corroborates the theoretical predictions of the model. However, we also find very different patterns of the static effect of crop diversity, which is likely to mirror the very different effects of crop diversity in different agro-ecological zones.

Table 2: Results Stochastic Frontier Models

	Northern Highlands		Central Highlands		Other		Enset		Enset (no bd3)	
Area	0.498***	0.056	0.652***	0.038	0.411***	0.082	0.513***	0.056	0.508***	0.056
Oxen	0.333	0.260	0.371***	0.100	0.162	0.174	1.448***	0.439	1.410***	0.439
Labour	0.161**	0.082	-0.425***	0.060	-0.144	0.105	-0.489***	0.102	-0.451***	0.102
Fertilizer	-0.002	0.101	-0.141***	0.022	-0.041	0.037	-0.185***	0.051	-0.190***	0.051
Hoe	-0.562***	0.172	0.366***	0.069	0.032	0.135	0.220	0.153	0.204	0.153
Plough	0.233**	0.106	-0.069	0.057	0.089	0.110	0.056	0.217	-0.0397	0.234
Fertilizer Dummy	-0.172***	0.063	-0.137***	0.031	-0.045	0.046	-0.124**	0.051	-0.138***	0.051
Oxen Dummy	-0.152***	0.033	-0.065***	0.020	-0.186***	0.033	-0.071**	0.036	-0.079**	0.036
Hoe Dummy	0.032	0.028	-0.021	0.020	-0.087***	0.029	-0.007	0.036	-0.007	0.036
Plough Dummy	-0.003	0.036	-0.055**	0.023	-0.018	0.039	-0.083***	0.031	-0.066**	0.032
Area^2	-0.017	0.025	-0.120***	0.013	0.026	0.032	-0.050***	0.018	-0.053***	0.018
Oxen^2	-0.375	0.347	0.008	0.097	0.387***	0.130	0.103	0.314	0.011	0.317
Labour^2	-0.027	0.054	0.210***	0.037	-0.014	0.068	0.317***	0.063	0.290***	0.063
Fertilizer^2	-0.087**	0.042	0.051***	0.007	0.039***	0.011	0.054***	0.016	0.051***	0.017
Hoe^2	0.112	0.111	0.094**	0.046	0.118	0.101	-0.214*	0.124	-0.241*	0.125
Plough^2	-0.055	0.068	0.066**	0.032	0.062	0.053	-0.077	0.136	-0.014	0.140
Biodiversity1	0.060	0.069	0.031	0.030	-0.0244	0.076	0.030	0.079	0.028	0.079
Biodiversity2	0.144***	0.031	0.073***	0.020	0.113**	0.045	0.124***	0.041	0.113***	0.041
Biodiversity3	0.246***	0.045	0.059**	0.030	0.218***	0.046	0.650***	0.177		
Trend Area	0.010*	0.005	-0.005*	0.003	-0.008*	0.005	-0.015***	0.003	-0.014***	0.003
Trend Oxen	0.006	0.015	-0.004	0.005	0.008	0.008	0.003	0.017	0.005	0.017
Trend Labour	-0.007	0.006	0.017***	0.003	0.029***	0.004	0.029***	0.006	0.028***	0.006
Trend Fertilizer	0.004	0.004	0.004***	0.001	0.004**	0.002	0.002	0.002	0.002	0.002
Trend Biodiversity	0.001	0.001	-0.006***	0.002	-0.001	0.002	0.003***	0.001	0.003***	0.001
Trend Hoe	-0.019	0.012	0.007**	0.003	0.004	0.007	-0.001	0.007	0.000	0.007
Trend Plough	-0.007	0.006	-0.003	0.003	0.007	0.005	0.007	0.008	0.008	0.008
PA-Year Fixed Effects	Yes		Yes		Yes		Yes		Yes	
Interactions	Yes		Yes		Yes		Yes		Yes	
Sigma	0.699***	0.013	0.739***	0.007	0.696***	0.013	0.841***	0.016	0.846***	0.016
Lambda	1.201***	0.064	1.945***	0.053	1.322***	0.063	1.408***	0.067	1.446***	0.068
N	175		305		175		184		178	

5.2 Descriptive Analysis Cereal diversity and efficiency

Having looked at the static and dynamic effect of crop diversity on frontier output, we now turn to a more descriptive analysis of the relationship between crop diversity and efficiency. We will now turn to a more descriptive analysis which looks at the cereal diversity-technical efficiency link. We show this in two ways. First, we compute the mean efficiency scores by quartiles of the Shannon index. Second, we also use a local polynomial regression to show this relationship.

Table 3 shows the mean efficiency scores for households at different quartiles of the average Shannon index. The results highlight a positive link between crop diversity and efficiency. Specifically, it shows that the average efficiency score for households in the first quartile of the average Shannon index is 0.621. This number increases to about 0.64 for the two middle quartiles and increases further to 0.66 in the top quartile. In addition to this, the differences are statistically significant with the mean efficiency score for households in the bottom quartile being statistically significantly lower than the mean efficiency score for every other quartile. These result seems to lay some support to the result found by Omer et al. 2007, who find higher levels of crop diversity to be associated with lower levels of inefficiency (higher levels of efficiency).

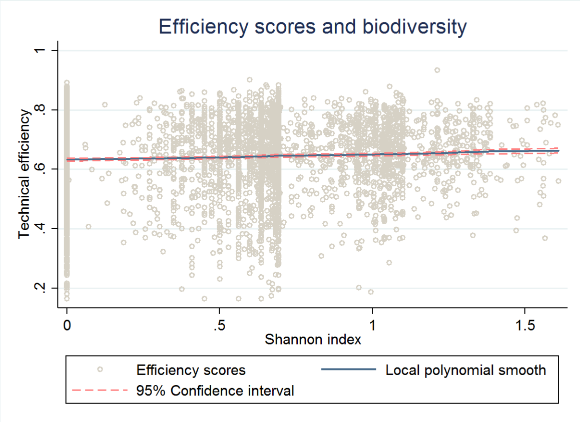
Table 3: Biodiversity and efficiency scores

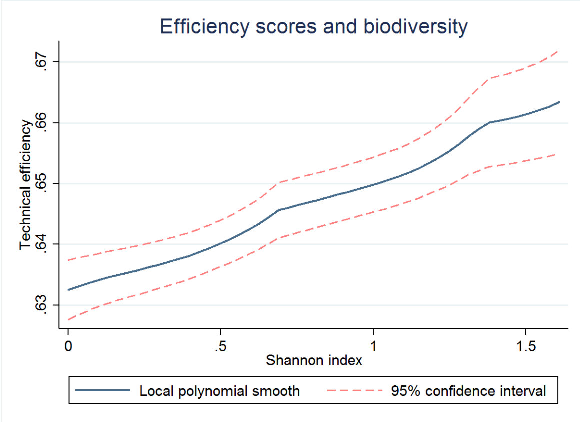
Variables	Group Description	N	Mean	SE	95% CI Lower	95% CI Upper
Biodiversity percentile Groupings						
Group 1	Shannon Index - Quartile 1	1254	0.621	0.004	0.614	0.628
Group 2	Shannon Index - Quartile 2	1256	0.640	0.004	0.633	0.647
Group 3	Shannon Index - Quartile 3	1253	0.644	0.004	0.637	0.651
Group 4	Shannon Index - Quartile 4	1247	0.660	0.003	0.654	0.666

This pattern is further corroborated by the results of a local polynomial regression between the Shannon index and the efficiency scores (Figure 3). This graph also seems to suggest that higher levels of cereal diversity are associated with higher levels of technical efficiency [15].

[15] All local polynomial analysis are performed with the rule-of-thumb bandwidth. The sensitivity of the results to alternative bandwidths (0.05 and 0.02) was tested. The results remain broadly similar, if noisier at low and high values of the Shannon index.

Figure 3: Efficiency scores and biodiversity - Local polynomial





6 Conclusion

The aim of this paper was to look at the productive implications of cereal diversity for cereal production over time. 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 over time.

Our results corroborate a number of previous results in the literature. For instance, we find large positive gains of cereal diversity on cereal production. As in Omer et al. 2007, we also find that these come from a positive effect on the frontier and our evidence is also suggestive of a positive effect on efficiency. However, unlike previous studies, we find that these effects are very heterogeneous. Specifically, we find insignificant effects on production at low levels of the Shannon index (between -2% and +6%)[16] and large but heterogeneous effects at higher values of the Shannon index (between 6% and 24%[17] [18]), depending on the agro-ecological zone.

[16]A low level of the Shannon index is a level above 0 but below 0.5. In order to illustrate what this means, a household who allocates all of his area to one crop (monoculture) will have a Shannon index of 0. In contrast, a household cultivating who allocates A household which allocates 90% of its land to one crop and the remaining 10% to another will have a Shannon index of approximately 0.32. In our sample, this corresponds to a "low" level of cereal diversity

[17]A household cultivating three evenly distributed crops will be considered to have "high" cereal diversity as it will have a Shannon index of approximately 1.1. A household cultivating two evenly distributed crops will be considered to have a "medium" level of cereal diversity. It will have a Shannon index of approximately 0.68. These coefficients should be interpreted as the effect of shifting from a monoculture (Shannon index=0) to these levels of cereal diversity

[18]We do not consider the "high" crop diversity coefficient for the Enset agro-ecological zone as it is based on solely 6 households and, as such, we do not have sufficient confidence to include it.

A key aspect about this paper relates to the dynamic effects. While we find large average effects (static) of crop diversity on production, these average effects do not always seem to be increasing over time. In areas where there are low levels of initial crop diversity, we find the productive effects of diversity to be increasing over time. The opposite pattern holds for areas at higher levels of initial crop diversity. One potential explanation for this pattern is the existence of a convergence to an optimal level of crop diversity. However, unfortunately, we can only interpret these results as providing weak evidence towards this result as the dynamic effect may also be capturing a number of other factors, such changes in technologies over time.

Taken together, these results suggest that cereal diversity is unlikely to be a panacea for cereal productivity. Conceptually, the existence of an optimal level of crop diversity may limit the potential dynamic gains achievable and our result, albeit imperfect, seem to provide some evidence for this. This raises the issue how best to direct conservation efforts. If the lack of dynamic gains allied to the development of alternative sources of insurance and the modernization of agriculture leads to a reduction of cereal diversity, then this 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, our finding is suggestive of a convergence pattern. However, this should be interpreted with some degree of caution as it may hide shifts in technology over time which may have affected the effectiveness of crop diversity. Understanding whether there indeed further support for such a pattern is a question that merits further attention. 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.

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Appendices

A Appendix A - Omer et al. Bio-economic model

This section summarizes a slightly modified version of the model presented in Omer et al. 2008. In this model, the objective of the farmer is to maximize the present value of utility flows derived from two outputs, namely agricultural output (limited to cereals, in our case) and ecosystem damage. On the one hand, the household derives utility from its flow of agricultural output from a given plot of land. On the other hand, there is a disutility associated with increased levels of ecosystem damage. Together, these imply that the utility function can be represented by equation A.1:

$$U = U[Y(t), D(t)] \tag{A.1}$$

Where positive but diminishing marginal returns to it is assumed that also assume that there are positive but diminishing returns to utility from production($U_y > 0$, $U_{yy} < 0$), Y and increasing (at an increasing rate) disutility from agro-ecosystem damage ($U_d < 0$, $U_{dd} < 0$), D. The Agricultural production function, is assumed to be a function of B(t), the level of biodiversity as well as of artificial inputs X(t). Following Omer et al 2008, we assume the production function to be twice differential and concave and X and B to be linearly separable. Linear separability is a strong assumption but Omer et al. 2010 show that, for a more complex version of the model, it is a simplifying assumption and that relaxing this assumption does not change the main conclusions of the model

The damage Function, which is given by equation A.2, determines the relationship between the use of X, B and degradation. It is assumed that increasing the stock of biodiversity increases the resilience of the agro-ecosystem, but that the marginal "buffering" effect of biodiversity on the agro-ecosystem damage is reduced at higher levels of B (i.e. it is assumed that $D_b < 0$ and $D_{bb} > 0$), a pattern somewhat suggested by the scientific literature on biodiversity (see Fornara and Tilman 2008 and Huston 1994[19]). Conversely, the use of conventional inputs is assumed to increase ecosystem damage and this relationship is assumed to be convex ($D_x > 0$ and $D_{xx} > 0$). Once again, given the ambiguous nature of the interactions of inputs and biodiversity on damage, we refrain from assuming such a relationship and assume that the damage function is linearly separable in X and B.

$$D(t) = D[X(t), B(t)] \tag{A.2}$$

The main difference between our version of the model and the original version of the model relates to the law of motion of biodiversity. In the original Omer et al. 2007 model, the authors, motivated by ecological studies (Altieri 1999 and Tscharntke et al. 2005), adopt a wider definition of biodiversity that include off-farm biodiversity such as such as field margins. As a result, in their framework, it makes sense that the authors assume a natural growth rate of biodiversity as well as a negative effect of inputs on levels of biodiversity. However, in our case, our definition of biodiversity is confined to farm-level cereal diversity. Thus, changes in biodiversity can be viewed explicitly as a choice/investment relating to how much area to allocate to each crop and therefore, the dynamics of biodiversity are entirely dependent on the investment made on biodiversity:

$$\dot{B} = \delta C(X, B) \tag{A.3}$$

[19]It should be noted, however, that in these two studies, the authors don't only look at cereals as in our case. In Huston 1993, an inverted u-shape relationship seems to exist between biodiversity and a number of soil fertility indicators (soil drainage, soil field capacity, soil relative P, k and Ca). In Fornara and Tilman 2008, the authors show that the soil N increases with the number of species. However, the difference in soil N between 1 and 2 species, for example, is much lower than the difference between 8 and 16 species, for most time periods in their data.

Where δ denotes the rate at which biodiversity is affected by the household's investment (choice). As a result, if a household decides to invest a non-zero amount on biodiversity, *ceteris paribus*, we would expect the growth rate of biodiversity to increase. The total amount of biodiversity can be seen as the difference in the total revenue and the total investment in production:

$$C(t) = F[X(t), B(t)] - Y(t) \tag{A.4}$$

In our case, this investment can be viewed as a pre-production investment necessary to enable the production of desired bundle Y. In our case, this can, for example, be viewed as the purchase of seeds, where the investment C(t) is the amount necessary to make the production of Y possible. The choice of the household thus revolves around two variables, namely the level of application of artificial inputs and the level of on-farm biodiversity. Both of these decisions then affect utility both directly, through a direct effect on the production function, and indirectly, via their effect on the the damage function. As a result we are left with the following optimization problem:

$$\max_{Y<X<C} W(Y(t), D(t)) = \int_{t=0}^{\infty} e^{-\rho t} u(Y(t), D(t))dt \tag{A.5}$$

Where equation A.6 is subject to the law of motion of biodiversity (equation A.3), two non-negativity constraints ($X \geq 0$ and $D \geq 0$), the initial stock of farm-level biodiversity (B_0), the impact function (Equation A.2) and the conservation investment decision (Equation A.4).

This therefore yields a simplified version of current-valued Hamiltonian in Omer et al. 2008, namely:

$$H_c = U(Y, D) + \phi(\delta C) \tag{A.6}$$

Where ϕ represents the shadow value of biodiversity. The necessary conditions are then given by equations A.7-A.10:

$$\frac{\partial H_c}{\partial \phi} = \dot{B} = \delta[F(.) - Y] \tag{A.7}$$

$$\frac{\partial H_c}{\partial Y} = U_y - \delta\phi = 0 \tag{A.8}$$

$$\frac{\partial H_c}{\partial X} = U_d\, D_x + \phi(\delta F_x) = 0 \tag{A.9}$$

$$\phi = -U_d D_b - \phi(\delta F_b - \rho) = -\frac{\partial H_c}{\partial B} + \rho\phi \tag{A.10}$$

Where equation A.7 restates the Biodversity law of motion, equation A.8 establishes that the shadow value of biodiversity must be positive (since we assume that $\frac{\partial U}{\partial Y} > 0$. Equation A.9 essentially states that, in equilibrium, the disutility of damage arising from increased use of inputs $U_d D_x$ be balanced by the additional utility from production of increased input use $\phi(\delta F_x)$. Finally, equation A.10 represents the non-arbitrage condition.

Using equations A.8 and A.9 we can obtain the equation that solves the optimal level of X (input use) as a function of Y and B. To do this, multiply equation A.9 by δ and then use the fact that, from A.8, $U_y = \delta\phi$, to obtain:

$$\delta U_d D_x + U_y \delta F_x = 0 \tag{A.11}$$

Then, taking the time derivative of A.8, we can obtain the following expression for the optimal growth rate of Y:

$$\dot{Y} = -\frac{U_y}{U_{yy}}\left[\delta F_b - \rho - \delta F_x \frac{D_b}{D_x}\right] \tag{A.12}$$

At this point, as mentioned in Omer et al. 2010, the system is assumed to have a unique solution that satisfies both the initial conditions and the following transversality conditions:

$$\lim_{t\to\infty} \phi(t) = 0 \quad i.e. \quad \phi(t) \to 0 \quad as\ \ t \to \infty^{20} \tag{A.13}$$

$$\lim_{t\to\infty} H = 0 \quad i.e. \quad H \to 0 \quad as\ \ t \to \infty^{21} \tag{A.14}$$

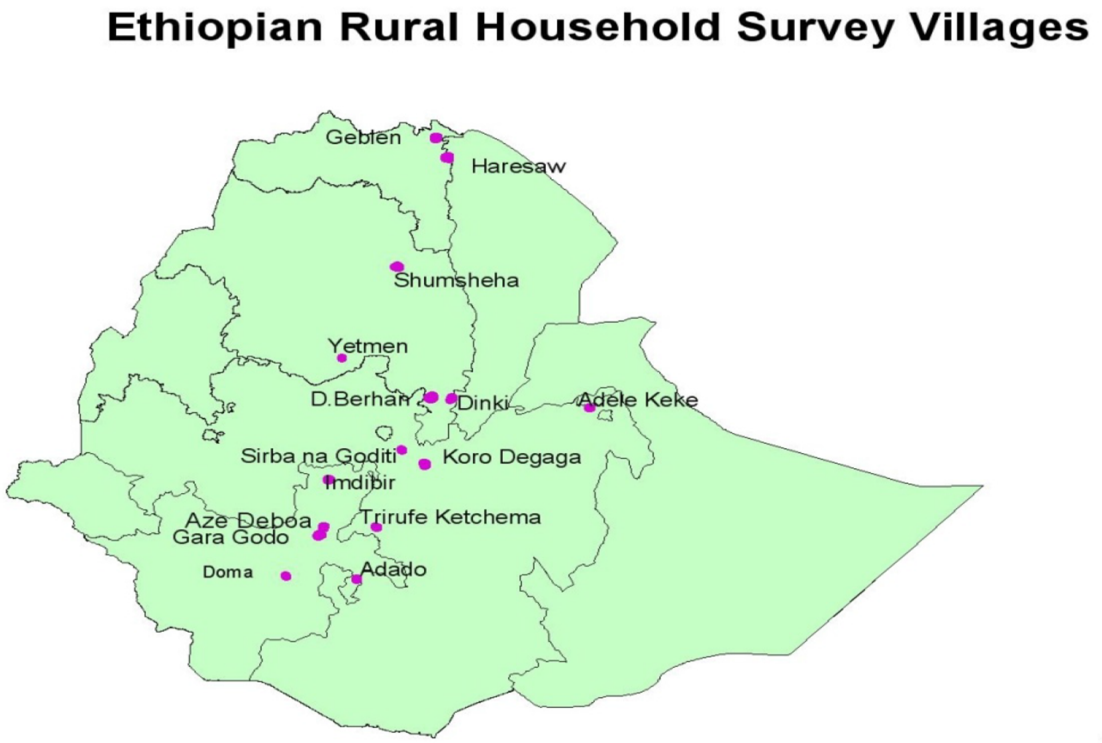
[20] As mentioned in Omer et al. 2010, equation A.8 shows the solution path to $\phi(t)$ as $\phi^* = \frac{1}{\delta}\frac{\partial U}{\partial Y^*}e^{-\rho t}$. In this model, however, Y^* does not tend to 0 as t approaches infinity, since setting $\frac{\partial U}{\partial Y} = 0$ rules out any corner solutions. Nevertheless, since the exponential term tends to 0 as t tends to infinity, the first transversality condition is satisfied.

[21] For this transversality condition, we note that the solution path for H is given by $H^* = U(Y^*, D^*)e^{-\rho t} + \phi^*(\delta F(.) - \delta Y^*)$. As we can notice, the first term tends to infinity since the exponential term tends to 0 as t tends to infinity. Secondly, by definition, the second term (the state equation) is, by definition, 0 at the steady state. Therefore, the second transversality condition also holds

In order for there to be a convergence towards an equilibrium we must have that the slope of the output isocline be steeper than that of the biodiversity isocline. Otherwise, there is no convergence.

B Appendix B - Additional figures and tables

Figure B.1: Map of Villages in the ERHS (up to 2004)



Source: Dercon and Hoddinott 2004

Figure B.2: Background information of Villages in the ERHS (up to 2004)

Survey site	Location	Background	Main crops	Perennial crops?	Mean Rainfall mm
Haresaw	Tigray	Poor and vulnerable area.	Cereals	no	558
Geblen	Tigray	Poor and vulnerable area; used to be quite wealthy.	Cereals	no	504
Dinki	N. Shoa	Badly affected in famine in 84/85; not easily accessible even though near Debre Berhan.	Millet, teff	no	1664
Debre Berhan	N.Shoa	Highland site. Near town.	Teff, barley, beans	no	919
Yetmen	Gojjam	Near Bichena. Ox-plough cereal farming system of highlands.	Teff, wheat and beans	no	1241
Shumsha	S.Wollo	Poor area in neighbourhood of airport near Lalibela.	Cereals	no	654
Sirbana Godeti	Shoa	Near Debre Zeit. Rich area. Much targeted by agricultural policy. Cereal, ox-plough system.	Teff	no	672
Adele Keke	Hararghe	Highland site. Drought in 85/86	Millet, maize, coffee, chat	yes, no food	748
Korodegaga	Arssi	Poor cropping area in neighbourhood of rich valley.	Cereals	no	874
Turfe Kechemane	S.Shoa	Near Shashemene. Ox-plough, rich cereal area. Highlands.	Wheat, barley, teff, potatoes	yes, some	812
Imdibir	Shoa (Gurage)	Densely populated enset area.	Enset, chat, coffee, maize	yes, including food	2205
Aze Deboa	Shoa (Kembata)	Densely populated. Long tradition of substantial seasonal and temporary migration.	Enset, coffee, maize, teff, sorghum	yes, including food	1509
Addado	Sidamo (Dilla)	Rich coffee producing area; densely populated.	Coffee, enset	yes, including food	1417
Gara Godo	Sidamo (Wolayta)	Densely packed enset-farming area. Famine in 83/84. Malaria in mid-88.	Barley, enset	yes, including food	1245
Doma	Gama Gofa	Resettlement Area (1985); Semi-arid; droughts in 85, 88,89,90; remote.	Enset, maize	yes, some	1150

Source: Dercon and Hoddinott 2004

Table B.1: List of Peasant Associations by AEZ

Agro-Ecological Zone	Peasant Association
Northern Highlands	Haresaw
	Geblen
	Shumsheha
Central Highlands	Dinki
	Debre Berhan Milki
	Debre Berhan Kormargefia
	Debre Berhan Karafino
	Debre Berhan Bokafia
	Yetmen
	Turufe Ketchema
Enset	Imdibir
	Aze-Deboa
	Adado
	Gara-Godo
	Do'oma
Other	Sirbana Godeti
	Korodegaga
	Adele Keke

Source: Adapted and changed slightly from Nisrane et al 2011