

Rainfall Shocks, Resilience, and the Effects of Crop Biodiversity on Agroecosystem Productivity

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ABSTRACT. *This paper investigates the dynamic effects of rainfall shocks on agroecosystems productivity. The analysis estimates a panel data model of cereal production in southern Italy. It documents the adverse effects of a reduction in rainfall on the agroecosystem productivity both in the short run and the long run. It investigates how increasing the level of spatial crop diversity can mitigate this negative impact. The empirical evidence shows how higher diversity supports resilience and maintains the system productivity under challenging climatic conditions.* (JEL Q24, Q54, Q57)

I. INTRODUCTION

Earth's climate has changed over time. Recent trends have seen an increase in average temperature as well as more volatile rainfall patterns (NAS 2001). Over the last century, some areas of the planet have become drier. Annual precipitation trends in southern Europe showed a reduction in annual rainfall up to 20%, and recent projections forecast a further decrease between 5% and 15% over the next decade (EEA 2004; IPCC 2003; Hulme et al. 1999; Parry 2000; Brunetti et al. 2001). The reduction of rainfall can have implications of paramount importance for managed ecosystems such as agroecosystems. Agroecosystems¹ are ecological systems transformed and simplified for the purpose of agriculture. Lower rainfall increases the level of environmental stress affecting the

capability of the system to maintain productivity (Tisdell 1996). However, given the complexity of agroecosystems dynamics, the nature and magnitude of productivity decline remain poorly understood. This may involve a regular decline in soil fertility because of nutrient mining. This may also involve the stability and resilience of the agroecosystems (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 how the system responds under stress (Perrings and Stern 2000). In the case of agroecosystems productivity, these systems have Holling resilience if, in some state, they are able to maintain productivity and withstand stress or external shocks. Thus, a "resilient" agroecosystem is more capable to provide a vital service, such as food production, when challenged by a severe drought or by a large reduction in rainfall. In many situations, crop biodiversity² provides the link

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² Biodiversity is the sum of genetic information that is contained in the genes of individuals, plants, animals and micro organisms. Crop biodiversity, a component of agricultural biodiversity, refers to all diversity within and among wild and domesticated crop species (Qualset, McGuire, and Warburton 1995; Lenne and Wood 1999). Crop biodiversity has crucial effects on food production, health, and life-support systems. In managed systems, such as agroecosystems, crop genetic resources are the raw materials for crop breeding, pest resistance, productivity, stability, and future agronomic improvements. In this paper, we will use the terms biodiversity and crop biodiversity interchangeably.

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¹ Agroecosystems are defined as ecological and socioeconomic system comprising domesticated plants and/or animals and the people who husband them, intended for the purpose of producing food, fiber, or other agricultural products (Conway 1985, 1986, 1987; Conway and Barbier 1990).

between stress and loss of resilience (Perrings et al. 1995). Genetic variation within species and within population increases the ability to respond to the challenges of environmental stress (Mainwaring 2001).

Much research has studied the relation between diversity, productivity, and resilience. For example, it has been argued that Holling resilience improves with the complexity of the ecosystem. Heal (2000) wrote that the “diversity of organisms in an ecosystem is required for that system to function and to provide services to human societies, and the removal or addition of even a single type of organism can have far reaching consequences.” In a series of plot experiments, plant biomass has been found to be an increasing function of diversity (Tilman and Downing 1994; Tilman, Wedin and Knops 1996), with higher diversity contributing to increases in the productivity of ecosystems (Tilman, Polasky, and Lehman 2005). Ecologists have provided two different explanations for a beneficial role of crop biodiversity on systems functioning. The first explanation is based on the observation that growing more diverse crop species increases the probability of growing the best-adapted species. This is known as the “sampling effect” hypothesis (Tilman, Polasky, and Lehman 2005). The second explanation, known as complementarity effect, stresses the role of niche partitioning and facilitation (Loreau and Hector 2001). Different crop species have different traits and characteristics. A more diverse agroecosystem will have a broader range of traits and be more likely to perform under different environmental conditions³ (Sala 2001). Therefore, the coexistence of multiple species can occur “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, Polasky, and Lehman 2005). When analyzed at the regional scale, the positive

relationship between biodiversity, resilience, and productivity seems to be due to “partitioning” (Cardinale, Ives, and Inchausti 2004). Indeed, at a regional level, agroecosystems are typically composed of many different patch types that generate spatial heterogeneity. Given that partitioning may occur both within and across patches, aggregate production can increase when biodiversity increases.⁴

Growing diverse crop species can, for instance, enhance productivity in years or “field locations” where rainfall regimes or environmental conditions are more challenging. Having functionally similar plants that respond differently to weather and temperature randomness contributes to resilience (Hollings 1973) and ensures that “whatever the environmental conditions, there will be plants of given functional types that thrive under those conditions” (Heal 2000). Maintaining in situ crop biodiversity tends to provide the agroecosystem a wider range of productive responses to weather shocks. This is particularly important in agroecosystems where complexity has been simplified and the number of crop species reduced for the purpose of agriculture (Conway 1993). In such systems, crop biodiversity is the most important component of the overall agrobiodiversity.

While the resilience benefit of crop biodiversity seems to be important and plausible in agroecology, the empirical economics literature on this issue remains unsatisfactory from at least three different viewpoints. First, to date empirical evidence on the effect of a higher crop biodiversity regime on production⁵ is rather scant and inconclusive; and it does not consider the

⁴ In essence, this is “niche partitioning at regional scale” (Bond and Chase 2002).

⁵ Some applied economists have focused on the empirical assessment of the determinant of in situ crop biodiversity (e.g., Evenson, and Gollin 1997; Heisey et al. 1997; Smale, Bellon, and Aguirre Gomez 2001; Smale et al. 2003; Di Falco and Perrings 2005). Other authors have addressed the issue of the measurement of biodiversity (Solow, Polasky, and Broadus 1993; Weitzman 1992) and its role on potential commercial profits and its social value (e.g., Goeschl and Swanson 2002; Simpson, Sedjo, and Reid 1996).

³ Genetic variability within and between species confers the potential to resist biotic and abiotic stresses, both in the short and the long term (Giller et al. 1997).

implications for resilience.⁶ Second, all these studies model crop biodiversity as an input in a static production process. As shown by Cardinale, Ives, and Inchausti (2004), the effect of biodiversity on productivity is “dynamic, growing stronger through successional time.” Previous studies have neglected the relevant dynamic implications of biodiversity. Third, crop biodiversity’s role is captured in these studies by using a spatial diversity index (i.e., Shannon index). However, this raises the possibility that these indices are endogenous. The potential for endogeneity bias can have adverse effects on the validity of previous econometric analyses and results.

The objective of this paper is to study the dynamic effects of changing rainfall patterns on the productivity of an agroecosystem. A special focus of the research is to explore the role of crop biodiversity in reducing the possible negative impact of climate change. The paper makes four contributions to the literature. First, it analyzes the dynamic effects of crop biodiversity on the productivity of cereal agroecosystems. The analysis is applied to regional data for the period 1970–1993 from one of the most important areas for cereals production in Europe, southern Italy. This area is a Vavilonian mega diversity spot for cereals that is considered under threat from desertification. The production environment is characterized by rainfed agriculture. In the absence of irrigation, the impact of rainfall reduction on the system productivity cannot be easily mitigated. Both environmental and market

conditions restrict potential economic substitution among different crops or activities (e.g., more than 70% of wheat for pasta and bakery products produced in Italy are from southern Italy). The area faces a Mediterranean dry climate that restricts the production possibilities for agriculture. In this context, we investigate the productivity of the agroecosystem in response to changing weather conditions. Second, the econometric analysis presented in the paper relies on a dynamic GMM estimator. This provides efficient parameter estimates, while correcting for potential endogeneity bias associated with the biodiversity index. Third, the paper investigates the role of biodiversity and its interaction effects with rainfall in the dynamic analysis of productivity. This provides a basis to test whether crop biodiversity can help mitigate the adverse effects of reductions in rainfall. Fourth, this paper illustrates the implications of the econometric estimates using a set of simulations.

The paper proceeds as follows. Next section presents the framework. A brief description of the agroecosystem is provided in Section 3. Section 4 gives background information on the data and the variables used into the econometric analysis. The econometric results are discussed in Section 5. Section 6 provides the simulation exercise and Section 7 offers concluding remarks.

II. FRAMEWORK

In agricultural productivity analysis, a range of mathematical representations of the production technology has been invoked (Mundlak 2001). Let $y_{it} = f_{it}(\mathbf{x}_{it}, \cdot)$ denote the production function, where y_{it} is quantity of durum wheat produced in the i -th region at time t , \mathbf{x}_{it} is the vector of inputs used in the i -th region at time t , and “ \cdot ” denotes other factors. The vector \mathbf{x}_{it} includes conventional inputs (i.e., land, labor, capital, and fertilizer) along with rainfall and crop biodiversity. To introduce dynamics into the analysis, consider that $f_{it}(\mathbf{x}_{it}, \cdot)$ takes the form $f_{it}(\mathbf{x}_{it}; y_{i,t-1}, \dots, y_{i,t-p}, x_{i,t-1}, \dots, x_{i,t-q})$ for some $p \geq 0$ and $q \geq 0$. This

⁶ Smale et al. (1998) studied the relationships between crop biodiversity and wheat production in the Punjab of Pakistan. They found that genealogical distance and number of varieties are associated with higher mean yield. Widawsky and Rozelle (1998) using data from regions of China found, instead, that the number of planted varieties reduces both the mean and the variance of rice yield. Di Falco and Perrings (2005), found a positive relationship between crop biodiversity and agricultural production in a case study on cereal production in southern Italy. Di Falco and Chavas (2006) found a positive correlation between crop genetic diversity and productivity. They also found that biodiversity reduces yields variability and the risk of crop failure.

means that the k -th lagged production $y_{i,t-k}$ enters the production function up to lag $k = p$. It also allows the k -th lagged inputs $x_{i,t-k}$ to affect production y_{it} up to lag $k = q$. As a result, the production process is represented by $y_{it} = f_{it}(\mathbf{x}_{it}; y_{i,t-1}, \dots, y_{i,t-p}, x_{i,t-1}, \dots, x_{i,t-q})$. We consider the following production function specification

$$\begin{aligned} \ln(y_{it}) = & A + \boldsymbol{\alpha} \ln(\mathbf{x}_{it}) + \sum_{k=1}^p \beta_k \ln(y_{i,t-k}) \\ & + \sum_{k=1}^q \gamma_k \ln(x_{i,t-k}) \\ & + \delta_0 \ln(\text{biodiversity}_t) \ln(\text{rainfall}_t) \\ & + \delta_1 \ln(\text{biodiversity}_t) \ln(\text{rainfall}_{t-1}) \\ & + \mu_i + v_{it}, \end{aligned} \quad [1]$$

where $\boldsymbol{\alpha}$ and $\boldsymbol{\gamma}_k$ are respectively vectors of parameters associated with the current and k -th lagged input vector \mathbf{x} , and β_k is the parameter of the k -th lagged dependent variable. And, μ_i and v_{it} are independently distributed error terms, each with mean zero and finite variance. The term μ_i measures region-specific effects, while the error term v_{it} denotes the remainder disturbance that can vary over time as well as across regions.

Note that the specification [1] reduces to a Cobb-Douglas specification when $\delta_0 = \delta_1 = 0$, and in the absence of dynamics (where $\beta_k = 0$ and $\gamma_k = 0$ for all k). It is well known that the Cobb-Douglas specification is not a flexible functional form (e.g., it imposes unitary elasticity of substitution among inputs). To allow for a more general representation of the underlying technology requires introducing second-order terms between inputs in [1]. In our analysis, we are particularly interested in the effects of rainfall and of biodiversity on productivity. Considering that both rainfall and biodiversity are among the inputs \mathbf{x} , we introduce the additional terms $[\ln(\text{rainfall}) \ln(\text{diversity})]$ in [1]. They show up both in terms of current interaction effect of rainfall with diversity (as captured by the parameter δ_0) and its lagged interaction effect (as captured by the parameter δ_1). This gives a flexible specification of the production function,

capturing dynamic as well interaction effects between rainfall and diversity.⁷

Equation [1] is a panel data model, combining data across regions as well as over time. The panel nature of the analysis has several advantages. First, it can control for cross-section heterogeneity and unobservable or missing values (Baltagi 2001). Second, it can improve the efficiency of the parameter estimates. Finally, panel data analysis provides a basis to study dynamics and the estimation of short-run effects, intermediate-run effects, as well as long-run effects of the explanatory variables. Equation [1] can be alternatively written as

$$\begin{aligned} \Delta \ln(y_{it}) = & \alpha \Delta \ln(x_{it}) + \sum_{k=1}^p \beta_k \Delta \ln(y_{i,t-k}) \\ & + \sum_{k=1}^q \gamma_k \Delta \ln(x_{i,t-k}) \\ & + \delta_0 \Delta [\ln(\text{biodiversity}_t) \ln(\text{rainfall}_t)] \\ & + \delta_1 \Delta [\ln(\text{biodiversity}_t) \ln(\text{rainfall}_{t-1})] \\ & + \Delta v_{it}, \end{aligned} \quad [2]$$

where $\Delta z_t = z_t - z_{t-1}$ is the first-difference operator. The first-difference transformation eliminates the individual effects (Baltagi 2001) and reduces serial correlation. Equation [2] provides a basis for estimating the parameters. When some of the explanatory variables are endogenous, a generalized method of moments (GMM) estimator can generate consistent parameter estimates. When the error terms v_{it} are serially uncorrelated, valid instruments in the estimation of the first-difference model [2] include lagged values of the dependent variable (see Arellano and Bond 1991). And given an appropriate choice of the instruments and weights, GMM can provide asymptotically efficient parameter estimates. Ahn and Schmidt (1995), and Blundell and Bond (1998) explored how using the initial conditions in levels, in addition to [2], can generate efficiency gains. This involves using a system GMM

⁷ A more general functional specification that allowed for interaction between other inputs was also estimated (i.e. translog). However, multicollinearity adversely affected the econometric estimates and made the results more difficult to evaluate.

estimator that uses lagged differences as instruments for the equation in levels, in addition to lagged dependent variables as instruments for the equation in first-difference. Both the usual GMM estimator of [2] and the system GMM estimator were used in the empirical analysis.

When applied to our data, the two estimation methods gave similar results. We found that the system approach did not provide significant efficiency gains. As a result, our discussion below focuses on the Arellano-Bond GMM estimator of [2]. Table 3 reports the associated econometric results. The estimated system GMM is available from the authors upon request.

III. AGROECOSYSTEM DESCRIPTION

The area considered in this study includes eight regions in southern Italy. These regions fall under the same climatic area (Buffoni, Maugeri, and Nanni 1999). Cultural and climatic characteristics of this area make agriculture an important sector. Indeed, agriculture in Southern Italy accounts for 8% of overall European Union agricultural land and the average ratio of value added in agriculture to value added in industry has been persistently 0.4 from 1960 to 1993. Cereals are among the most important crops in this agroecosystem. Between 1990 and 2000, on average, cereals accounted for 4% of the overall European cereal production. And on a regional basis, they accounted for 43% of total agricultural land use, with the percentage reaching 70% in the Basilicata region. In the past twenty years, 68% of national durum wheat production, a staple product in Italy, came from regions in southern Italy. Durum and soft wheat production is spread uniformly, with some areas producing large quantities of output. For instance, the regions Abruzzo and Campania have produced respectively 72,144 and 75,838 tons of soft wheat (using around 25 different cultivars). The Sicily and Puglia regions produced the largest part of the durum wheat with the latter accounting for 482,689 tons and the former for 434,730 tons. Thus, wheat (soft

and hard) is very dominant. Barley, oats, and corn are less common. For instance, barley and oats account for respectively 5% and 4% of land share for cereals. Corn is even less cultivated, with four regions out of eight allocating less than 1% of their land to corn.

The production of cereals is particularly favored since the dry and warm weather in this area suits this family of crops. Cold, frosty winters and sudden changes in the temperature affect yields negatively. These weather conditions may, to some extent, reduce the spread and proliferation of pests. Pests are, indeed, more likely to spread when humidity is high. In some areas the soil is sandy. This reduces the ability of plant roots to absorb fertilizers, and hence the benefit of fertilizer use. In the time span considered in this paper, institutional conditions were quite homogeneous. The entire region was classified as "objective one" by the European Common Agricultural Policy, implying that agricultural assistance involved the same set of policy instruments.

IV. DATA SOURCES AND VARIABLES DESCRIPTION

Data were obtained from ISTAT, the Italian National Institute of Statistics (ISTAT 1970–1993), and the INEA, the National Institute for Agricultural Economics. The series are drawn from the *Statistiche Agrarie and Annuario* for eight regions in Southern Italy (Abruzzo, Molise, Campania, Puglia, Basilicata, Calabria, Sicily, and Sardegna), including the years from 1970 to 1993. As mentioned in the previous section, during this time span all the regions in the studies were under the same institutional framework (objective one of the Common Agricultural Policy, CAP). This implies that the set of financial instruments aimed to support farm income were homogeneous. Thus, farms would face the same incentives (i.e., price support, grants, etc) for growing different cereals.

Table 1 and Table 2 present the descriptive statistics and the definitions of the variables used in this empirical analysis.

TABLE 1
VARIABLE DESCRIPTIONS

Variable	Definition
Labor	Labor force in thousands of units
Fertilizer	Quantity of fertilizers and chemicals in 100 kg per hectare
Capital	Expenditure in machinery and buildings in thousands million Italian lira
Land	Land size to cereal production in hectare
Biodiversity	Shannon Index for biodiversity
Rain	Annual rainfall in mm

The quantity of cereal produced is expressed in tons. Fertilizer applications per hectare and labor force participation are conventional inputs. Capital is measured as investment in structure and machineries (at constant prices). The quantity of rainfall per year captures the weather impact on productivity.

The ecological literature has developed many metrics to calculate ecological diversity (Magurran 1988). In agricultural systems, one of the most commonly adopted measures of diversity is crop species richness or evenness found in a given geographical area. Both richness and evenness are intuitive concepts and data are easily available at some geographical level for agroecosystems. In this study, the Shannon⁸ index is adapted to measure the spatial biodiversity of the agroecosystem (e.g., Smale et al. 1998, 2003). As shown by Weitzman (2000), this index represents the unique functional form allowing consistent aggregation over classification levels. The Shannon index is

$$H = -\sum_i p_i \cdot \log(p_i),$$

where p_i is the planted area share of the i -th species in a reference region. Note that alternative diversity indices have appeared in previous literature. They include the commonly used Simpson index. These indices belong to the Hill family of indices, they “can be linked to a more general information theory” and to a generalized

formulation of entropy (Keylock 2005). However, the Simpson index is “heavily weighted toward the most abundant species in the sample while being less sensitive to species richness” (Magurran 1988, p. 40). On that basis, the Simpson index appears ill-suited to represent spatial diversity in interspecies crop biodiversity because of the dominance of one crop (durum wheat). By construction, these spatial indices are a source of endogeneity bias. Indeed, the share of land to be allocated to the i -th species is a choice variable.

The adoption of a Shannon spatial index bears two important benefits. First benefit of the Shannon index in this context is that it is sensitive to both evenness (that is how equally abundant crop species are) and richness. Thus, it takes into account both the number of species and the evenness of their proportional abundance. It means that a greater number of crop species, or the evenness of the planting to different crop species can both increase the diversity index. A contested issue in biodiversity analysis is the existence of the so-called “sampling” effect (Tilman, Polasky, and Lehman 2005). Such effect can reflect the performance of one particular crop species rather than the effect of heterogeneity. Given that the spatial Shannon index increases with evenness in land allocation, it can help control for such effect. A second benefit is that, coupled with modeling aggregate cereals production, it captures the restricted economic substitution for cereals. This takes into account the potential bias that can arise in production function approaches modeling a single crop (Mendelsohn, Nordhaus, and Shaw 1994). Indeed, the index implicitly incorporates

⁸ Assumptions underlying the use of the Shannon index include random sampling from an infinitely large population and the representation of all species from the defined area in the sample (Magurran 1988).

TABLE 2
DESCRIPTIVE STATISTICS

Variable	Mean	Std. Dev.	Min.	Max.
Labor	68.88	53.88	9.02	330.299
Fertilizer	2.68	1.26	0.85	13.05
Capital	557.4	287.67	89	1,260.9
Land	684,456	440,784	176,484	1,643,634
Biodiversity	1.02	0.32	0.22	1.45
Rain	615.49	234.18	181	1531

information on possible economic substitutions among cereals.

Finally, it is important to stress that other measures of biodiversity have been used in the literature (e.g., genetic distance indices). This includes Weitzman (1992) who proposed a distance measure that maximizes diversity among the surviving members of the set. This also includes Solow, Polasky, and Broadus (1993) who proposed that the distance measures should take into account the size of the set (to capture richness) as well as the distance among members.

Given the complexity of biodiversity valuation, at this point, no specific measure has been identified to be always superior to others (e.g., Mainwaring 2001). However, “ecologically oriented measures” seem to be appropriate when the benefit of biodiversity stems from its contribution to agroecosystems services, such as food production (Brock and Xepapadeas 2003).⁹

V. EMPIRICAL RESULTS

The dynamic production function given in [2] is estimated using the generalized method of moments (GMM) approach proposed by Arellano and Bond (1991).¹⁰ Two lags are included for the dependent variable ($p = 2$), and one lag for the explanatory variables ($q = 1$). This provides a reasonable flexible representation of the dynamics of productivity. Rainfall is con-

sidered strictly exogenous, conventional inputs are considered as predetermined variables and the lagged values of the dependent variable and the biodiversity index are considered endogenous. To test for endogeneity for the diversity index, we adopted a residual based test (Davidson and MacKinnon 1993; Wooldridge 2002). Lagged values of the index were used as instruments. We rejected the null hypotheses of exogeneity at the 10% significance level. This suggests the need to estimate the model using an instrumental variable method that can correct for endogeneity bias.

The results are reported in Table 3. In the Arellano-Bond approach, the error term v_{it} is assumed to be serially uncorrelated. This is essential to obtain consistent parameter estimates. If v_{it} is not serially correlated, there should be no evidence of second-order serial correlation in Δv_{it} . Using the standardized average residual autocorrelation and following Arellano and Bond (1991), we tested whether Δv_{it} exhibited second-order serial correlation. The Arellano-Bond test statistic of second-order serial correlation was $z = -0.65$. Under the null hypothesis of no serial correlation in v_{it} , the associated p -value is 0.513. Therefore, we fail to reject the null hypothesis. This indicates that the assumption that the v_{it} are serially uncorrelated appears supported by the data. Next, we implemented a Sargan/Hansen test of the overidentifying restrictions. The hypothesis being tested with the Sargan/Hansen test is that the instrumental variables are uncorrelated with the residuals, a key assumption to support the consistency of the GMM estimator. The null hypothesis is not rejected. Thus, from the Sargan/Hansen

⁹ Brock and Xepapadeas (2003) showed that even if genetic distance is very small, the value of biodiversity can be large.

¹⁰ As mentioned above, we also estimated the model using a system GMM estimator exploiting the initial conditions. The econometric results were similar.

TABLE 3
DYNAMIC PANEL DATA (GMM) ESTIMATION RESULTS

Variable	Dynamic Model Arellano-Bond GMM Estimation of (2) (A)	Arellano-Bond GMM Estimation of (2) with Selected Regressors (B)
Production _{<i>t-1</i>}	0.12 (0.2)	0.129 (0.18)
Production _{<i>t-2</i>}	0.12* (0.07)	0.156* (0.08)
Biodiversity _{<i>t</i>}	10.4*** (3.82)	9.87*** (3.65)
Biodiversity _{<i>t-1</i>}	4.24* (2.5)	3.94* (2.4)
Interaction Biodiversity _{<i>t</i>} and Rain _{<i>t</i>}	-1.5*** (0.56)	-1.4*** (0.53)
Interaction Biodiversity _{<i>t</i>} and Rain _{<i>t-1</i>}	-0.41** (0.2)	-0.35* (0.2)
Land _{<i>t</i>}	2.82*** (1.1)	3.02*** (1.2)
Land _{<i>t-1</i>}	-1.36* (0.8)	-1.2* (0.7)
Labor _{<i>t</i>}	1.18* (0.7)	1.107* (0.62)
Labor _{<i>t-1</i>}	-0.38 (0.5)	-0.5 ^a (0.4)
Fertilizer _{<i>t</i>}	1.18*** (0.29)	1.17*** (0.36)
Fertilizer _{<i>t-1</i>}	0.14 (0.2)	—
Capital _{<i>t</i>}	1.41** (0.67)	1.38** (0.61)
Capital _{<i>t-1</i>}	-0.184 (0.7)	—
Rain _{<i>t</i>}	0.06 (0.15)	0.248 (0.36)
Constant	0.43 (0.99)	0.0145 (0.071)

Notes: Robust standard errors are in parentheses. Arellano-Bond test, H₀ of no first-order serial correlation in the residuals: $z = -5.85$. Arellano-Bond test, H₀ of no second-order serial correlation in the residuals: $z = -0.65$, p -value = 0.513. Significance levels: *** = 1%; ** = 5%; * = 10%; “a” = 10% one-tailed test.

test results, the instruments pass the test: they appear to satisfy the orthogonality conditions required by GMM.

Table 3 column (A) reports the model where lags are included for all variables. Some of the lagged explanatory variables are found to be statistically significant. This stresses that the role of dynamics can be important. Both $y_{i,t-1}$ and $y_{i,t-2}$ are positive although only the latter is statistically significant, thus current production is related to past production values. This indicates that dynamic productivity effects generate a positive correlation between past and current production.¹¹ Crop biodiversity is positively related with production both in current and in lagged effects, indicating that maintaining a more diverse agroecosystem enhances agricultural productivity both in the short run and in the intermediate run. This result is consistent with experimental evidence showing that the effect of biodiversity on productivity is increasingly positive through time (Cardinale, Ives, and Inchausti 2004). Changes in biomass can result from local processes and species interactions, but also from pest and path-

ogens evolutions. Indeed, “the crop mix dynamics are controlled to maintain a desirable gene pool equilibrium” (Brock and Xepapadeas 2003). In our case, this suggests that agroecosystem productivity exhibits significant dynamics as it generates services (i.e., food production) both in the short and in the longer run (Gunderson and Holling 2001; Brock and Xepapadeas 2003).

The interaction terms between crop biodiversity and rainfall are negative and significant in both current and lagged effects. This result stresses the relevance of a higher biodiversity regime as a means of coping with scarce rainfall. This provides evidence that crop biodiversity ensures that the agroecosystem remains productive when facing lower or scarce rainfall. The effects of land on production are found to be statistically significant both in current and in lagged effects. As expected, the estimated impact of land is relatively large. The significance of lagged land captures how bringing some “marginal land” into production affects productivity over time. The coefficients for the current levels of other conventional inputs (fertilizer, capital, and labor) are all positive and statistically

¹¹ We thank the anonymous referee for this comment.

significant. However, in column (A) of Table 3, the lagged effects of these conventional inputs are not statistically significant.

The dynamic panel data framework allows the assessment of dynamic responses, including the evaluation of short-run and long-run elasticities. The estimated coefficients from model [3] are used to calculate dynamic elasticities of production. Evaluated at sample means, the elasticity of production with respect to crop biodiversity is 0.87 in the short run, and 3.29 in the long run. This gives two important results. First, crop biodiversity has a positive and fairly large impact on productivity both in the short run and in the long run. This provides evidence that crop biodiversity plays an important role in supporting agroecosystem productivity. Second, the long-run impact is much larger than its short-run impact. This stresses the importance of dynamics in the functioning of the agroecosystem.

The interaction effects in model [3] imply that the role of biodiversity varies with rainfall. To illustrate, consider the production elasticity with respect to crop biodiversity when rainfall is 20% below the sample mean. Compared to the evaluation at sample means, this elasticity increases from 0.87 to 1.14 in the short run, and from 3.29 to 3.75 in the long run. This shows that the productivity benefits of biodiversity are larger when rainfall declines and the ecosystem faces environmental stress. This issue is further investigated in the following section by means of a simulation exercise.

The econometric estimates reported in Table 3 column (A) show that some of the lagged conventional inputs do not have statistically significant effects on production. Thus, we find no evidence of dynamic behavior for capital or fertilizer. To evaluate the implications of these effects, the model was also estimated without the lagged variables for fertilizer and capital. The results are presented in Table 3 column (B). Note that the results remain quantitatively as well as qualitatively similar. This indicates that our empirical findings appear to be fairly robust to the model specification.

VI. RAINFALL, RESILIENCE, AND DIVERSITY

This section investigates the implications of our analysis for the dynamics of agroecosystem productivity. The estimated model, reported in column (B) of Table 3, is used to simulate production under alternative scenarios. We start with a base scenario where the agroecosystem production is simulated forward in time, with all other variables set at their sample means. All scenarios have the same initial conditions (at time $t = 0$). At time $t \geq 1$, alternative scenarios face different conditions and thus evolve along different paths. The comparison of these paths across scenarios provides useful insights into resilience and agroecosystem dynamics.

According to the IPCC projection (IPCC 2003), we can expect a rainfall decline in Southern Italy between 5% and 15% over the next decade. To evaluate these effects, we investigate the dynamic implications of *permanent* reductions in rainfall, holding other variables at their sample mean. The results are presented in Figure 1. Figure 1 shows simulations of the base scenario (where rainfall is set at its sample mean of the last two decades), and three scenarios representing different levels of rainfall reductions: 5%, 10%, and 15% *permanent* decreases in rainfall. Figure 1 illustrates the adverse effects of rainfall reduction on productivity. As expected, lower rainfall has a negative effect on agroecosystem production. It shows that drier environments make the system move from its original equilibrium to other paths that are less productive. The magnitude of productivity loss increases with the decline in rainfall, showing that adaptation is more difficult under greater stress. Moreover, the productivity losses are higher in the long run than in the short run. This reflects the dynamics of the ecosystem: some of the adverse effects of rainfall reduction can be buffered in the short run and not in the long run. These results provide a useful illustration of the way environmental stress (i.e., lower rainfall) affects the dynamics of

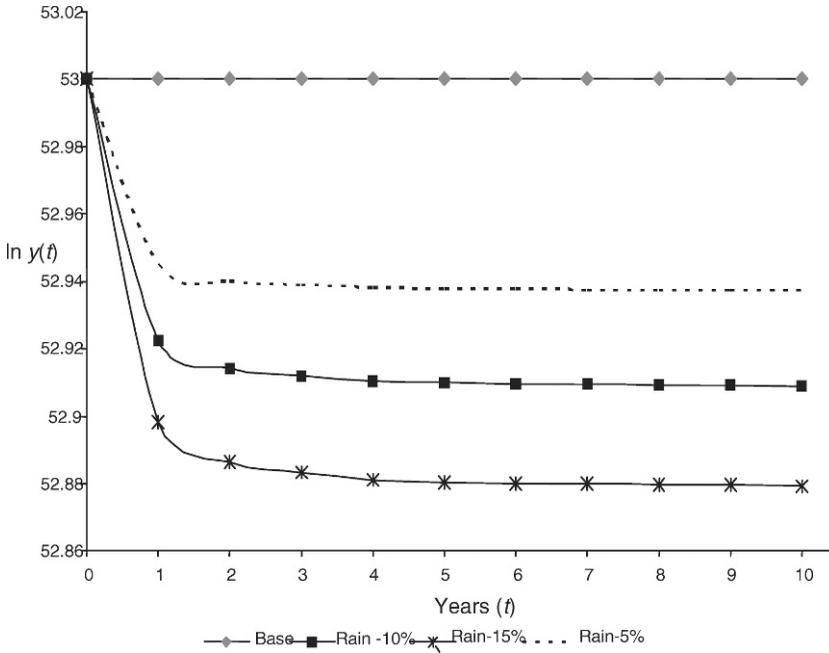


FIGURE 1
THE DYNAMIC IMPACT OF RAINFALL REDUCTION ON AGROECOSYSTEM PRODUCTIVITY

agroecosystem productivity. They show how the productive capability of the agroecosystem is adversely affected under increased environmental stress.

What about the effects of crop biodiversity? Figure 2 presents dynamic simulation results under alternative levels of diversity, holding all other variables at their sample means. Besides the base scenario, three scenarios are presented corresponding to a 5%, 10%, and 15% permanent decline in biodiversity. Figure 2 shows how a reduction in biodiversity has a negative effect on the productivity of the agroecosystem. It illustrates that a loss of crop biodiversity makes the system less productive. The magnitude of productivity loss increases with the decline in the diversity index. Figure 2 also indicates that the productivity losses are much higher in the long run than in the short run. For example, under a 15% reduction in diversity, production decreases by 14% in the short run (at time $t = 1$) but as much as 45% in the long run (for $t \geq 6$). This reflects the dynamics of the ecosystem. It shows that a large part of the benefits of

biodiversity are obtained only in the longer term.

Finally, we use our estimated model to investigate the resilience benefits of diversity under climatic change. In our analysis, resilience comes from the dynamic interaction effects between rainfall and biodiversity. We investigate these issues by simulating the dynamic effects of biodiversity under alternative rainfalls, as shown in Figure 3. Besides the base scenario (where all variables are set at their sample means), Figure 3 presents three alternative scenarios: one where rainfall exhibits a 10% permanent decline while diversity equals its sample mean; one where rainfall decreases 10% while diversity increases by 2%, and one where biodiversity increases by 4%. That is, we investigate the productive response of the agroecosystem to climatic variation when the system is characterized by more biodiversity. Comparing these latter two scenarios provides useful insights into the resilience benefits of diversity. Figure 3 shows that, while a sharp decline in rainfall sees a decrease in system productivity, this

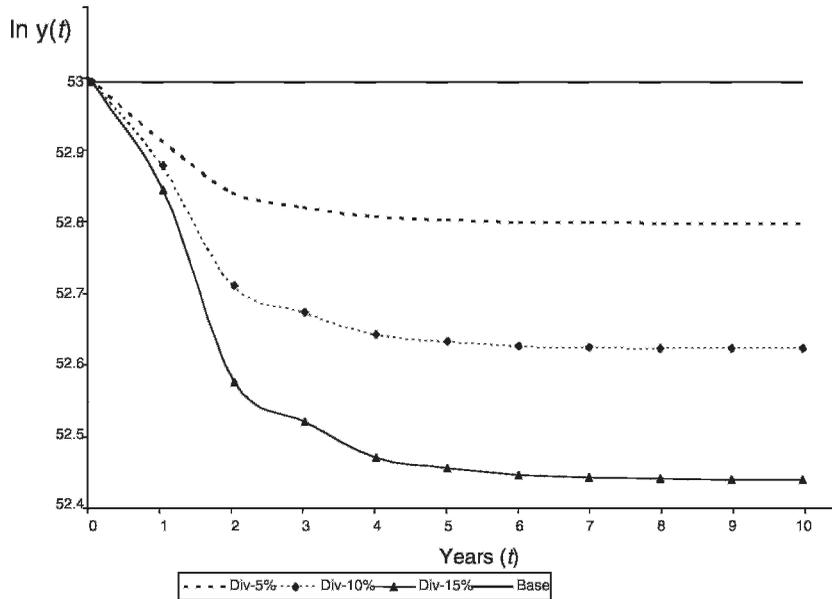


FIGURE 2
DYNAMIC PRODUCTION UNDER ALTERNATIVE BIODIVERSITY SCENARIOS

decline can be buffered and reversed under higher diversity. Indeed, under a 2% increase in biodiversity (the dotted line in Figure 3), production after one year is reduced by only 6% and eventually will be reduced by 3% in the long run. However, if the system is characterized by a 3% increase in biodiversity, then a 10% reduction in rainfall yields a 2.5% reduction in short-run productivity (after a year). As such, higher diversity cannot prevent the lower rainfall from decreasing agroecosystem production. Yet, this short term negative effect disappears in the longer term. Indeed, after 3 years or more, the system would reach a level of productivity similar to the one obtained before the shock. Thus, in the longer run ($t \geq 3$), the benefits of biodiversity become large enough to compensate for the adverse effects of lower rainfall. This illustrates how biodiversity is buffering against the negative effects of adverse environmental conditions. This is the essence of how biodiversity supports the resilience of the system: at least in the longer term, it can help keep the agroecosystem at a level of productivity that is similar to the one

obtained without the shock. It implies that crop biodiversity has an important role to play in a changing environment. It should be stressed that we simulated increases in the Shannon index for spatial biodiversity. This implies that both spatial abundance and evenness of the distribution of the crop species matter. On the one hand, oversimplified agroecosystems, such as a monoculture, may not be able to cope adequately with climatic change. On the other hand, under climatic changes, enhancing the biodiversity of an agroecosystem can help maintain its long term productivity and its ability to produce food.

VII. CONCLUDING REMARKS

Previous studies focusing on the determinants of crop biodiversity conservation have found that risk hedging, market integration, and agro-ecological conditions are key variables in determining the level of agro-biodiversity. Yet, one of the major issues in the debate on biodiversity is to understand the potential role of crop diversity on the productivity of agroecosys-

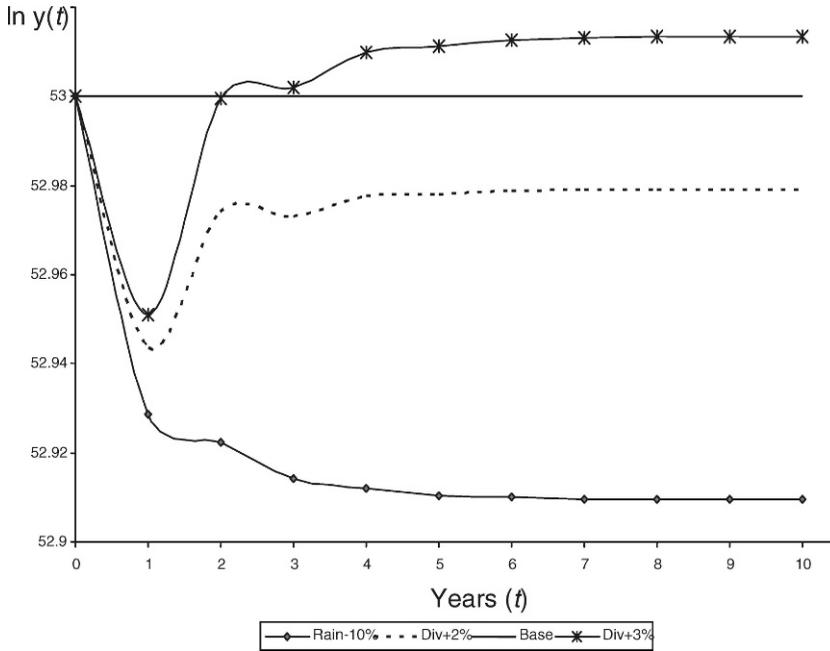


FIGURE 3
THE RESILIENCE ROLE OF DIVERSITY UNDER REDUCED RAINFALL BY 10%

tem. This paper contributes to this understanding by presenting an empirical assessment of the effects of crop biodiversity on agroecosystem production, with a focus on cereals. Diversity is measured using a Shannon index of spatial diversity. Using regional data from southern Italy (an area classified as mega-diversity spot for cereals) over a twenty-year period, we investigated empirically the dynamics of productivity. Relying on dynamic panel data econometrics and accounting for endogeneity in the diversity index, we investigated how rainfall, biodiversity, and their interactions affect cereal production.

The econometric results show that levels of crop biodiversity is positively and significantly related to production. Reflecting the dynamics of ecosystem productivity, these positive effects are found to be 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 found to be stronger when the level of rainfall is lower. This result

stresses that maintaining high crop biodiversity helps the productivity of the agroecosystem when a limiting physical factor becomes important. Moreover, simulation results highlight that the agroecosystem resilience to rainfall shocks depend heavily on the level of biodiversity. According to recent climate change projections in Southern Italy, rainfall will decrease at the rate between 5% and 15% in the next decade. We simulated the impact of different permanent changes in rainfall. While rainfall reductions have adverse effects on agroecosystem productivity, we found that these adverse effects can be buffered in the short term and possibly reversed in the longer term under increased biodiversity. We, thus, find evidence that agro-biodiversity can buffer and insure against negative environmental effects and support the resilience of the system under adverse weather conditions associated with anticipated climate changes. Finally, our results are consistent with the concept of regional complementarity. When the analysis of the relation between diversity and production is conducted at higher spatial

scales, crop biodiversity may become increasingly important for agroecosystem functioning. Regions are prone to heterogeneous conditions. In such situations, niche partitioning can occur and provides the system with a set of environmental tolerances that can guarantee ecosystems functioning at the landscape level.

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