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## On the Productive Value of Crop Biodiversity: Evidence from the Highlands of Ethiopia

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Land Economics, Volume 88, Number 1, February 2012, pp. 58-74 (Article)

Published by University of Wisconsin Press  
DOI: 10.1353/le.2012.0009

**LAND  
ECONOMICS**

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# On the Productive Value of Crop Biodiversity: Evidence from the Highlands of Ethiopia

*Jean-Paul Chavas and Salvatore Di Falco*

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**ABSTRACT.** *This paper investigates the productive value of crop biodiversity, with an application to a farming system in the Tigray region in the highlands of Ethiopia. We examine a general measure of the productive value of crop biodiversity and its components. Using Ethiopian farm-level data, agroecosystem productivity is investigated empirically. The analysis gives estimates of the value of diversity and its components. The value of crop biodiversity is estimated to be positive. The complementarity component is found to be large and statistically significant: it is the main source of crop biodiversity value in this agroecosystem of Ethiopia. However, the convexity component is negative, indicating that nonconvexity contributes to reducing the value of crop biodiversity.* (JEL D61, Q18)

## I. INTRODUCTION

Biodiversity has been identified as an important component of ecological systems (e.g., Heal 2000; Tilman and Downing 1994; Tilman, Wedin, and Knops 1996; Tilman, Polasky, and Lehman 2005; Wood and Lenné 1999). The relevance of biodiversity in the provision of ecosystem services is highlighted by growing evidence that it can support system productivity and that its loss can have adverse effects on the functioning of ecosystems (e.g., Loreau and Hector 2001; Naeem et al. 1994; Cork et al. 2002; Hooper et al. 2005; Tilman and Downing 1994; Tilman, Wedin, and Knops 1996; Tilman, Polasky, and Lehman 2005; Zhu et al. 2000; Landis et al. 2008). Agroecosystems are an important part of earth ecosystems. Indeed, about 40% of earth land is used for agricultural purposes. And agroecosystem services help support economic livelihood everywhere, especially in developing countries where the agricultural

sector constitutes a large part of the economy. Farmers in developing countries often face poorly functioning markets and limited opportunities for technological progress. While incomplete (or missing) markets reduce farmers' options, they imply an enhanced reliance on nature's services and emphasize the economic importance of agroecosystem management in developing countries. One-quarter of undernourished people in the developing world live in so-called biodiversity hot spots, areas that are rich in crop biodiversity (Cincotta and Engelman 2000). Loss of biodiversity and the consequent reduction in ecosystem services (i.e., food production) are seen as a primary obstacle to the achievement of Millennium Development Goals (Millennium Ecosystem Assessment 2005).

In this paper, we investigate the productive value of crop biodiversity with an empirical application to an agroecosystem in the Highlands of Ethiopia. We focus on one specific subset of biodiversity in agroecological systems: crop diversity in managed agricultural systems. The analysis seeks to examine two questions. First, how important is crop biodiversity in agroecosystem productivity? Second, what are the sources that generate positive linkages between crop diversity and productivity? These two questions have been the subject of significant interest. Previous research documenting positive effects of biodiversity on agroecosystem productivity (sometimes called overyielding) includes that of Di Falco and Chavas (2009), Heisey et al. (1997), Meng et al. (1998), Priestley and Bayles (1980), and Smale et al. (1998, 2002, 2003). But where do such benefits come from? Two possible explanations can be

found in the existing, broader, agroecological literature:<sup>1</sup> complementarity effects and scale effects (Callaway and Walker; Loreau and Hector; Sala et al. 2000; Tilman and Downing 1994; Tilman, Wedin, and Knops 1996).<sup>2</sup>

Complementarity effects arise in an ecosystem when particular species perform better in the presence of others, implying that biomass production is greater in diversified systems (compared to more specialized systems). This reflects positive synergies between species. These synergies can have several sources. First, they can come from more effective use of resources. For example, under a rotation scheme, a crop benefits from higher nitrogen content in the soil if planted after a nitrogen-fixing legume. In addition, crop rotations can help spread labor requirements more evenly during the growing season, thus possibly reducing labor bottlenecks. Second, crop rotations help control pest populations, thus contributing to lower pest damages and higher yields. Third, diversification can help maintain and/or enhance soil productivity (e.g., fallowing in extensive farming systems or the use of manure in mixed crop-livestock farming systems). Finally, diversified systems can benefit from a better adaptation to local agroclimatic conditions. This can generate complementarity benefits from niche partitioning (Loreau and Hector 2001), especially when environmental heterogeneity is large. Indeed, different crop species may have different responses to temperature, soil conditions, or resistance to biotic and abiotic stresses (Zhu et al. 2000; Sala et al. 2000; Landis et al. 2008). As such, farms facing a diverse agroecosystem will have a broader range of traits and be more likely to perform under different environmental conditions (Heal 2000; Sala et al. 2000; Cardinale, Ives, and Inchausti 2004; Tilman and Kareiva 1997; Tilman, Polasky, and Lehman 2005). Each of these sources can contribute to

synergies in the agroecological system, meaning that farm diversification can generate complementarity benefits and increase farm productivity. While identifying the exact mechanism(s) generating these synergies can be difficult, evaluating the existence and magnitude of complementarity benefits remains of significant interest.

Scale effects arise when the functioning of an ecosystem is affected by its size and its degree of fragmentation. In general, these effects can be complex, as size, spatial density, and spatial heterogeneity can interact in their impact on ecosystem productivity (Bissonette and Storch 2002; Giller et al. 2004; Tilman and Kareiva 1997). On the one hand, scale effects can reflect the presence of limited resources, implying that the average productivity of an ecosystem may decline when it becomes "too large." At the other extreme, the performance of an ecosystem may deteriorate when it becomes "too small." For example, this can occur when the reproductive functions of a species weaken below some minimum population threshold.

In the context of a particular agroecosystem, this raises the following questions: How large are the effects of crop diversity on agroecosystem productivity? How important are complementarity effects in agroecosystems? Does scale matter? Are there other important factors influencing the effects of crop diversity on agroecosystem productivity?

This paper answers these questions, with an empirical focus on a farming system in the Tigray region in the Highlands of Ethiopia. Tigray is the northernmost of the nine ethnic regions of Ethiopia. As the rest of Ethiopia, Tigray has one of the highest rates of soil nutrient depletion in Sub-Saharan Africa (Grepnerud 1996; FAO 2001). Coupled with harsh climatic conditions, this has contributed to frequent harvest failures and famines. Indeed, during the last millennia, at least 25 severe drought periods were recorded, and crop production in most areas "never topped subsistence levels" (REST/Noragric 1995, p137). Agriculture is the source of livelihood for a majority of the population. It employs more than 80% of the labor force and accounts for 45% of the GDP and 85% of the export revenue (MFED 2007). Cereals are staple food

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<sup>1</sup> While we investigate the role of diversity in a managed agroecosystem, note that the ecological literature has focused on the relation between plot biodiversity and productivity in unmanaged ecosystems.

<sup>2</sup> Another possible explanation is the "sampling effect," stating that increasing diversity improves the chances that specific species would be adapted to a particular ecological condition (Tilman, Polasky, and Lehman 2005).

in the region, and Ethiopia is a recognized global center of crop diversity for several cereal crops, including barley and teff (Vavilov 1949; Harlan 1992). All these characteristics make this area a relevant case study of farmers' reliance on ecosystem services, with a focus on evaluating the productive value of crop biodiversity.

Using farm survey data from Ethiopia, we estimate the value of biodiversity and its components in the Highlands of Ethiopia. Our sample involves multiplot and multicrop farms (Benin et al. 2004). This provides a good opportunity to investigate the presence and magnitude of complementarity effects at the farm level. The analysis is presented in the broader context of measuring the productive value of crop biodiversity. It also provides a basis for evaluating the factors affecting the value of crop biodiversity at the farm level.

The technology underlying an agroecosystem is represented by a multi-output production function used to characterize the productivity effects of biodiversity. Following Chavas (2009), we evaluate the productive value of diversity as the productivity difference between an integrated system and a less diverse system, holding aggregate resources constant. This captures how the value of an ecosystem can be greater than the sum of its parts. Following Chavas, the productive value of diversity can be decomposed into four additive components: one associated with complementarity, one with scale effects, one with convexity effects, and one with catalytic effects. Our application aims to shed light on the role of crop diversity on productivity and the factors affecting the value of diversity in an Ethiopian farming system. Of special interest is the investigation of the relative importance of these effects (complementarity, convexity, and scale). Our empirical analysis will examine whether these effects play a significant role in the value of crop diversity.

The empirical investigation of the productive value of crop diversity and its components is a novel exercise. Note that our approach does not rely on a specific biodiversity index. This contrasts with other approaches that have appeared in previous literature. One approach is based on relative abundance or evenness of species. This is cap-

tured by ecological diversity indices including the Margalef index, the Shannon index, and the Simpson index (e.g., Hill 1973; Lande 1996; May 1975; Simpson 1949). These indices have been used extensively in the empirical analysis of biodiversity issues (e.g., Di Falco and Chavas 2009; Heisey et al. 1997; Meng et al. 1998; Priestley and Bayles 1980; Smale et al. 1998, 2002, 2003). Yet, they raise several issues. First, different indices can deliver very different results, and there is a debate on which diversity index is most appropriate (e.g., Routledge 1979). At this point, it appears that no particular index is always superior. This point is made clear when the value of biodiversity is found to depend on the presence and nature of complementarity among ecosystem services (e.g., Faith et al. 2003; Justus and Sarkar 2002; Loreau and Hector 2001). Second, diversity indices do not identify the sources of diversity value. This is problematic to the extent that knowing the source and nature of diversity value is often important in evaluating alternative management strategies for diversity. Another approach developed by Weitzman (1992, 1998), Polasky and Solow (1995), and Solow, Polasky, and Broadus (1993) measures biodiversity through a diversity function based on a measure of dissimilarity.<sup>3</sup>

We use the Ethiopian farm survey data to estimate agroecosystem productivity. This involves estimating a multi-output production function. To deal with endogeneity issues, we rely on an instrumental variable estimator. The estimated coefficients are then used to investigate the magnitude and determinants of biodiversity value. We find that the value of biodiversity is positive. The complementarity component is found to be large and statistically significant. This provides evidence that complementarity is the main source of biodiversity value in this agroecosystem. The statistical evidence indicates that neither the scale effect nor the catalytic effect is impor-

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<sup>3</sup> Brock and Xepapadeas (2003), however, have shown that a more diverse ecosystem can be much more valuable even when the increase in dissimilarity is small. This reflects the complexity of ecosystems, indicating that simple diversity indices may fail to capture accurately the value of biodiversity.

tant. However, the convexity component is negative. This shows that nonconvexity contributes to reducing the value of biodiversity at the farm level.

## II. THE PRODUCTIVE VALUE OF DIVERSITY

The productivity of an agroecosystem can be modeled in the context of a production process involving a set of  $m$  goods  $z = (z_1, z_2, \dots, z_m) \in R^m$ . We use the netput notation, where inputs are defined to be negative (with  $z_i \leq 0$ ) while outputs are defined to be positive (with  $z_i \geq 0$ ). The underlying production technology is denoted by the set  $Z \subset R^m$ , where  $z \in Z$  means that  $z$  can be feasibly produced. We do not assume that the set  $Z$  is convex. This means that our analysis does not assume that diminishing marginal productivity necessarily applies. We are interested in providing a general representation of the frontier technology given by the boundary of  $Z$ . Such a representation is the shortage function proposed by Luenberger (1995) and discussed by Chavas (2009). Let  $g \in R_+^m$  be a reference bundle of goods satisfying  $g \geq 0$ , and  $g \neq 0$ . Below, we assume that the nonzero elements of  $g$  are private goods. For a given  $g$ , the shortage function  $S(z, g)$  evaluated at point  $z$  is defined as

$$\begin{aligned} S(z, g) &= \min_{\alpha} \{ \alpha : (z - \alpha g) \in Z \}, \\ &\quad \text{if there is an } \alpha \text{ s.t. } (z - \alpha g) \in Z, \\ &= +\infty \text{ otherwise.} \end{aligned} \quad [1]$$

The shortage function  $S(z, g)$  measures the number of units of the reference bundle  $g$  reflecting the distance between point  $z$  and the frontier technology. The general properties of the shortage functions are discussed by Luenberger (1995). In general,  $z \in Z$  implies  $S(z, g) \leq 0$ . And under free disposal,<sup>4</sup>  $Z = \{z: S(z, g) \leq 0\}$ , implying that  $S(z, g) \leq 0$  provides a complete characterization of the technology. In this case,  $S(z, g) = 0$  if and only if  $z$  is on the upper bound of the feasible set  $Z$ , with  $S(z, g) = 0$  providing a multi-input multi-output

functional representation of the underlying frontier technology. To illustrate, consider the special case where  $g = (1, 0, \dots, 0)$ . Then  $S(z, g) = z_1 - G(z_c)$  where  $z_c = (z_2, \dots, z_m)$  and  $G(z_c) = \max\{z_1: (z_1, z_c) \in Z\}$  is the largest possible  $z_1$  that can be obtained given other netputs  $z_c$ . When  $z_1$  is an output,  $G(z_c)$  is a standard production function representing the underlying technology, where feasibility is given by  $z_1 \leq G(z_c)$ . In this case, under differentiability,  $\partial S / \partial z_1 = 1$  and  $\partial S / \partial z_c = -\partial G / \partial z_c$ , implying that  $-\partial S / \partial z_c$  can be interpreted as measuring the marginal product of  $z_c$ . As discussed below, either  $S(z, g)$  or  $G(z_c)$  can provide an empirical basis to evaluate the productivity of an agroecosystem.

For a given  $z$ , the shortage function  $S(z, g)$  in [1] provides a convenient basis for analyzing productivity. Following Chavas (2009), the productivity effect of a change from  $z^1$  to  $z^2$  can be measured by

$$P(z^1, z^2, g) = S(z^1, g) - S(z^2, g). \quad [2]$$

$P(z^1, z^2, g)$  in [2] measures the number of additional units of the reference bundle  $g$  that can be obtained by moving from point  $z^1$  to point  $z^2$ . When the private goods in  $g$  are market goods with prices  $g$ , then a monetary evaluation of a change from  $z^1$  to  $z^2$  is given by  $P(z^1, z^2, g)(p \cdot g) = (S(z^1, g) - S(z^2, g))(p \cdot g)$ , with  $(p \cdot g)$  denoting the monetary value of value of one unit of  $g$ . If we choose the reference bundle  $g$  such that  $(p \cdot g) = 1$ , then  $P(z^1, z^2, g) = S(z^1, g) - S(z^2, g)$  in [2] has a monetary interpretation and changes in the shortage function give a general measure of the productive value of a change from  $z^1$  to  $z^2$ .

To evaluate diversity, we follow Chavas (2009) and consider dividing the original system into  $K$  separate subsystems, the  $k$ th system involving netputs  $z^k$ ,  $k = 1, \dots, K$ ,  $2 \leq K \leq m$ . Each of the  $K$  systems is "more specialized" than the original system and satisfies  $z^k \neq 0$  and  $z^k \neq z/K$ ,  $k = 1, \dots, K$ . We want to compare the productivity of the original system versus the  $K$  "more specialized" subsystems. To keep the analysis meaningful, we focus our attention on the case where the aggregate netputs are held constant, with

<sup>4</sup> The technology exhibits free disposal if, for any  $z \in Z$ ,  $z' \leq z$  implies that  $z' \in Z$ .

$\sum_{k=1}^K z^k = z$ . In this context, using the shortage function [1], Chavas proposed the following measure of the productive value of diversity:

$$D(z, g) = \sum_{k=1}^K S(z^k, g) - S(z, g), \tag{3}$$

where  $z = \sum_{k=1}^K z^k$ . Equation [3] compares two

situations: one where the netputs  $z$  are involved in an integrated production process; and the other situation where there are  $K$  “more specialized” production processes, with  $z_k$  being the netputs used in the  $k$ th production process. Note that the restriction

$z = \sum_{k=1}^K z^k$  implies that, in each situation, the

same aggregate amounts of resources are used to produce the same aggregate netputs. It means that  $D(z, g)$  in [3] provides a measure of the number of units of the reference bundle  $g$  that can be obtained by producing  $z$  in an integrated system (compared to producing the same aggregate netputs  $z$  in  $K$  separate and “more specialized” production processes). Intuitively,  $D(z, g) > 0$  if there are productivity gains associated with an integrated use of the netputs  $z$ . This reflects that  $D(z, g) > 0$  corresponds to situations where the function  $S(z, \cdot)$  is subadditive<sup>5</sup> and “the whole is worth more than the sum of the parts.” And as discussed above, when the reference bundle  $g$  is chosen such that  $p \cdot g = 1$ , then  $D(z, g)$  in [3] provides a monetary measure of the value of diversity.

Our analysis considers situations where diversity concerns focus on specific goods. Let  $I = \{1, \dots, m\}$  denote the set of netputs. To analyze the productivity of the  $K$  “more specialized” systems in [3], rewrite the netput set  $I$  as  $I = \{I_a, I_{b1}, I_{b2}, \dots, I_{bK}\}$ , where  $I_b = \{I_{b1}, I_{b2}, \dots, I_{bK}\}$  is the subset of netputs relevant in the evaluation of diversity, and  $I_{bk}$  is the set of goods that the  $k$ th production process specializes in,  $k = 1, \dots, K$ , with  $2 \leq K \leq m$ . From

equation [3], let  $z^k$  denote the netputs involved in the  $k$ th system,  $k = 1, \dots, K$ , and satisfying

$\sum_{k=1}^K z^k = z$ . Let  $\beta_k \in (1/K, 1]$  characterize the

degree to which the  $k$ th situation is specialized in the goods in  $I_{bk}$ ,  $k = 1, \dots, K$ . Following Chavas (2009), we consider the following pattern of diversification:

$$z_i^k = z_i/K, \text{ if } i \in I_a, \tag{4a}$$

and

$$z_i^k = z_i^+ \equiv \beta_k z_i \text{ if } i \in I_{bk}, \tag{4b}$$

$$= z_i^- \equiv z_i(1 - \beta_{k'})/(K - 1) \text{ if } i \in I_{bk'} \neq I_{bk}, \tag{4c}$$

for some  $\beta_k \in (1/K, 1]$ ,  $k = 1, \dots, K$ .<sup>6</sup> First, equation [4a] divides the goods in  $I_a$  equally among the  $K$  production processes. This means that we focus our attention only on the diversity of goods in  $I_b$ . Second, equations [4b] and [4c] establish the patterns of specialization for the goods in  $I_b$ . To illustrate, consider the case where  $I_b = \{1, 2, 3\}$  and  $K = 3$ . Then, equations [4b] and [4c] give  $(z_1^1, z_2^1, z_3^1) = (\beta_1 z_1, (1 - \beta_2)z_2/2, (1 - \beta_3)z_3/2)$ ,  $(z_1^2, z_2^2, z_3^2) = ((1 - \beta_1)z_1/2, \beta_2 z_2, (1 - \beta_3)z_3/2)$ , and  $(z_1^3, z_2^3, z_3^3) = ((1 - \beta_1)z_1/2, (1 - \beta_2)z_2/2, \beta_3 z_3)$ , which always satisfy  $\sum_{k=1}^3 z_i^k = z_i$ ,

$i \in I_b$ . When  $\beta_k = 1$  for all  $k$ , this implies complete specialization in  $I_b$ , with  $z_i^k = z_i$  for  $i \in I_{bk}$  and  $z_i^k = 0$  for  $i \in I_{bk'} \neq I_{bk}$ . Alternatively, when  $\beta_k \in (1/K, 1)$ , this allows for partial specialization. Thus, the parameter  $\beta_k \in (1/K, 1]$  allows for varying amounts of specialization in the netputs  $z_b$ , in other words, varying amount of diversity among the  $K$  processes. In general, the degree of specialization in the  $k$ th process increases with  $\beta_k$ . This means that the loss in diversity in the  $K$  processes also increases with the  $\beta_k$ 's.

With  $z^k \equiv (z_a^k, z_b^k)$  given in [4a] and [4c], equation [3] becomes

<sup>5</sup> This is similar to the subadditivity of the cost function discussed by Baumol, Panzar, and Willig (1982) in the context of economies of scope.

<sup>6</sup> This extends the analysis presented by Chavas and Kim (2007). By allowing the  $\beta_k$ 's to vary, our approach can capture heterogeneous patterns of specialization.

$$D(z, \beta, g) = \sum_{k=1}^K S(z^k, g) - S(z, g), \quad [5]$$

where  $\beta = (\beta_1, \dots, \beta_K)$ . When applied to an ecosystem, equation [5] provides a measure of the productive value of diversity.<sup>7</sup> It measures the number of units of the reference bundle  $g$  that can be obtained when the goods  $z$  are part of a joint production process in the ecological system (compared to the case where goods  $z$  are part of  $K$  specialized production processes satisfying [4a] and [4c] and producing the same aggregate netputs  $z$ ).

While equation [5] provides a basis to evaluate the productive value of diversity, it is of interest to identify the sources of this value. Following Chavas (2009), the value of diversity can be decomposed into additive components. First, let  $S(z, g) \equiv S_V(z, g) + S_F(z, g)$ . This decomposes the shortage function  $S(z, g)$  into two parts: a “variable function”  $S_V(z, g)$  assumed to be continuously differentiable in  $z$ , and a “fixed function”  $S_F(z, g)$  assumed to be a step function that is constant for  $z \neq 0$  and satisfies  $S_F(0, g) = 0$  (with possible discontinuities at  $z = 0$ ). Thus,  $S_F(z, g)$  (and hence  $S(z, g)$ ) can exhibit jump-discontinuities in  $z$  when any netput  $z_i$  changes between zero and an arbitrarily small nonzero number. As discussed by Chavas (2009), the jump-discontinuities reflect the presence of catalysts (or repressors) when the presence of a small quantity of  $z_i$  generates a large increase (decrease) in productivity. It follows that the fixed function  $S_F(z, g)$  can capture “catalytic effects” when a small increase in some netputs from 0 has a large effect on productivity.

Second, consider ordering the netputs such that  $(z^1, \dots, z^m) = (\{z_i: i \in I_a\}, \{z_i: i \in I_{b1}\}, \dots, \{z_i: i \in I_{bK}\})$ . Let  $z_a = \{z_i: i \in I_a\}$ ,  $z_{bk} = \{z_i: i \in I_{bk}\}$ ,  $z_b = (z_{b1}, \dots, z_{bK})$ ,  $z_{b \setminus bk} = (z_{b1}, \dots, z_{b, k-1}, z_{b, k+1}, \dots, z_{bK})$ , and  $z_{b, i: j} = (z_{bi}, z_{b, i+1}, \dots, z_{b, j-1}, z_{bj})$  for  $i < j$ . Using this notation and equations [4], it follows that  $z^k = (z_a/K, z_{bk}^+, z_{b \setminus bk}^-)$ ,  $k = 1, \dots, K$ . In this con-

text, Chavas showed that the value of diversity  $D(z, \beta, g)$  in [5] evaluated at netputs  $z = (z_a, z_b)$  can be decomposed as follows:

$$D \equiv D_C + D_R + D_V + D_F, \quad [6]$$

where

$$D_C \equiv \sum_{k=1}^{K-1} \left\{ \int_{z_{bk}^-}^{z_{bk}^+} \frac{\partial S_V}{\partial \gamma}(z_a/K, z_{b, 1:k-1}^-, \gamma, z_{b, k+1:K}^-, g) d\gamma - \int_{z_{bk}^-}^{z_{bk}^+} \frac{\partial S_V}{\partial \gamma}(z_a/K, z_{b, 1:k-1}^-, \gamma, z_{b, k+1:K}^+, g) d\gamma \right\}, \quad [7a]$$

$$D_R \equiv KS(z/K, g) - S(z, g), \quad [7b]$$

and

$$D_V \equiv S(z_a/K, z_b^+, g) + (K-1)S(z_a/K, z_b^-, g) - KS(z/K, g), \quad [7c]$$

$$D_F \equiv \sum_{k=1}^K S_F(z_a/K, z_{bk}^+, z_{b \setminus bk}^-) - S_F(z_a/K, z_b^+, g) - (K-1)S_F(z_a/K, z_b^-, g). \quad [7d]$$

Equation [6] decomposes the value of diversity  $D(z, g)$  in [5] into four additive terms:  $D_C$ ,  $D_R$ ,  $D_V$ , and  $D_F$ . As discussed by Chavas (2009), each term characterizes a different component of  $D$ . The term  $D_C$  in [7a] is the complementarity component, with  $D_C > 0$  in the presence of complementarity, that is, when  $z_{bk}$  has positive effects on the marginal product of  $z_{b \setminus bk}$  (implying positive synergies between  $z_{bk}$  and  $z_{b \setminus bk}$ ),  $k = 1, \dots, K$ . This establishes that complementarity (as reflected by the term  $D_C$ ) is one of the components of the value of diversity. This supports the arguments that complementarity is an important contributing factor to the value of diversity (e.g., Faith et al. 2003; Justus and Sarkar 2002; Loreau and Hector 2001). In the context of agrobiodiversity, complementarity comes from positive externalities across agricultural activities due to more effective use of resources (e.g., labor, nutrients), reduction in pest infestation, increases in soil productivity, and/or better adaptation to local agroclimatic conditions. While the empirical identification of the exact source of complementarity re-

<sup>7</sup> It should be noted that the methodology is very general. It can be used to measure biodiversity value under general conditions. This includes crop biodiversity as a special case, as analyzed below in the context of a farming system in Ethiopia.

mains challenging, our analysis will provide a basis for evaluating both the presence and magnitude of complementarity effects among crops (see below).

The term  $D_R$  in [7b] captures scale effects. As shown by Chavas (2009),  $D_R$  vanishes under constant return to scale (CRTS) but is positive under increasing return to scale (IRTS) and negative under decreasing return to scale (DRTS). This establishes how returns to scale (as captured by the term  $D_R$ ) can affect the value of diversity. For example, under IRTS, scale effects generate a positive value of diversity because fragmented systems are “too small” to function effectively. This supports the arguments that scale effects can play an important role in the evaluation of ecological functioning (e.g., Debinski and Holt 2000; Bisonette and Storch 2002).

The term  $D_V$  in [7c] reflects the effect of convexity. Chavas (2009) showed that  $D_V \geq 0$  under a convex technology. Intuitively, a convex technology means diminishing marginal productivity, a standard characterization of resource scarcity. It means that the term  $D_V$  captures the role of resource scarcity. This shows that resource scarcity contributes positively to the value of diversity. Alternatively, our analysis indicates that  $D_V < 0$  can arise only under a nonconvex technology. The identification of such effect seems to be new in the literature. Its empirical relevance will be evaluated below.

Finally, the term  $D_f$  in [7d] reflects catalytic effects associated with discontinuous productivity effects. In the absence of discontinuity,  $S_f(z, g) = 0$ , implying that  $D_f = 0$  in equation [7d]. Associating discontinuities with catalytic effects around  $z = 0$ , this shows that catalytic effects can affect the value of diversity. However, such effects are expected only around  $z = 0$ . From equation [7d], it means that  $\beta \in (1/K, 1)$  implies  $D_f = 0$ . Alternatively, the catalytic component  $D_f$  can be nonzero only when some  $\beta_k = 1$ , that is, only under a complete loss of diversity.

From equations [7], the value of diversity can arise from complementarity among environmental goods in  $z_b$  ( $D_C > 0$ ), from increasing returns to scale ( $D_R > 0$ ), from a convex technology ( $D_V \geq 0$ ), and/or from catalytic effects (when  $D_f \geq 0$ ). This identifies the role of

complementarity as an important contributing factor to the value of diversity. However, it also shows that the presence of complementarity is in general not sufficient to generate a positive value for diversity. For example, when  $D_R < 0$  under decreasing returns to scale (DRTS) or when  $D_V < 0$  under a nonconvex technology, it becomes possible to obtain  $D < 0$  even in the presence of complementarity. This indicates a need to evaluate each of the components identified in equations [6] and [7]. To the extent that the relative importance of each component may vary across ecosystems, this stresses the need for empirical analyses.

### III. EMPIRICAL APPLICATION

This section presents an empirical illustration of the methodology discussed above. Our empirical analysis focuses on an agricultural system where inputs  $x = (x_1, x_2, \dots)$  are being used to produce outputs  $y = (y_1, y_2, y_3, \dots)$ , with  $z \equiv (y, -x) \in Z$ . Choosing  $g = (1, 0, \dots, 0)$  and assuming that  $y_1$  is an output satisfying free disposal, it follows that the production technology  $Z$  can be written as  $Z = \{(y, -x) : S(y_1, y_2, y_3, \dots, -x, g) \leq 0, (y, -x) \in \mathbb{R}^{m+n}\}$ , where  $S(y_1, y_2, y_3, \dots, -x, g)$  is the shortage function defined in [1]. Letting  $S(y_1, y_2, y_3, \dots, -x, g) \equiv y_1 - F(y_2, y_3, \dots, x)$ , the frontier technology is represented by the multi-output production function  $y_1 = F(y_2, y_3, \dots, x)$ . An empirical application of our methodology then requires the specification and estimation of the production function  $y_1 = F(y_2, y_3, \dots, x)$ .

First, we specify a parametric form for the production function:  $F(y_2, y_3, \dots, x) = f(y_2, y_3, \dots, x, \beta)$ , where  $\beta$  is a set of parameters to estimate. Second, we add an error term to generate the econometric model

$$y_1 = f(y_2, y_3, \dots, x, \beta) + e, \quad [8]$$

where  $e$  is a random variable distributed with mean  $\mu$  and finite variance. Equation [8] is an econometric model that can be used to generate a consistent estimate  $\beta^e$  of  $\beta$ . When the error term reflects only measurement errors,



then we can assume that  $e$  has mean zero, with  $\mu = 0$ . But in the presence of technical inefficiency, one can expect  $\mu < 0$ , as  $\mu$  reflects the distance (measured in number of units of  $y_1$ ) between an actual production plan and the upper bound of the feasible set (see Kumbhakar and Lovell [2000] for a review of the literature on stochastic frontier estimation). Except for the intercept, equation [8] can then be estimated econometrically to give a consistent estimate  $\beta^e$  of the parameters  $\beta$ . The associated mean shortage function is  $E[S(y_1, y_2, y_3, \dots, -x, g)] = y_1 - f(y_2, y_3, \dots, x, \beta^e) - \mu$ . Below, we assume that technical inefficiency remains constant between the original situation and the  $K$  specialized scenarios used in the evaluation of diversity. This means that the inefficiency effects cancel each other in the empirical evaluation of equations [3], [6], and [7], in other words, that technical inefficiencies do not affect the empirical estimation of the value of diversity and its components. This assumption is used in the empirical investigation of the value of crop biodiversity presented below.

The estimation of equation [8] poses at least two econometric challenges. First, we would like  $f(y_2, y_3, \dots, x, \beta)$  to provide a flexible representation of the effects of outputs ( $y_2, y_3, \dots$ ) on the productivity of the ecosystem. This is feasible when the number of outputs remains small. However, this becomes problematic if the number of outputs becomes large (e.g., more than five). Indeed, a flexible representation of output effects with a large number of outputs requires a large number of parameters, implying the prospects of facing severe collinearity problems. Second, when applied to an agroecosystem, equation [8] involves netputs that are subject to direct management. This means that the choice of  $(y, x)$  generates the possibility of endogeneity issues. Indeed, if the netput decisions for  $(y, x)$  depend on information that is not available to the econometrician, then they would become correlated with the error term  $e$  in [8], implying the presence of endogeneity bias. This bias means that standard estimation methods (e.g., least squares) will provide biased and inconsistent parameter estimates. This suggests the need to address endogeneity issues explicitly in the econometric analysis. This can be done by using instrumental variable

estimation methods that provide consistent parameter estimate in the presence of endogeneity.

Our empirical analysis focuses on analyzing the productivity effects of diversification among three outputs (as further discussed below). Three is “large enough” to allow the investigation of the benefit of diversity in an agroecosystem, yet “small enough” to avoid collinearity problems. In this context, with three outputs, we specify [8] to be quadratic function of outputs  $y$ . This provides a parsimonious specification allowing for a flexible representation of how each output affects the marginal product of other outputs. We also assume that inputs  $x$  enter [8] in log form.<sup>8</sup> To address endogeneity issues, we adopt an instrumental variables estimation approach. A detailed discussion on the choice of instruments and testing procedures is presented in Section V below. We also adopt village fixed effects to control for village-specific unobservable characteristics.

#### IV. SITE DESCRIPTION AND DATA

Our empirical analysis focuses on the productivity of an agroecosystem in Ethiopia. It relies on a dataset from a farm survey conducted in 1999 and 2000 in the Tigray region of Ethiopia. The data were collected by researchers from Mekelle University, the International Food Policy Research Institute, and the International Livestock Research Institute. The survey involved a stratified sampling of farm households, with the strata being chosen according to agricultural potential, market access, and population density (Pender et al. 2001). In the Tigray region, peasant associations (PAs) were stratified by distance to the *woreda* town (greater or less than 10 km). Three strata were defined, with 54 PAs randomly selected across the strata. PAs closer to towns were selected with a higher sampling frequency to assure adequate representation. From each of the remaining PAs, two villages were randomly selected, and from each village, five households were randomly selected.

<sup>8</sup> Alternative specifications were also estimated. They provided results that were qualitatively similar to the ones reported below.

TABLE 1  
Descriptive Statistics

Variable	Definition	Mean	Std. Dev.	Min.	Max.
Teff	Quantity produced (kg)	151.007	207.685	0	1,292
Barley	Quantity produced (kg)	179.521	235.828	0	1,363
Wheat	Quantity produced (kg)	82.1179	142.365	0	777
Animal traction	Animal traction (oxen-days)	28.825	19.8131	2	144
Land	Land for cereals (m <sup>2</sup> )	6,631.93	4,694.81	612	43,194
Labor	Labor (person-days)	86.2286	53.1831	15	429
Fertilizer	Fertilizer use (kg)	18.8431	23.1647	0	150
Rainfall	Rainfall (mm/year)	648.909	120.912	420.4	893.55
Soil fertility	Share of land classified as high fertility	0.092857	0.290752	0	1
Soil erosion	Share of land affected by severe erosion and waterlogging	0.442857	0.497613	0	1
Slope	Share of land on steep slope	0.088525	0.219294	0	1
South	Location dummy	0.264286	0.441742	0	1
East	Location dummy	0.275	0.447314	0	1
West	Location dummy	0.128571	0.335324	0	1
Improved seeds	Adoption of improved seeds (Yes = 1; No = 0)	0.107143	0.309849	0	1
Soil conservation	Share of land under reduced tillage	0.10861	0.263086	0	1
Farmer's experience	Number of years of farming the plots	9.25	2.36	2	20
Other crops	Land in other crops (Yes = 1; No = 0)	0.44	0.6	0	1

A total of 50 PAs, 100 villages, and 500 households were surveyed. Usable data were available for 96 villages. After dealing with outliers and observations with missing values, 292 households remained.

The survey data provide a basis for evaluating the effects of diversification on farm productivity. Cereals are the most important crops grown in the Tigray region of Ethiopia. The three most cultivated crops are teff, barley, and wheat. Ethiopia is a “biodiversity hot spot”: it is a recognized global center of genetic diversity for cereals (Vavilov 1949; Harlan 1992). This is reflected in the farm diversification strategies documented in the survey data. Our analysis of the productivity effects of crop biodiversity focuses on three outputs: teff, barley, and wheat. They are produced, respectively, by 61%, 50% and 34% of the farms in the sample. About 45% of farmers in the sample grow other crops (other than these three crops). The use of conventional inputs is minimal. Farmers rely mostly on labor and oxen power. Table 1 reports the variables used in this analysis, along with their descriptive statistics. Agroecological conditions in the Tigray region are challenging because of pervasive land degradation and erratic rainfall. It has been argued that biodi-

versity benefits may be larger when agroecological conditions are more difficult (Callaway and Walker 1997). This provides a strong motivation for our empirical analysis and its documentation of the productivity effects of crop biodiversity.

## V. ECONOMETRIC RESULTS

Using farm-level data from the Ethiopian survey, equation [8] was specified and estimated by instrumental variable method. The analysis considers the three main outputs:  $y_1 = \text{teff}$ ,  $y_2 = \text{barley}$ , and  $y_3 = \text{wheat}$ . The inputs  $x$  include animal traction, land, labor, fertilizer, and rainfall. To address the issue of potential heterogeneity across farms, a number of additional variables were added to capture the variations in agroclimatic conditions across observations in the sample. They include soil fertility, soil erosion, slope, location, the use of improved seeds, and the presence of soil conservation practices. We also include other crops and farmers' experience as additional explanatory variables. The relevance of these last two variables was evaluated econometrically by estimating the model with and without such variables. We also included village fixed effects in the

model. The inclusion of village fixed effects controls for unobserved heterogeneity related to institutional factors and location-specific factors (Di Falco and Chavas 2009). As noted above, equation [8] was specified to be quadratic in outputs ( $y_2$ ,  $y_3$ ); linear in the logarithm of land, labor, and animal traction; and linear in other variables. The quadratic output terms allow for flexible patterns of marginal productivity, including the effect of any output on the marginal product of other outputs.

As mentioned earlier, we rely on instrumental variable (IV) estimation to address endogeneity issues. The choice of instruments can, notoriously, be complex. The instruments should all be correlated with the set of endogenous variables but not correlated with the error terms. We identified a set of suitable instruments following both theory and existing literature (Pender et al. 2001; Di Falco and Chavas 2009). Farm agroecological heterogeneity and land share under conservation measures can be used as instruments for the output variables, the adoption of conservation measures, and the interaction terms. We extend the matrix of instruments using also the information on the distance from the input supplier. This is a measure of access to the seeds market that should be correlated with the acreage allocation decisions among crops, but uncorrelated with the error terms.

Using these instruments, we tested for endogeneity of outputs (barley and wheat), their interactions, and the soil conservation measure. The *C*-test statistic for endogeneity is reported at the bottom of Table 2: it provides strong evidence of endogeneity for these variables. On that basis, the IV estimation method is used to obtain consistent parameters estimates. To assess the validity of these instruments, both the Hausman test and regression residuals tests for endogeneity were applied. The Sargan-Hansen test of overidentifying restrictions was used to investigate whether the orthogonality conditions between the instruments and the error term are satisfied. We failed to reject the null hypothesis of orthogonality. Therefore these instruments appear to be uncorrelated with the error term. We then addressed the issue of the “relevance” of the instruments, meaning that the instruments should be partially correlated with the endog-

enous regressors. We used the underidentification Kleibergen-Paap LM test to check whether the equation is identified. The test result is 10.9 (with  $p$ -value = 0.05). We complemented the diagnostic with a Stock-Wright test statistic where the null hypothesis is that the coefficients of the endogenous variables in the structural equation are jointly equal to zero. The test statistic is 81.46 ( $p$ -value < 0.01). These statistics provide evidence that the instruments seem both relevant and not correlated with the error term. Therefore the choice of instruments seems appropriate.

A number of specification tests were conducted (they are reported at the bottom of Table 2). The null hypothesis of homoskedasticity was tested against the alternative hypotheses of (1) general heteroskedasticity, and (2) multiplicative heteroskedasticity. Tests results confirmed the presence of heteroskedasticity and that multiplicative heteroskedasticity was present. To obtain efficiency gains, we therefore implemented a weighted estimation method using weights obtained from the consistent estimate of the error variance. We report below the results for both robust White standard errors and weighted regression. The estimation results are reported in Table 2. For comparison purpose, the ordinary least squares estimates are shown in Column (a). The IV estimates reported in Table 2 include three specifications: IV without and with controls for farmer’s experience and “other crops” (in Columns (b) and (c), respectively), and IV with village fixed effects (in Column (d)).

The empirical estimates appear qualitatively robust. Indeed, comparing the results from the different estimators, we find that the conventional inputs (animal traction, land, labor, and fertilizer) are all positive and statistically significant. Also, the estimated coefficients for outputs show statistical significance. The coefficient of the linear term for barley is negative and statistically significant at the 5% level in three different estimations. It is significant at the 10% level in the remaining estimator (IV with controls). The interaction term (barley  $\times$  wheat) is positive and statistically significant at the 5% level for all the estimators. This indicates the presence of positive interaction effects across crops. Such

TABLE 2  
Shortage Function Estimation

Variable	OLS (a)	OLS, Weighted Least Squares (b)	IV (c)	IV, Village Fixed Effects (d)	IV, Village Fixed Effects, Weighted Least Squares (e)
Barley	-0.42*** (0.08)	-0.477*** (0.0939)	-0.52* (0.3)	-0.688** (0.269)	-0.648*** (0.0940)
Barley <sup>2</sup>	0.00028*** (8.30E-05)	0.000319*** (0.0000767)	-0.00017 (0.0004)	0.000190 (0.000258)	0.000423*** (0.0000834)
Wheat	-0.273*** (0.1)	-0.350*** (0.114)	-0.6 (0.7)	-1.234** (0.492)	-0.469*** (0.0614)
Wheat <sup>2</sup>	6.83E-06 (0.00015)	0.0000176 (0.000126)	-0.0029* (0.0017)	0.0000409 (0.000403)	0.0000856*** (0.0000311)
Barley × Wheat	0.00033*** (0.0001)	0.000277*** (0.0001)	0.0045** (0.0018)	0.00259** (0.00104)	0.000534*** (0.000140)
Animal traction	60.18*** (15.68)	71.93*** (18.28)	121.36*** (30.7)	89.34*** (25.09)	84.04*** (5.025)
Land	16.85** (8.3)	7.338 (9.005)	10.62 (12.9)	0.596 (8.671)	-2.566 (2.450)
Labor	87.3*** (15.19)	75.57*** (21.66)	60.97* (33.52)	81.03*** (26.95)	84.83*** (10.73)
Fertilizer	1.11*** (0.436)	1.363** (0.649)	0.94* (0.56)	1.405** (0.712)	1.425*** (0.116)
Rainfall	0.11 (0.157)	0.0154 (0.177)	0.178 (0.33)	0.0600 (0.415)	0.441 (0.407)
Soil fertility	14.42 (25.02)	19.40 (38.55)	31.02 (43.86)	37.40 (40.83)	36.42*** (6.138)
Soil erosion	-13.2 (14.6)	-15.59 (18.61)	-18.9 (26.2)	-3.219 (19.31)	-3.394 (4.482)
Slope	-37.09 (30.59)	-48.67 (30.79)	-96.61* (57.7)	-54.29 (37.71)	-49.29*** (12.24)
South	-23.1 (20.1)	3.570 (27.39)	-27.4 (35.99)		
East	-63.7*** (19.9)	-63.42*** (21.81)	-123.4** (51.14)		
West	59.09* (25.97)	59.78 (38.76)	13.85 (45.73)		
Improved seed	-15.4 (23.08)	-19.30 (24.76)	125 <sup>a</sup> (81.03)	70.84 (47.14)	-7.963 (8.655)
Soil conservation	59.7* (34.2)	61.01* (34.50)	241.80*** (86.8)	154.7*** (59.27)	70.34*** (9.315)
Experience			-0.636 (5.2)	2.639 (3.230)	-1.458 (1.408)
Other crops			-107.2*** (32.71)	-98.12*** (28.75)	-50.29*** (4.799)

Note: Dependent variable: teff production.  $N=292$ . Hansen  $J$ -test: chi-square test statistic 3.56 (with 2 degrees of freedom),  $p$ -value = 0.168.  $C$ -test for endogeneity of Barley, Wheat, Barley<sup>2</sup>, Wheat<sup>2</sup>, Barley × Wheat, Soil conservation: 17.31 ( $p$ -value = 0.008). Underidentification test, Kleibergen-Paap  $LM$ -statistic: 10.9 (0.05). Breusch-Pagan test for heteroskedasticity: chi-square test statistic 193.92 (with 18 degrees of freedom),  $p$ -value < 0.001. Robust standard errors have been used in Columns (a), (c), and (d). IV, instrumental variable; OLS, ordinary least squares.

<sup>a</sup> 10% two-sided test; robust standard errors in parentheses.

\* Significant at the 10% level; \*\* significant at the 5% level; \*\*\* significant at the 1% level.

positive interaction effects on productivity capture the presence of complementarity in the agroecosystem. Such effects and their implications for the value of diversity are further evaluated below. In Table 2, while the coef-

ficients related to agroecological conditions are consistent with expectation, none of them are statistically significant at the 10% level in any of the estimated models. Among the location dummies, only the dummy for “east”

TABLE 3

Simulated Value of Diversity  $D$  and its Decomposition (Complementarity Effect  $D_C$ , Scale Effect  $D_R$ , and Convexity Effect  $D_V$ )

Diversity	$D = D_C + D_R + D_V$	$D_C$	$D_R$	$D_V$	$D_C + D_V$
Diversity measure	56.75	99.18	-1.15	-41.28	57.90
Standard error	134.47	29.78	107.99	14.14	34.31
$p$ -Value for testing $D=0$	0.34	0.001	0.507	0.001	0.090

Note: Evaluated at a farm size equal to 1.75 times the sample mean, and at a degree of specialization  $\beta = 0.8$ .

displayed a negative and strongly significant coefficient. This is consistent with evidence that the eastern part of the region has the worst conditions for agricultural production (Gebremedhin, Smale, and Pender 2006). The use of improved seeds does not have a statistically significant effect. The share of land under reduced tillage is found to have an important impact on productivity. The estimated coefficient, indeed, is always positive and statistically significant. This result indicates that soil conservation measures can be a win-win strategy in this agricultural system. Finally, the farmer's experience is not statically significant, while the amount of land allocated the other crops is negatively and significantly related to teff production.

We also investigated whether the production function  $f(\cdot)$  in [8] exhibited discontinuities at  $y=0$ . This was done by introducing dummy variables equal to 1 if  $y_i=0$  and zero otherwise, followed by testing their statistical significance. Using a Wald test and a 10% significance level, we failed to reject the null hypothesis that these dummy variables have a significant effect on productivity. Thus, we did not find statistical evidence that the production function  $f(\cdot)$  was discontinuous at  $y=0$ . This means that we did not find statistical evidence of significant "catalytic effects." On that basis, our analysis proceeds assuming that the production function  $f(\cdot)$  in [8] is continuous everywhere.

## VI. IMPLICATIONS

The estimated production function (reported in Table 2) provides a basis for investigating the productivity of the agroecosystem. Of special interest are the implications for the value of diversity  $D$  given in [5] and its com-

ponents given in [6] and [7]: scale effect  $D_R$ , complementarity effect  $D_C$ , and convexity effect  $D_V$ .<sup>9</sup> In this context, based on the estimated production function, a Monte Carlo simulation is used to evaluate the distribution of  $D$  and its components. This provides a basis for assessing both the magnitude of the diversity measures and their statistical significance. Based on the parameter estimates reported in Table 2 (Column (c)),<sup>10</sup> the simulation results are presented in Tables 3, 4, and 5.

Table 3 shows the diversity measure  $D$  and its components: complementarity  $D_C$ , scale  $D_R$ , and convexity  $D_V$ , evaluated for a farm of a size equal to 1.75 times the sample mean and facing a degree of specialization  $\beta$  equal to 0.8.<sup>11</sup> Table 3 shows that both the convexity effect and the complementarity effect are statistically significant. The complementarity effect  $D_C$  is found to be positive and significant at the 5% level. This provides evidence that each crop tends to have a positive effect on the marginal productivity of other crops. Comparing  $D_C=99.18$  with an average teff production of 151, the productivity benefit associated with complementarity amounts to a 65% boost in productivity. These large effects are presumably capturing the positive effects of niche partitioning and crop rotation on soil fertility. Thus, our analysis documents that the complementarity component of diversity provides significant productivity benefits to the functioning of the agroecosystem.

<sup>9</sup> Given the lack of statistical evidence about catalytic effects, the estimated model implicitly assumes that  $D_f=0$ .

<sup>10</sup> The simulation was also conducted using the other IV estimates reported in Table 2. While this affected the quantitative results, the qualitative conclusions were similar.

<sup>11</sup> Alternative degrees of specialization were also explored. See below.

The scale component  $D_R$  in Table 3 is negative ( $-1.15$ ) but not statistically significant. As discussed above,  $D_R = 0$  is obtained under constant returns to scale (CRTS). This indicates that the scenario evaluated in Table 3 corresponds to a situation where CRTS cannot be rejected. We also conducted the analysis reported in Table 3 under different farm sizes. We did find some evidence that  $D_R$  became positive and statistically significant for very small farms. This indicates the presence of increasing returns to scale (IRTS) for very small farm sizes, where  $D_R > 0$  under IRTS means that scale effects can contribute positively to the value of diversity. However, such evaluations involved simulating farm sizes that were at the lower bound of observations from the sample. This means that the statistical evidence in favor of IRTS has to be interpreted with caution: it is not wise to extrapolate outside of the sample information. We found that, within the range of most farm sizes observed in the sample,  $D_R$  was not statistically different from zero (as in the case reported in Table 3). This means that, for most farms, the technology of the agroecosystem seems to exhibit CRTS (in which case  $D_R = 0$ ).<sup>12</sup> Thus, the evidence against CRTS is weak, implying that the scale effect  $D_R$  does not appear to be an important part of the value of diversity in our agroecosystem.

Table 3 shows that the convexity effect  $D_V$  is negative:  $-41.28$ . And it is statistically significant at the 1% level. As discussed above,  $D_V$  is expected to be positive under convex technology (i.e., a technology exhibiting decreasing marginal returns). This provides evidence that our agroecosystem does not exhibit decreasing marginal returns in outputs, and that its underlying technology is not convex. Moreover, this nonconvexity means that the convexity component  $D_V$  provides an incentive to specialize. Comparing  $D_V = -41.28$  with an average teff produc-

tion of 151, the productivity loss associated with (non)convexity amounts to a 27% decline in productivity. Besides being statistically significant, this also appears to be economically important. In other words, our empirical analysis indicates that nonconvexity in the technology of the agroecosystem provides disincentives to diversify and contributes to reducing the value of diversity. We conjecture that such effects are related to the fact that diverse systems can become more complex to manage, suggesting that managerial difficulties may provide incentives to specialize.

When putting all components together, Table 3 shows that the value of diversity  $D$  remains positive:  $D = 56.75$ . This amounts to a 37% contribution to productivity. This reflects the fact that the complementarity component ( $D_C = 99.18$ ) is large enough to dominate the negative convexity component ( $D_V = -41.28$ ). Even if we ignore the (non-significant) scale component  $D_R$ , note that  $D_C + D_V = 57.90$  is positive and contributes to a 38% boost in productivity. However, neither  $D$  nor ( $D_C + D_V$ ) is statistically different from zero at the 5% significance level. This means that the evidence of significant overall value of diversity in our agroecosystem is weak. The reason is that, even in the presence of significant complementarity benefits, such benefits are canceled out by opposite effects from the (non)convexity component.

Table 4 presents simulation results evaluating the effects of the degree of specialization  $\beta$  on the complementarity component  $D_C$  and the convexity component  $D_V$ . It shows that both  $D_C$  and  $D_V$  are small under mild specialization (e.g.,  $\beta = 0.4$ ). However, their magnitude increases rapidly with  $\beta$ , reflecting large effects on productivity. In all cases, the magnitude of the complementarity component dominates the magnitude of the (non)convexity component. This means that their combined effect ( $D_C + D_V$ ) is always positive. However, these two effects tend to cancel each other, implying that their combined effect tends to be smaller and is no longer statistically significant. Thus, the evidence of nonsignificant overall value of diversity reported in Table 3 remains valid under alternative diversification schemes.

<sup>12</sup> We also conducted the analysis assuming CRTS. This was done by defining all inputs and outputs on a per-hectare basis. As discussed above, this implied  $D_R = 0$ . The estimates of the value diversity and its components were similar to the ones reported in this paper. This is consistent with the results reported in Table 3 showing no strong evidence against the CRTS hypothesis (where  $D_R = 0$ ).

TABLE 4  
Simulated Effects of the Degree of Specialization  $\beta$  on Complementarity  $D_C$  and Convexity  $D_V$

Measure of Diversity: Degree of Specialization $\beta$	$D_C$		$D_V$		$D_C + D_V$	
	Diversity Measure	Std. Err.	Diversity Measure	Std. Err.	Diversity Measure	Std. Err.
$\beta = 0.4$	2.02***	0.81	-0.84***	0.29	1.18	0.70
$\beta = 0.6$	32.37***	12.99	-13.48***	4.62	18.91	11.20
$\beta = 0.8$	99.18***	29.78	-41.28***	14.14	57.90	34.31
$\beta = 1$	202.41***	81.19	-84.25***	28.85	118.17	70.01

Note: Evaluated at a farm size equal to 1.75 times the sample mean.  
\*\*\* Significant at the 1% level.

TABLE 5  
Simulated Effects of Farm Size on Complementarity  $D_C$  and Convexity  $D_V$

Measure of Diversity: Farm Size (Proportion of Sample Mean)	$D_C$		$D_V$		$D_C + D_V$	
	Diversity Measure	Std. Err.	Diversity Measure	Std. Err.	Diversity Measure	Std. Err.
0.5	8.09***	3.25	-3.37***	1.15	4.72	2.80
1	32.39***	12.99	-13.49***	4.61	18.91	11.20
1.5	72.87***	29.33	-30.33***	10.39	25.20	25.20
2	129.54***	51.96	-53.92***	18.46	75.62	44.81

Note: Evaluated at a degree of specialization  $\beta = 0.8$ .  
\*\*\* Significant at the 1% level.

Table 5 presents simulation results evaluating the effects of farm size on the complementarity component  $D_C$  and the convexity component  $D_V$ . It shows that, although they remain statistically significant, both  $D_C$  and  $D_V$  tend to be small on small farms. However, their magnitude increases rapidly with farm size. This indicates large and significant impacts of each component on larger farms. Table 5 provides evidence that, in absolute value, both the complementarity component and the (non)convexity component increase with farm size. In all cases, the magnitude of the complementarity component dominates the magnitude of the (non)convexity component. This means that their combined effect ( $D_C + D_V$ ) is always positive. Again, these two effects tend to cancel each other, implying that their combined effect is no longer statistically significant. This indicates that the evidence of nonsignificant overall value of diversity reported in Table 4 remains valid for a wide range of farm sizes.

## VII. CONCLUDING REMARKS

We have presented an analysis of the value of crop biodiversity in an agroecosystem, with an application to food production in the Highlands of Ethiopia. The approach applies under general conditions. For example, it allows for a nonconvex technology (where diminishing marginal productivity may not hold). The analysis relies on Luenberger's (1995) shortage function to provide a measure of the productive value of crop biodiversity. When positive, this value reflects the fact that an ecosystem is worth more than the "sum of its parts." Following Chavas (2009), this value can be decomposed into four additive components, reflecting complementarity effects, scale effects, convexity effects, and catalytic effects. These components provide a useful framework to better understand the role of diversity in agroecosystems. For example, complementarity comes from positive externalities across agricultural activities. These

externalities can be associated with more effective use of resources, reduction in pest infestation, increases in soil productivity, and/or better adaptation to local agroclimatic conditions. While identifying the exact source of complementarity remains challenging, our analysis provides a basis for evaluating both the presence and the magnitude of complementarity effects among crops. This is illustrated in an application to an agroecosystem in Ethiopia.

The empirical analysis involved specifying and estimating the shortage function as a representation of the underlying technology. Relying on an instrumental variables estimator, the estimates were used to evaluate the productive value of crop biodiversity and its components. Results show that the value of crop diversity is positive. The complementarity effect was found to be positive and significant at the 5% level. In the context of the Ethiopian agroecosystem, this provides evidence that each crop tends to stimulate the marginal productivity of other crops. Our analysis shows that complementarity provides a positive and significant contribution to the productive value of crop diversity in the Ethiopian agroecosystem. We also found evidence that the convexity component of diversity value is negative and statistically significant. This corresponds to a technology that is not convex, that is, where marginal products of outputs are not diminishing. This means that the convexity component provides an incentive to specialize. In general, the (negative) convexity component is dominated by the (positive) complementarity component, generating a positive overall value of diversity. However, as these two terms tend to cancel each other, our estimate of the overall value of diversity is not statistically significant.

Our empirical analysis did not find statistical evidence that either the scale effect or the catalytic effect played a significant role in the value of crop biodiversity. The lack of evidence of a scale effect means that farm size does not have a large impact on the functioning of the agroecosystem in Ethiopia. However, our empirical results did suggest that both complementarity effects and convexity effects may increase with farm size.

While our investigation focused on the productive value of crop biodiversity, we should note that this value is only a part of the total value of the biodiversity of an ecosystem. This indicates that biodiversity issues need to be analyzed in a broader context (i.e., including nonagricultural activities). Additional research is also needed in evaluating the role of uncertainty, risk preferences, and their implications for the design and implementation of risk management schemes. In a dynamic context, this would mean addressing the issue of how new information that becomes available over time is used in ecosystem management. It should also be noted that, while we have documented the importance of some drivers behind the positive value of diversity, disentangling the exact mechanisms behind complementarities remains a challenging task. This is a good topic for future research. Finally, while our analysis of an Ethiopian agroecosystem illustrated the usefulness of our approach to biodiversity valuation, we should keep in mind that our empirical findings may not apply to alternative ecosystems. There is a need for additional empirical investigations of the productivity implications of ecosystem functioning. These appear to be good topics for future research.

### Acknowledgments

We would like to thank Fitsum Hagos, Menale Kasie, and Berhanu Gebremedhin for very useful comments on an earlier version of the paper. We thank two anonymous reviewers for useful comments and suggestions. The usual disclaimer applies.

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