On the Value of Agricultural Biodiversity

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Abstract

Crop biodiversity is very important for both the functioning of ecological systems and the generation of a vast array of ecosystem services. More agricultural biodiversity is associated with higher agriculture production and lower risk exposure. This article explores the recent contributions on the economics of agrobiodiversity. The focus is (mostly) on the empirical literature. Future issues are also highlighted.

1. INTRODUCTION

Agricultural biodiversity (or agrobiodiversity) is a component of biodiversity[1] referring to all diversity within and among species found in crop and domesticated livestock systems, including wild relatives, interacting species of pollinators, pests, parasites, and other organisms (Qualset et al. 1995, Wood & Lenné 1999). Domesticated biodiversity (i.e., crops) is located in agricultural landscapes (in situ). But it is also complemented by wild relatives stored in gene banks and breeders' collections (Smale 2006).[2]

Maintaining diverse plant varieties in farmers' fields, i.e., in situ conservation, vis-à-vis storing germplasms in gene banks, is increasingly regarded as an effective way of conservation of plant genetic resources (Benin et al. 2004, Bezabih 2008). At the heart of whether in situ conservation could be pursued as a fruitful strategy of keeping important germplasms alive is whether it generates farm-level benefits that are internalized by farmers.[3] Biodiversity is an important component of ecological systems (e.g., Tilman & Downing 1994; Tilman et al. 1996, 2005; Wood & Lenné 1999; Heal 2000). The relevance of biodiversity in the provision of ecosystem services is highlighted by growing evidence that biodiversity can support system productivity and that its loss can have adverse effects on the functioning of ecosystems (e.g., Naeem et al. 1994; Tilman & Downing 1994; Tilman et al. 1996, 2005; Zhu et al. 2000; Loreau & Hector 2001; Cork et al. 2002; Hooper et al. 2005; Landis et al. 2008).

Agricultural biodiversity is key for food production and supply.[4] In one view, agrobiodiversity is a part of natural capital, and the flow of services is the interest on the capital (Kontoleon et al. 2009). Farmers and breeders use biodiversity to adapt crops to different and changing production environments. Crop biodiversity is thus very important for both the functioning of ecological systems and the generation of a vast array of ecosystem services (e.g., Naeem et al. 1994, Tilman & Downing 1994, Tilman et al. 1996, Wood & Lenné 1999, Loreau & Hector 2001). These functions of biodiversity are crucial from an economic valuation perspective. Following Perrings (2010), there are two main implications. First, the value of biodiversity derives from the value of the final goods and services it produces. In this setup, biodiversity is an input into the production of these final goods and services. Second, this approach requires the specification of production functions that embed the ecosystem processes and ecological functions that connect biodiversity and ecosystem services. This article explores the recent contributions to the economics of agrobiodiversity. Of special interest is its relationship to agroecosystem services. The focus is (mostly) on the empirical literature. Future issues are also highlighted.

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[1] Here I use the terms biodiversity, diversity, and agrobiodiversity interchangeably.

[2] This is termed ex situ conservation. The emphasis in this article is on the in situ management of biodiversity. Conservation of genetic resources in situ refers to the continued cultivation and management by farmers of crop populations in the open, genetically dynamic systems in which the crop has evolved (Benin et al. 2004). On-farm conservation implies the choice of farmers to continue cultivating biologically diverse crops and varieties in their agroecosystems (Bellon et al. 1997).

[3] Benin et al. (2004) observe that on-farm conservation of crop diversity poses obvious policy challenges in terms of the design of appropriate incentive mechanisms and possible trade-offs between conservation and productivity. Smale et al. (2003) note that a fundamental problem affects the design of policies to encourage on-farm conservation. Crop genetic diversity is an impure public good, meaning that it has both private and public economic attributes.

[4] Goeschl & Swanson (2002) and Simpson et al. (1996) explore the role of diversity on potential commercial profits and its social value.

The rest of the review is organized as follows. In Section 2, we provide a brief background. Sections 3, 4, and 5 provide a theoretical model. Section 6 analyzes the link between biodiversity and resilience. Section 7 concludes the article.

2. BACKGROUND

Why does agricultural biodiversity matter? In both ecological and resource economics literature, three mechanisms that relate crop biodiversity to agroecosystem functioning and productivity have been identified. First, biodiversity increases the level at which certain ecosystem services are provided. Compared with a single-species (or a less diverse) ecosystem, in diverse ecosystems there is a greater likelihood that key species with a large impact on ecosystem performance are present in the system. This is known as the sampling effect or the selection probability effect (Aarssen 1997, Huston 1997, Loreau 2000, Tilman et al. 2005). Growing multiple species makes possible the productive exploitation of synergies among crops and niche partitioning (Di Falco & Chavas 2009), as a series of experimental studies reports. These studies show that plant biomass is an increasing function of diversity (Tilman & Downing 1994, Tilman et al. 1996, Lehman & Tilman 2000) and that higher-diversity systems result in greater yields than do lower-diversity systems (Tilman et al. 2005). These results can be more important in a setting where agroecological heterogeneity and harsh weather conditions may increase positive interactions among plants. Plants can exhibit a greater reliance on positive synergies and display facilitation (rather than competition).[5] The implication is that conserving diversity in the field delivers important productive services and allows farmers to mitigate some of the negative effects of harsh weather and agroecological conditions (Bellon et al. 1997, Walker et al. 1999, Di Falco & Chavas 2009).

Second, diversity enhances the possibility of species complementarities. Complementarities among crop species imply an efficient use of total available resources both in time and in space (Trenbath 1974, Harper 1977, Ewel 1986, Vandermeer 1989, Loreau & Hector 2001). Multiple crop species can also reduce the implication of price and production risk (Baumgärtner & Quaas 2008, Di Falco & Chavas 2009) and allow farmers to market their produce several times throughout the year.

Third, diversity increases facilitative interaction among species by ensuring the presence of species with different sensitivities to suite environmental conditions (Bertness & Callaway 1994, Mulder et al. 2001). Because certain species can buffer against harsh environmental conditions or provide a critical resource for other species, the probability that some of these species can react in a functionally differentiated way to external disturbance of the system and changing environmental conditions increases with the number of functionally different species. Therefore, biodiversity can act as insurance in carrying out ecological processes (MacArthur 1955, Chapin & Shaver 1985, Lawton & Brown 1993, Naeem & Li 1997, Naeem 1998, Petchey et al. 1999, Trenbath 1999, Borrvall et al. 2000, Baumgärtner & Quaas 2009).[6]

The level of complementarity and interspecific facilitation between species depends on the extent of both spatial and temporal heterogeneity in the system. Tilman et al. (2005), for instance, demonstrate that in a homogeneous environment, a single species best adapted

[5] See Bertness & Callaway (1994), Callaway (1995), Callaway & Walker (1997), and Vandermeer (1989).

[6] For a comprehensive assessment of the contribution of diversity to ecosystem functioning, see Hooper et al. (2005).

to environmental conditions will produce the greatest biomass. With heterogeneous habitats, however, diversity tends to be more beneficial. Norberg (2001) presents a similar but more comprehensive approach of multispecies competition that relates aggregate biomass, average phenotype (a measure of environmental responsiveness), and environmental variability. Norberg's framework suggests that phenotypic variance within functional groups is linearly related to their ability to respond to environmental changes. As a result, the long-term productivity for a group of species with high phenotypic variance may be higher than for the best single species.

Most evidence from agroecology is based on experimental analysis. In applied and agricultural economics, a growing body of literature focusing on the same research question, but using different methods, reveals similar evidence. Evenson & Gollin (1997) provide evidence of the role of genetic diversity on yields. The role of biodiversity on productivity is also found to be positive and not negligible by Di Falco et al. (2007) and Smale et al. (1998). These findings are based on two different empirical approaches: aggregate panel data and farm-level cross-section analyses. The aggregate panel data analysis makes use of regional or district-level data to estimate aggregate production functions in which biodiversity is typically modeled as an input to the production process (e.g., Smale et al. 1998, Widawsky & Rozelle 1998, Omer et al. 2007). These studies exploit the benefits of fixed-effects panel data in terms of removing time-invariant unobserved heterogeneity. However, the scale of these analyses does not allow one to control for farm agroecological characteristics, and such analyses implicitly assume that the underlying theoretical model can be scaled up to the macro level. The second approach of using farm-level cross-section analysis, although overcoming the aggregation problem, has the obvious shortcoming of neglecting dynamics (Di Falco & Chavas 2009). A more recent paper (Di Falco et al. 2010) attempts to circumvent these shortcomings by using farm-level panel data from the Central Highlands of Ethiopia. The data set, collected in 2002 and 2005, was from a survey of 1,500 farm households in Ethiopia. The adoption of farm-level panel data, besides helping us to deal with endogeneity, allows us to address the issue of time-invariant heterogeneity at the household level (e.g., farmers' ability or farm-specific unobserved characteristics). Again, the study is conducted in a setting where environmental conditions are difficult due to poor soil quality and challenging weather conditions: the drought-prone and moisture-stressed production environment of Ethiopia.[7] The empirical strategy is very comprehensive. It assesses the relationship between productivity, diversity, and rainfall and addresses the possible endogeneity of diversity in productivity. Di Falco et al. (2010) jointly estimate two separate equations representing farm productivity and the determinants of biodiversity, respectively. This analysis provides useful information on the determinants of crop biodiversity at the farm level and sheds light on the way farmers use in situ diversity (see also Benin et al. 2004, Van Dusen & Taylor 2005) in food production. Omer et al. (2007) use a stochastic production frontier approach to empirically test the hypothesized positive relationship between biodiversity stock and optimal levels of crop output. This analysis is based on data from a panel of UK specialized cereal farms for the period 1989–2000. The results support the theoretical hypothesis. Increases in biodiversity can lead to a continual outward shift in the output frontier. Agricultural transition toward biodiversity conservation may be consistent with an increase in crop output in already biodiversity-poor modern agricultural landscapes.

[7]Some evidence has been provided at a more aggregate level; see Di Falco & Chavas (2008).

Table 1 Summary of studies on biodiversity, productivity, and risk

Study	Area	Dimension of diversity	Findings
Evenson & Gollin (1997)	Different countries	Rice genetic improvement	Genetic improvement has an economic payoff. It also expands the land race pool
Smale et al. (1998)	Punjab of Pakistan	Intraspecific diversity in wheat	Crop genetic diversity is positively correlated with mean yields and is negatively correlated with the variance of yields
Widawsky & Rozelle (1998)	China	Rice	The number of planted varieties reduces both the mean and the variance of rice yield
Di Falco & Perrings (2003, 2005)	Italy	Interspecific cereals	Crop genetic diversity is positively correlated with mean yields and is negatively correlated with the variance of yields. This relation can be weakened by access to financial support from the European Union
Di Falco & Chavas (2006)	Italy	Intraspecific wheat	Biodiversity supports productivity and reduces the risk of crop failure
Di Falco et al. (2007)	Ethiopia	Intraspecific wheat	Biodiversity can reduce the variance of yields
Omer et al. (2007)	UK	On-farm functional biodiversity	Increases in biodiversity can lead to increases in productivity in modern agricultural landscapes
Di Falco & Chavas (2009)	Ethiopia	Intraspecific barley	Biodiversity supports productivity and reduces the risk of crop failure. These results are more relevant in the presence of degraded land
Di Falco et al. (2010)	Ethiopia	Intraspecific cereals	More biodiversity and more productivity

The relationship between risk exposure and crop biodiversity has also attracted empirical attention. Smale et al. (1998) studied the relationships between crop biodiversity and wheat production in the Punjab of Pakistan. They find that genealogical distance and number of varieties are associated with higher mean yield. Widawsky & Rozelle (1998), using data from regions of China, find instead that the number of planted varieties reduces both the mean and the variance of rice yield. This was found also by Di Falco & Perrings (2005) and Di Falco et al. (2007). These three studies use a mean and variance framework. Risk exposure is therefore captured by the variance of crop yields or revenues.

In a significant departure from this framework, Di Falco & Chavas (2006, 2009) include the role of diversity on the skewness of the distribution of crop yields. This approach fully captures the extent of risk exposure in more arid environments. Di Falco & Chavas find that biodiversity reduces the probability of crop failure. **Table 1** summarizes the studies discussed in this section.

3. AN ECOLOGICAL ECONOMICS FRAMEWORK

Both risk and productivity are the most relevant contributions of biodiversity to welfare. This section provides a model that combines these two elements in an ecological economics framework.[8] How do we model farmer's choice over crop biodiversity? From an economist's perspective, the study of diversification is the natural place to start. Diversification has often been studied in the context of risk management. Under uncertainty, risk-averse decision makers have incentives to diversify (e.g., Tobin 1958, Markowitz 1959). This is illustrated by the rule of thumb: "Don't put all your eggs in one basket." Risk management has provided useful insights into financial and investment decisions under uncertainty. In agriculture, growing more crop species enhances the possibility of producing in years in which rainfall regimes or environmental conditions are more challenging. Thus, having functionally similar plants that respond differently to weather and temperature ensures that "whatever the environmental conditions there will be plants of given functional types that thrive under those conditions" (Heal 2000). Therefore, the presence of significant uncertainty in agriculture explains why most farms are multioutput diversified enterprises (Lin et al. 1974).

Risk management is not the only motivation behind crop diversification. The presence of economies of scope is another possible avenue. Scope economies arise when diversification implies a cost reduction associated with multioutput production processes (Baumol 1977, Willig 1979, Baumol et al. 1982).[9] This has stimulated research examining the cost properties of multioutput enterprises, with applications to the organization and performance of many industries.

An agroecosystem can be modeled in the context of a production process. Consider a farm facing a multioutput production process involving m crops or varieties $y = (y1, \ldots, ym) \in \mathrm{R}^m_+$ and n inputs $x = (x1, \ldots, xn) \in \mathrm{R}^m_+$. We use the netput notation, where netputs are $z \equiv (-x, y)$; outputs are positive and inputs negative. The underlying technology is represented by the set $F(e)$, where e is a vector of random variables (e.g., weather effects in agricultural production) representing production uncertainty and $z \in F(e)$ means that netputs z are feasible given e.[10]

The farm faces output prices $p \in \mathrm{R}^m_{++}$, generating farm revenue $p{\cdot}y$. Farm income is $[I(x) + p{\cdot}y]$, where $I(x)$ denotes other net income, which includes other sources of income as well as input cost (treated as negative income). The farm manager has a subjective probability distribution of all random variables characterizing his/her uncertain environment. Under the expected utility hypothesis, the decision maker has risk preferences represented by a von Neumann–Morgenstern utility function $U(I(x) + p{\cdot}y)$, where $U(\cdot)$ is strictly increasing. Then, the farm manager makes decisions in a way consistent with the maximization of the expected utility

$$\mathrm{Max}\,\{EU(I(x) + p \cdot y : (-x, y) \in F(e))\},$$

where E is the expectation operator based on the subjective probability distribution of all uncertain variables. In this analysis, it will be useful to rely on a functional representation

[8]For a more extended version of this paper, see Chavas & Di Falco (2012b).

[9]Baumol et al. (1982) characterize economies of scope involving complete specialization schemes. Below, we interpret economies of scope in a broader context that allows for partial specialization (as discussed by Evans & Heckman 1984, Berger & Ofek 1995, and Ferrier et al. 1993).

[10]As the feasible set $F(e)$ depends on e under production uncertainty, technical efficiency implies that at least some netputs must be chosen ex post. To illustrate, consider the case in which inputs x are chosen ex ante. The output possibility set under state e becomes $Y(x, e) = \{y: (-x, y) \in F(e)\}$. Therefore, being on the upper bound of $Y(x, e)$ implies that y must vary with e, i.e., that at least some outputs must be chosen ex post. This analysis assumes implicitly that some netput choices are state dependent.

of the technology. Let $g \in \mathrm{R}^m_+$ be a reference output bundle satisfying $g \neq 0$. Following Luenberger (1995), define the shortage function as

$$
\begin{aligned}
S(-x,\ y,\ e) &= \mathrm{Inf}\,\beta\,\{\beta\colon\ (-x,\ y-\beta\, g) \in F(e)\} \text{ if there is a } \beta \text{ satisfying } (-x,\ y-\beta\, g) \in F(e),\\
&= +\infty \text{ otherwise.} \qquad (1)
\end{aligned}
$$

The shortage function measures the distance (measured in number of units of the reference bundle g) between point $(-x, y)$ and the upper bound of the feasible set $F(e)$. In general, given e, $S(-x, y, e) = 0$ means that point $(-x, y)$ is on the frontier technology. Alternatively, given e, $S(-x, y, e) < 0$ implies that $(-x, y)$ is technically inefficient (as it is below the frontier),[11] whereas $S(-x, y, e) > 0$ identifies $(-x, y)$ as being infeasible (as it is located above the frontier). Luenberger (1995, p. 20–22) provides a detailed analysis of the properties of $S(-x, y, e)$. First, from the definition in Equation 1), $(-x, y) \in F(e)$ implies that $S(-x, y, e) \leq 0$ (because $\beta = 0$ is then feasible in Equation 1), meaning that $F(e) \subset \{(-x, y)\colon S(-x, y, e) \leq 0\}$. Second, consider the case of a technology exhibiting free disposal in outputs y, where starting from any $(-x, y) \in F(e)$, then $(-x, y') \in F(e)$ holds for all $y' \leq y$. Note that, from Equation 1, $S(-x, y, e) \leq 0$ implies that $(-x, y - S(-x, y, e)g) \in F(e)$. It follows that, under free disposal in y, $S(-x, y, e) \leq 0$ implies that $(-x, y) \in F(e)$, meaning that $F(e) \supset \{(-x, y)\colon S(-x, y, e) \leq 0\}$. Combining these two properties, one obtains the following result: under free disposal in outputs y, $F(e) = \{(-x, y)\colon S(-x, y, e) \leq 0\}$, implying that $S(-x, y, e)$ provides a complete representation of the underlying technology. Importantly, besides being convenient, this result is general: It allows for an arbitrary multioutput technology, and it holds under production uncertainty. We make extensive use of it below. Note that $p \in \mathrm{R}^m_{++}$, $g \in \mathrm{R}^m_+$, and $g \neq 0$ imply that $(p\cdot g) > 0$. Through the use of the shortage function $S(-x, y, e)$, the following result will prove useful:

Lemma 1: Given $(p\cdot g) > 0$,

$$\mathrm{Max}\ \{EU[I(x) + p \cdot y]\colon (-x, y) \in F(e)\} = \mathrm{Max}\ \{EU[I(x) + p \cdot y - S(-x,\ y,\ e)(p \cdot g)]\}. \quad (2)$$

Lemma 1 provides two equivalent formulations for expected utility maximization. It applies under general conditions, including in the case of a multioutput farm facing both price and production uncertainty. Feasibility constraint $\{(-x, y) \in F(e)\}$ is imposed onto the left-hand side of Equation 2, but not onto its right-hand side. Thus, Equation 2 shows that subtracting the term $[S(-x, y, e)(p\cdot g)]$ from income is equivalent to imposing the feasibility constraint. Given $(p\cdot g) > 0$, the shortage function $S(-x, y, e)$ in Equation 2 provides a formal linkage between the productivity/efficiency of point $(-x, y, e)$ and its welfare evaluation under uncertainty. Using the right-hand side of Equation 2 and following Arrow (1965) and Pratt (1964), we define the certainty equivalent (CE) as follows:

$$EU[I(x) + p \cdot y - S(-x,\ y,\ e)(p \cdot g)] = U(\mathrm{CE}), \quad (3)$$

which implies that $\mathrm{CE} = U - 1EU(\pi)$, with $\pi = I(x) + p\cdot y - S(-x, y, e)(p\cdot g)$. CE is the smallest sure amount of money the decision maker is willing to receive to give up the uncertain income $\pi = [I(x) + p\cdot y - S(-x, y, e)(p\cdot g)]$. Being evaluated ex ante, CE in

[11]Note that $S(-x, y, e)$ includes as special cases many measures of technical inefficiency that have appeared in the literature. For example, the directional distance function proposed by Chambers et al. (1996) is just the negative of $S(-x, y, e)$. Chambers et al. discuss relationships with Shephard's output distance function or Farrell's measure of technical efficiency.

Equation 3 depends on $z \equiv (-x, y)$: CE(z). Through the shortage function in Equation 3, CE(z) captures the effects of efficiency and productivity. Indeed, given x and e, note from Equation 1 that $[y - S(-x, y, e)g]$ is located on the upper bound of the production technology. Thus, finding that $S(-x, y, e) < 0$ means that point $(-x, y, e)$ is technically inefficient, in which case subtracting $S(-x, y, e)(p \cdot g)$ in Equation 3 corresponds to an efficiency-improving move to the frontier technology and an increase in CE(z). Alternatively, finding that $S(-x, y, e) > 0$ means that point $(-x, y, e)$ is infeasible, in which case subtracting $S(-x, y, e)(p \cdot g)$ in Equation 3 corresponds to a move to feasibility and a decrease in CE(z). CE(z) also depends on the probability distribution of e and on risk preferences. The utility function $U(\cdot)$ is strictly increasing, and thus Equations 2 and 3 show that maximizing expected utility is equivalent to maximizing CE(z). As such, CE(z) provides a basis for evaluating the economic performance of the owner-managed farm under risk.

4. CROP BIODIVERSITY

We now want to investigate the economics of farm diversification. Under what conditions would a farm benefit from being diversified? To analyze this issue, consider a scenario where the farm reorganizes its activities to become more specialized. Start with an original farm producing netputs $z \equiv (-x, y) \in F(e)$.[12] Then, split this farm into K specialized farms, where the kth farm produces netputs $zk \equiv (-xk, yk)$, $k = 1, \ldots, K$. We make two assumptions. First, assume that $z = \sum_{k=1}^{K} zk$, so that aggregate netputs are held constant. Second, assume that $zk \neq z/K$, so that each of the K farms exhibits some form of relative specialization.[13]

Definition 1: Economies of diversification (diseconomies of diversification) exist if

$$D \equiv \mathrm{CE}(z) - \sum_{k=1}^{K} \mathrm{CE}(zk) > 0\ (< 0), \tag{4}$$

where $\sum_{k=1}^{K} zk = z$.

Equation 4 measures the change in CE due to a move toward greater specialization, holding aggregate netputs constant $\left(\sum_{k=1}^{K} zk = z\right)$. It shows that economies of diversification exist ($D > 0$) when the CE of producing netputs z is higher from an integrated farm compared with K more specialized farms. This identifies the presence of synergies or positive externalities across activities in the production process. Alternatively, diseconomies of diversification exist ($D < 0$) when the CE of producing netputs z is lower from an integrated farm compared with K more specialized farms. This indicates the presence of negative externalities across activities in the production process.

Equation 4 provides a monetary measure of diversification benefits. Assuming that CE(z) > 0, a relative measure can be defined as

$$D' \equiv \left[\mathrm{CE}(z) - \sum_{k=1}^{K} \mathrm{CE}(zk)\right] / \mathrm{CE}(z), \tag{5}$$

[12]Under production uncertainty, technical efficiency means that at least some of the netputs z are chosen ex post.

[13]Except for these two assumptions, our analysis applies to general specialization schemes for the K farms: zk, $k = 1, \ldots, K$. In particular, we allow some zk to be either infeasible or technically inefficient. The case of infeasibility could occur if the associated specialization scheme generated productivity losses. It would force the kth specialized farm to purchase additional resources to restore feasibility, thus lowering CE. Alternatively, the case of technical inefficiency would arise if specialization yielded productivity gains, thus increasing CE.

where $\sum_{k=1}^{K} zk = z$. Then, D' in Equation 5 provides a unit-free measure: It is the proportional increase in the CE obtained by producing z in a single integrated farm versus K more specialized farms. Again, $D' > 0$ (< 0) identifies economies (diseconomies) of diversification.

Given $\sum_{k=1}^{K} zk = z$ and $zk \neq \sum_{k=1}^{K} z/K$, Equations 4 and 5 allow for various forms of specialization among the K farms. For example, the kth farm could be completely specialized in the jth output, with $yjk = yj$ and $yjk' = 0$ for $k' \neq k$. In this case, the kth farm is the only specialized farm producing the kth output. Alternatively, our definition of economies of diversification allows for partial specialization. If we assume that $yj > 0$, having $yjk > 0$ for all j implies that each farm continues to produce each of the m outputs. With $zk \neq \sum_{k=1}^{K} z/K$, this implies only partial specialization among the K farms. In general, economies of specialization in Equation 4 or 5 depend on the patterns of specialization among the K farms.

5. BENEFITS AND COSTS OF CROP BIODIVERSITY

This section investigates the sources of the benefits and costs of diversification. We begin with a decomposition of CE(z). Following Arrow (1965) and Pratt (1964), define the risk premium as the value R that satisfies

$$EU(\pi) = UE(\pi) - R, \tag{6}$$

where $\pi = I(x) + p{\cdot}y - S(-x, y, e)(p{\cdot}g)$. Equation 6 implies that $R = E[\pi] - U\ -1EU(\pi)$. It defines the risk premium R as the smallest sure amount of money the decision maker is willing to pay to replace the risky prospect $\pi = I(x) + p{\cdot}y - S(-x, y, e)(p{\cdot}g)$ with its expected value $E(\pi)$. As Arrow and Pratt discuss, R provides a monetary measure of the private cost of risk bearing. Being evaluated ex ante, R in Equation 6 depends on $z \equiv (-x, y)$: $R(z)$. It also depends on the probability distribution of all uncertain variables and on risk preferences. The sign of R has been used to characterize the nature of risk behavior. Following Arrow and Pratt, the decision maker is said to be risk averse, risk neutral or risk loving when $R > 0$, $R = 0$, or $R < 0$, respectively.

Combining Equation 3 and Equation 6 gives the standard decomposition of CE:

$$\text{CE}(z) = E\pi(z) - R(z), \tag{7}$$

where $\pi(z) \equiv I(x) + p{\cdot}y - S(-x, y, e)(p{\cdot}g)$ denotes income, $E\pi(z)$ is expected income, and $R(z) = E[\pi(z)] - U - 1EU[\pi(z)]$ is the risk premium. Equation 7 shows that CE can always be written as the sum of expected income $E\pi(z)$ minus the risk premium $R(z)$. This shows that both expected income $E\pi(z)$ and the cost of private risk bearing $R(z)$ affect the welfare of the decision maker. Under risk aversion [where $R(z) > 0$], it provides an incentive to reduce risk exposure.

Consider the case in which risk preferences $U(\pi)$ remain constant for all farm types. Let $R(zk) = E[\pi(zk)] - U - 1EU[\pi(zk)]$ denote the risk premium for the kth farm, $k = 1, \ldots, K$. Combining Equations 4 and 7 gives the following result:

Proposition 1: Economies of diversification (diseconomies of diversification) exist if

$$D \equiv D\pi + DR > 0 (< 0), \tag{8}$$

$$\text{where } D\pi = E\pi(z) - \sum_{k=1}^{K} E\pi(zk), \tag{9a}$$

$$\mathrm{DR} = -\left[R(z) - \sum\nolimits_{k=1}^{K} R(zk)\right], \tag{9b}$$

with $\sum\nolimits_{k=1}^{K} zk = z$.

Equation 8 identifies two additive components of the benefits of diversification: the expected income component $D\pi$ and the risk premium component DR. $R = 0$ in the absence of risk, and thus $D \equiv D\pi$ in a riskless world, where the expected income component $D\pi$ captures all the economic effects of diversification. Such effects have been analyzed in the literature on economies of scope (see below). In a risky world, Equation 8 shows that DR also plays a role. As discussed below, such effects have been analyzed in the literature on the role of risk in diversification strategies. Thus, Equation 8 provides a step toward integrating these two literatures.

The decomposition given in Equation 8 applies in general for any pattern of specialization among the K farms. Next, we explore further the benefits and costs generated by diversification strategies. We focus our attention on more specific patterns of diversification and specialization among outputs. For that purpose, let $I = \{1, \ldots, m\}$ be the set of outputs. Consider a partition of the set of outputs $I = \{I1, I2, \ldots, Ik\}$, where Ik is the subset of outputs that kth farm specializes in, with $2 \leq K \leq m$. Let $\beta k \in (1/K, 1]$ be the proportion of the original outputs $\{yi: i \in Ik\}$ produced by the kth farm, $k = 1, \ldots, K$. As discussed below, βk reflects degrees of specialization (as different βks capture different specialization schemes). Then, given $zk \equiv (-xk, yk)$ for the kth farm, consider choosing

$$xk = x/K, \tag{10a}$$

$$yik = yi+ \equiv \beta k\ yi \text{ if } i \in Ik, \tag{10b}$$

$$= yi- \equiv yi(1 - \beta k')/(K - 1) \text{ if } i \in Ik' \neq Ik, \tag{10c}$$

for some $\beta k \in (1/K, 1]$, $k = 1, \ldots, K$. First, Equations 10a–c always satisfy $z \equiv (-x, y) = \sum\nolimits_{k=1}^{K} zk$. This keeps the aggregate netputs constant. Second, Equation 10a divides the inputs x equally among the K farms. This means no specialization in inputs across the K farms, as our analysis focuses on output specialization. Third, Equations 10b–c establish the patterns of specialization for outputs y. To illustrate, consider the case in which $m = K = 3$. Then, Equations 10b–c yield $y1 = (\beta 1 y1, 1/2(1 - \beta 2)y2, 1/2(1 - \beta 3)y3)$, $y2 = (1/2(1 - \beta 1)y1, \beta 2 y2, 1/2(1 - \beta 3)y3)$, and $y3 = (1/2(1 - \beta 1)y1, 1/2(1 - \beta 2y2)$, $\beta 3 y3)$, which satisfies $y = \sum\nolimits_{k=1}^{3} yk$. In general, having $\beta k = 1$ means that the kth farm produces the same outputs in Ik as does the original farm. If $\beta k = 1$ for all k, then each of the K farms becomes completely specialized in a subset of outputs. Alternatively, $\beta k \in (1/K, 1)$ represents partial specialization in outputs. It allows for varying amounts of specialization, as a rise in βk from $1/K$ toward 1 means that the kth farm becomes more specialized in $\{yi: i \in Ik\}$, $k \in K$.

The expected income component $D\pi$ in Equations 8 and 9a identifies the role of mean income in the benefit of diversification. Assume that the outputs are ordered such that $(y1, y2, \ldots, ym) = (\{yi: i \in I1\}, \{yi: i \in I2\}, \ldots, \{yi: i \in Ik\})$. Given $yi+ \equiv \beta k\ yi$ with $i \in Ik$, let $y^{+} = (\overset{+}{y^{1}}, \ldots, \overset{+}{y^{m}})$, $\overset{+}{y^{k}} = \{\overset{+}{y^{i}}: i \in Ik\}$, and, for $k < k'$, $\overset{+}{y^{k:k'}} = (\overset{+}{y^{k}}, \overset{+}{y^{k+1}}, \ldots, \overset{+}{y^{k'}})$. Similarly, given $yi- \equiv yi(1 - \beta k')/(K - 1)$ with $i \in Ik'$, let $y^{-} = (\overset{-}{y^{1}}, \ldots, \overset{-}{y^{m}})$, $\overset{-}{y^{k}} = \{\overset{-}{y^{i}}: i \in Ik\}$, and, for $k \leq k'$, $\overset{-}{y^{k:k'}} = (\overset{-}{y^{k}}, \overset{-}{y^{k+1}}, \ldots, \overset{-}{y^{k'}})$. Then, from Equations 10b–c, the outputs of the kth farm are $yk = (\overset{-}{y}^{1:k-1}, \overset{+}{y}^{k}, \overset{-}{y}^{k+1K})$, $k = 1, \ldots, K$. The following decomposition of $D\pi$ will prove useful. The proof is given in Chavas & Di Falco (2012a,b).

Proposition 2: Given Equation 9, the expected income component $D\pi$ in Equation 9a can be written as

$$D\pi = D\pi C + D\pi S + D\pi V, \tag{11}$$

where

$$\begin{aligned} D\pi C = {} & \sum\nolimits_{k=1}^{K-1} E\pi(-x/K, \overset{-}{y}^{1:k-1}, \overset{+}{y}^{k}, \overset{+}{y}^{k+1:K}) - \sum\nolimits_{k=1}^{K-1} E\pi(-x/K, \overset{-}{y}^{1:k-1}, \overset{+}{y}^{k}, \overset{+}{y}^{k+1:K}) \\ & - \sum\nolimits_{k=1}^{K-1} E\pi(-x/K, \overset{-}{y}^{1:k-1}, \overset{-}{y}^{k}, \overset{+}{y}^{k+1:K}), \end{aligned} \tag{12a}$$

$$D\pi S = E\pi(z) - K\, E\pi(-x/K,\, y/K), \tag{12b}$$

$$D\pi V = K\, E\pi(-x/K,\, y/K) - E\pi(-x/K,\, y^{+}) - (K-1)E\pi(-x/K,\, y^{-}). \tag{12c}$$

Proposition 2 decomposes $D\pi$ into three additive parts: $D\pi C$ given in Equation 12a, $D\pi S$ given in Equation 12b, and $D\pi V$ given in Equation 12c. As discussed below, $D\pi C$ is a complementarity component, $D\pi S$ is a scale component, and $D\pi V$ is a concavity component related to expected income.

First, consider $D\pi C$. The term $D\pi C$ in Equation 12a depends on how yk affects the marginal expected income of other outputs. It reflects the presence of complementarity among outputs. To see that, consider the case in which the expected income is twice continuously differentiable in y. Then, Equation 12a can be written as

$$D\pi C \equiv \sum\nolimits_{k=1}^{K-1} \int_{y^{-}_{k+1:K}}^{y^{+}_{k+1:K}} \int_{y^{-}_{k}}^{y^{+}_{k}} \frac{\partial^2 E\pi}{\partial\gamma_1\, \partial\gamma_2} (-x/K, \overset{-}{y}^{1:k-1}, \gamma 1, \gamma 2)\, d\gamma 1\, d\gamma 2, \tag{12a$'$}$$

where $\gamma 1$ and $\gamma 2$ are dummies of integration for y^{k} and $y^{k+1:K}$, respectively.

Equation 12a$'$ shows that the sign of $D\pi C$ is the same as the sign of $\partial 2E\pi/\partial yk\partial yk'$, $k' \neq k$. In this context, define complementarity between yk and yk' as any situation in which the expected income function satisfies $\partial 2E\pi/\partial yk\partial yk' > 0$, $k' \neq k$. This means that, under complementarity, yk has positive effects on the marginal expected income of yk', implying positive synergies between yk and yk', $k' \neq k$. Then, Equation 12a shows that $D\pi C > 0$ if the expected income function exhibits complementarity between yk and yk' for all $k' \neq k$. Thus, Proposition 2 establishes that complementarity among outputs (as reflected by the term $D\pi C$) is one of the components of D. It shows that complementarity is one of the factors contributing to economies of crop diversification.

Second, consider $D\pi S$. Note from Equation 12b that $D\pi S = 0$ when $E\pi(z)$ is linear homogeneous in z. Then, $D\pi S = 0$ corresponds to situations in which $[E\pi(\lambda z)/\lambda]$ is a constant for all $\lambda > 0$. Define the ray-average expected income as $\mathrm{RAE}(\lambda, z) \equiv [E\pi(\lambda z)/\lambda]$, where λ is a positive scalar reflecting the scale of operation. Define $\left\{\begin{array}{c}\text{increasing returns to scale (IRTS)}\\ \text{constant returns to scale (CRTS)}\\ \text{decreasing returns to scale (DRTS)}\end{array}\right\}$ as situations in which $\mathrm{RAE}(\lambda, z)$ is $\left\{\begin{array}{c}\text{increasing}\\ \text{constant}\\ \text{decreasing}\end{array}\right\}$ in $\lambda > 0$. It follows that $D\pi S = 0$ under CRTS. Alternatively, $D\pi S$ in Equation 12a is nonzero only when there is a departure from CRTS, with $D\pi S > 0$ (< 0) under IRTS (DRTS). Thus, $D\pi S$ captures scale effects. Equation 11 implies that IRTS contributes to economies of diversification (with $D\pi S > 0$).[14]

Third, the term $D\pi V$ in Equation 12c reflects a concavity effect. To see that, note that $E\pi\left(\sum_{k=1}^{K}\theta k\, zk\right)\begin{Bmatrix}\geq\\=\\\leq\end{Bmatrix}\sum_{k=1}^{K}\theta k\, E\pi(zk)$ if the function $E\pi(z)$ is $\begin{Bmatrix}\text{concave}\\\text{linear}\\\text{convex}\end{Bmatrix}$ in z for any $\theta k \in [0, 1]$ satisfying $\sum_{k=1}^{K}\theta k = 1$. If we choose $\theta j = 1/K$, $zl = (-x/K, y^{+})$ and $zk = (-x/K, y^{-})$ for $k = 2, \ldots, K$, it follows from Equation 12c that $D\pi V\begin{Bmatrix}\geq\\=\\\leq\end{Bmatrix}0$ if the function $E\pi(z)$ is $\begin{Bmatrix}\text{concave}\\\text{linear}\\\text{convex}\end{Bmatrix}$ in z. In other words, from Equation 11, the concavity of $E\pi(z)$ in z contributes to economies of diversification. The concavity of $E\pi(z)$ in z reflects diminishing marginal productivity in netputs. Thus, diminishing marginal productivity plays a role in economies of diversification. In addition, the concavity of $E\pi(z)$ in Equation 12c is evaluated along a hyperplane (because $z = \sum_{k=1}^{K} zk$). Following Baumol et al. (1982, p. 81), a function is transray concave (transray convex) if it is concave (convex) along a hyperplane. Thus, the concavity (convexity) properties just discussed are transray concavity (transray convexity) of the expected income function $E\pi(z)$. It follows from Equation 12c that transray concavity of $E\pi(z)$ contributes to economies of diversification.[15]

6. AGROBIODIVERSITY AND RESILIENCE

The above sections elucidate the risk-reducing role of crop biodiversity. Growing more crop species enhances the possibility of producing in years in which rainfall regimes or environmental conditions are more challenging. Functionally similar plants that respond differently to weather and temperature randomness also contribute to resilience (Holling 1973). Holling resilience is defined as the propensity of a system to retain its organizational structure and productivity following a perturbation (Holling 1973). This definition is rooted in the concept of system stability and in how the system responds under stress (Perrings & Stern 2000). In the case of agroecosystem productivity, these systems have Holling resilience if, in some state, they are able to maintain productivity and withstand stress or external shocks (e.g., due to lower rainfall and droughts). In many situations, biodiversity provides the link between stress and loss of resilience in a system (Perrings et al. 1995). Genetic variation within species and within populations increases the ability to respond to the challenges of environmental stress (Mainwaring 2001). This is because

[14] Fixed costs can contribute to IRTS for small farms. Thus, the presence of fixed costs in production/marketing/investment decisions can imply $D\pi S > 0$, meaning that the scale effect would provide an incentive for farms to diversify.

[15] How does Proposition 2 relate to previous research? Evans & Heckman (1984), Baumol (1977), Baumol et al. (1982), Willig (1979), and others have investigated the role of economies of scope. Our analysis of the role of scale and of transray concavity effects reduces to the analysis of diversification presented by Baumol and Baumol et al. Indeed, Baumol and Baumol et al. show that complementarity among outputs contributes to the presence of economies of scope. This is captured by the complementarity effect $D\pi C$ in Equations 11 and 12a. They also show that IRTS contribute to the presence of economies of scope. This finding is captured by the scale effect $D\pi S$ in Equations 11 and 12b. This shows how both returns to scale and output complementarity can affect economies of diversification. It illustrates how our approach extends previous literature on the economics of the multiproduct farm.

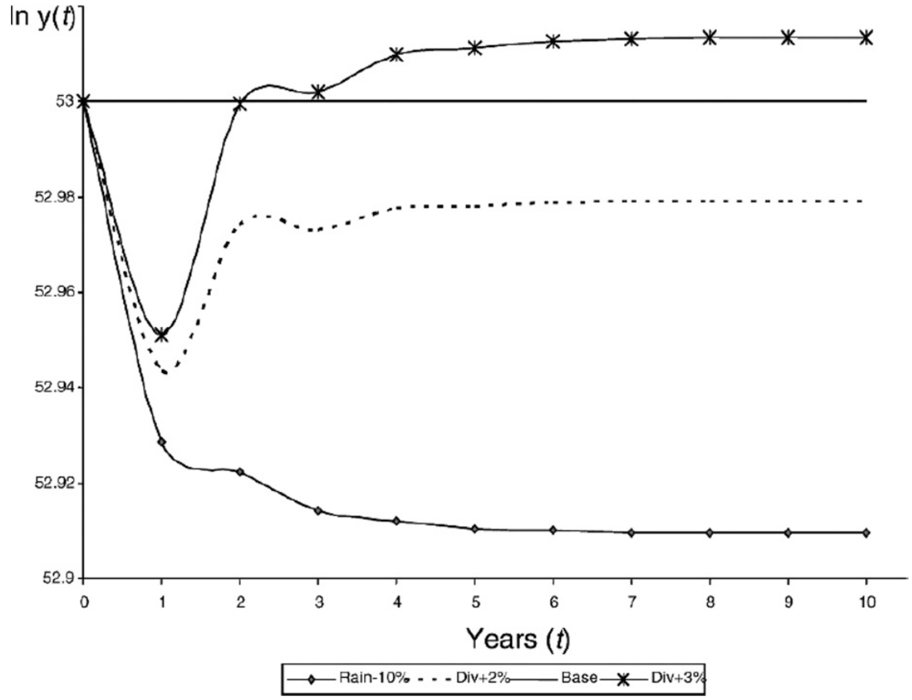

Figure 1

The resilience role of diversity under reduced rainfall. From Di Falco & Chavas (2008).

"multiple species coexistence occurs if there is an interspecific tradeoff such that each species is a superior competitor for a limited range of values of the physical factor, and if the physical factor is heterogeneous" (Tilman et al. 2005). Also, genetic variability within and between species confers the potential to resist biotic and abiotic stresses, both in the short term and in the long term (Giller et al. 1997).

Although empirical literature has addressed this issue, the link between biodiversity and resilience is still underexplored. From a theoretical perspective, a notable exception is the Common & Perrings model (1992). This paper combined the efficiency requirements of economic sustainability with the stability requirements of an ecological approach. It showed that an intertemporally efficient allocation of resources that satisfies the conditions for constant levels of consumption is not necessary to assure ecological sustainability. Ecological sustainability, instead, requires that the allocation of economic resources not result in the instability of the economy-environment system as a whole. In the empirical literature, Di Falco & Chavas (2008) analyze the dynamic effects of changing rainfall patterns on the productivity of an agroecosystem. Their focus was to explore the role of crop biodiversity in reducing some of the possible negative impact of climate change. In other words, crop biodiversity supports ecosystem resilience and helps mitigate the adverse effects of the lower rainfall and droughts associated with changing climates. The econometric analysis relies on a generalized method of moments estimator, which provides efficient parameter estimates while correcting for the potential endogeneity bias associated with the diversity index. The econometric results show that levels of crop biodiversity are positively and significantly related to production. Reflecting the dynamics of ecosystem productivity, these positive effects are stronger in the long term than in the short term. Thus, conserving in situ crop biodiversity enhances agricultural production in agroecosystems. Importantly, the positive contribution of crop biodiversity is stronger when the level of rainfall is lower. This result stresses that maintaining high crop biodiversity helps agroecosystem productivity when a limiting physical factor becomes important. Moreover, simulations results highlight that agroecosystem resilience to rainfall shocks depends heavily on biodiversity level. According to recent climate change projections in Southern Italy, rainfall will decrease between 5% and 15% in the next decade.

The impact of different permanent changes in rainfall was simulated. **Figure 1** reproduces this exercise. Although rainfall reductions have adverse effects on agroecosystem productivity, these adverse effects can be buffered in the short term and possibly reversed in the longer term under increased biodiversity. Agrobiodiversity can buffer against negative environmental effects and can support the resilience of the system under the adverse weather conditions associated with anticipated climate change.

7. CONCLUSIONS

Crop biodiversity is important for both the functioning of ecological systems and the generation of a vast array of ecosystem services. More agricultural biodiversity is associated with higher agriculture production and with lower risk exposure. Biodiversity also plays a crucial role in supporting system resilience. Therefore, more diverse agroecosystems seem more able to cope with weather randomness and other sources of external shocks. These results seem particularly evident in more challenging production environments. In arid agroecosystems of developing countries, for instance, the food production service of crop biodiversity is crucial. In these countries the agricultural sector constitutes a large part of the economy. Moreover, farmers in developing countries often face poorly functioning markets and limited opportunities for technological progress. Although incomplete (or missing) markets reduce farmers' options, such markets imply an enhanced reliance on nature's services and emphasize the economic importance of agroecosystem management in developing countries. Maintaining a certain level of crop biodiversity is thus crucial for the achievement of Millennium Development Goals such as supporting food security and reducing hunger.

FUTURE ISSUES

1. Collaboration between economists, agroecologists, and other natural scientists is essential for future progress in valuing the contribution of crop biodiversity to ecosystem services. There is large scope for collaboration.
2. The implementation of empirical analysis poses a number of critical challenges (e.g., endogeneity, unobservable heterogeneity, external validity). The availability of better data sets (e.g. panel data) can help with these issues.
3. The dynamic implications of crop biodiversity need to be elucidated both theoretically and empirically.
4. The interaction between crop biodiversity and other dimensions of biodiversity (i.e., soil biodiversity) should be explored.

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