REPORT

Soil fertility, crop biodiversity, and farmers' revenues: Evidence from Italy

Salvatore Di Falco, Elisavet Zoupanidou

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Abstract This paper analyzes the interplay between soil fertility, crop biodiversity, and farmers' revenues. We use a large, original, farm-level panel dataset. Findings indicate that both crop biodiversity and soil fertility have positive effects on farmers' revenues. It is also shown that crop biodiversity and soil fertility may act as substitutes. These results provide evidence for the important role of diversity in the resilience of agroecosystems. Crop diversification can be a potential strategy to support productivity when soils are less fertile.

Keywords Agroecosystems · Crop diversification · Italy · Panel data · Soil fertility

INTRODUCTION

Agriculture relies heavily on the ecosystem services provided by soil and crop biodiversity. Soil and crop biodiversity also support both the productivity and resilience of agroecosystems (Holling 1973; Giller et al. 1997; Tilman et al. 1997; Diaz and Cabido 2001). The main purpose of this work is to study and estimate the interplay between crop biodiversity, soil, and farmers' revenues. To this end, we use a large household panel dataset from Italian agriculture. Of special interest are the dynamic effects of crop biodiversity, soil quality, and their interplay on productivity. The econometric analysis therefore relies on a dynamic generalized method of moments (GMM) estimator, which provides consistent estimates while correcting for potential endogeneity bias, and provides a basis for testing whether (i) the individual effect of crop diversification¹ and soil fertility on revenues is positive, and (ii) whether crop diversification can help to moderate the adverse effects of poor soil fertility.

The definition of crop biodiversity combines information on the number of crops cultivated on a farm and/or the number of livestock activities, whereas the definition of soil fertility combines information on the average soil fertility of farms with similar agricultural orientation in the same region.² We find that both crop biodiversity and soil fertility have individually positive effects on farmers' revenues. It is also shown that crop biodiversity and soil fertility may act as substitutes. These results provide evidence for the important role of biodiversity in enhancing the resilience of agroecosystems. Results are robust to the inclusion of a number of controls including land, livestock, fertilizers, access to irrigation, temperature, and rainfall.

The policy implications of this study are potentially great. Crop diversification may be a potential strategy to support productivity and revenues when soils are less fertile. Agricultural policies that reduce incentives for monoculture can deliver very important payoffs in rural areas. Our results can be seen as contributing to the empirical literature, documenting the roles of biodiversity in agriculture, which also includes the role of genetic diversity in wheat and barley in Pakistan and in dry and degraded environments in the northern Ethiopian Highlands (Smale et al. 1998; Di Falco and Chavas 2007; Di Falco and Chavas 2009), the role of crop diversification as a strategy to reduce environmental risk (Culas and Mahendrarajah 2005), and the efficiency-enhancing role of

¹ Crop biodiversity can individually have a positive effect on the output, with the level of diversity being selected for specific purposes, e.g., resistance to disease, tolerance to different climatic conditions or poor soils, or ensuring greater stability of production.

² Data for both variables come from the Italian Farm Accountancy Data Network (*Rete di Informazione Contabile Agricola*, RICA).

a mixed crop–livestock production system (Beshir et al. 2012).

Our results can also be seen as a contribution to the small volume of current literature on soil quality and crop choice. Bellon and Taylor (1993) examined the effect of land quality on maize variety selection in Chiapas and explained that the partial adoption of modern maize types in Chiapas and technology adoption significantly depend on farmers' perceptions of soil quality on their farms.

The next section presents a brief discussion of soil and agricultural systems. In “[Soil characteristics in Italy](#)” section, we present a general geoeological outline of the Italy Peninsula. A description of the data and the variables used in the empirical analysis is provided in “[Agricultural data description](#)” section. In “[Empirical framework](#)” section, we propose our empirical framework-based econometric analysis. The econometric results are then discussed in “[Results](#)” section, while in the final section of the paper, conclusions are drawn from the findings of this study.

BACKGROUND

Soil biodiversity, and agricultural systems

Soil systems are characterized by complexity and heterogeneity. The main factors related to soil formation are parent material, climate, organisms, relief, and time. These factors are interdependent, with each modifying the effectiveness of the others. Due to these various processes associated with its formation and genesis, the dynamics of soil reveals high complexity that can be observed at several levels: physical, biological, interaction, and evolutionary (De Bartolo et al. 2011). Soil biodiversity is often considered to be an indicator of soil health, considering its importance in regulating soil processes which are essential for soil formation and protection against soil degradation (de Bruyn 1997). Soil health, also often referred to interchangeably in literature as soil quality (Karlen et al. 1997), is defined as follows: “The capacity of the soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health” (Doran and Parkin 1994).

Different terms are often used to describe a soil's ability to perform functions that are essential to people and the environment. Soil provides a set of goods and services, the value of which varies according to the interests of those who benefit from using them, thus people often have different ideas of what soil quality is; For example, for a farmer, it is sustaining or enhancing productivity, maximizing profits, and maintaining soil resources. On the other hand, for an environmentalist, it is the capacity of the soil to function in an ecosystem with respect to biodiversity, water quality, nutrient cycling, and biomass production.

Soil conservation is a global issue mentioned in numerous international agreements such as the Conference of Rio de Janeiro in 1992 for the fight against desertification and the latest Kyoto Protocol on climate change due to greenhouse gases, which have, of course, highlighted the importance of soil as a resource to be protected. “Healthy soils for healthy life” was initially presented in the 144th Session of the FAO Council and has been proposed within the framework of the Global Soil Partnership (GSP), as a theme for raising awareness of the importance of sustainable soil management as the basis for food systems, fuel and fiber production, essential ecosystem functions, and better adaptation to climate change for the present and future generations. Under the GSP framework, the 68th UN General Assembly declared 2015 as the International Year of Soils.

A key priority, and the most urgent one, of the Commission of the European Community is to ensure the protection and conservation of more productive soils, together with the rational management of soils, not only for agricultural and forestry practices but also for esthetic purposes, i.e., landscapes. Since 1992, the Common Agricultural Policy (CAP) reform package has contributed to sustainable agricultural production of food and services through the single farm payment scheme, also aiming at broader objectives such as environmental protection and nature conservation, including maintenance of soils, landscapes, and biodiversity. One of the fundamental objectives of the Sixth Environment Action Programme (6EAP) is to promote “a sustainable use of the soil, with particular attention to preventing erosion, deterioration, contamination and desertification” (Withana et al. 2010). European Commission (2002) 179, entitled “Towards a Thematic Strategy for Soil Protection,” reported the main threats to which European soil is exposed, i.e., erosion, a decline in the level of organic matter, pollution, desertification, a decline in soil biodiversity, and salinization.

Agroecosystems are ecological systems transformed and simplified for the purpose of producing food, fiber, or other agricultural products (Di Falco and Chavas 2008). Agroecosystems are connected with natural ecosystems, particularly with soils. Soil ecosystem services of particular importance for agroecosystems involve the maintenance of the genetic diversity essential for successful crop and animal breeding, nutrient cycles, biological control of pests and diseases, erosion control and sediment retention, and water regulation (Swift et al. 2004).

Agricultural practices have an acute effect on degradation of soils by affecting the critical soil biological processes (e.g., nitrogen fixation, macropore formation, respiration rates) essential for many ecosystem functions. The agricultural management practices that have the most significant impact are the massive diffusion and excessive

use of broad-spectrum chemical fertilizers and pesticides, slash-and-burn shifting cultivation, soil tillage and compaction, reduction in crop biodiversity, and irrigation (Giller et al. 1997).

Soil biodiversity performs ecosystem services and provides soil functions that are essential for plant growth. In intensive agroecosystems, some soil functions have been widely replaced by conventional soil management, artificial fertilizers, and agrochemicals. In turn, the loss of soil biodiversity in these systems threatens fundamental self-regulating mechanisms, turning farms into highly vulnerable agroecosystems dependent on external inputs (Swift et al. 2004).

Soil is considered a finite natural resource that is non-renewable over human timeframes. In many parts of the world, farmers face challenging conditions, such as land degradation, erosion, and frequent extreme climatic events. Therefore, it is important to understand how soil and all the vital ecosystem functions it provides are essential to food security. The fact that the agricultural sector constitutes a significant part of the economy of many countries indicates the need for more effective soil and land management practices. Furthermore, due to the demand for food for an increasing population, agricultural expansion has the potential to have massive, irreversible environmental impacts (Tilman et al. 2001). Different land-use planning, mechanisms, and policies could mitigate some of the effects of agricultural expansion. In this regard, there is a growing consensus on soil biodiversity and the sustainability of many existing managed systems (e.g., Vitousek et al. 1997; Tilman et al. 2002; Green et al. 2005). Fundamental questions, therefore, are whether or not biodiversity impacts the provisioning of ecosystem services and how land management affects these ecosystem services. Agricultural biodiversity includes both the components of biological diversity relevant to food and agriculture and the components that constitute and sustain vital functions of the agroecosystem (Hoffmann 2011). According to Drucker et al. (2005), agricultural biodiversity refers to all species that exist in domesticated crop, tree, aquatic, and livestock systems. These species can be classified based on their role in the functioning of crop systems, also including all the associated but non-economically productive plants, animals, and microbes (Swift et al. 1996).

Crop biodiversity refers to the biological diversity of crops, including the variance in genetic and phenotypic characteristics of plants used in agriculture.³ Likewise, livestock biological diversity comprises both phenotypic and genotypic variations (Drucker et al. 2005). In this

regard, the agricultural biodiversity—crops, trees, and animals—chosen by farmers plays a determining role in the diversity and complexity of the agroecosystem (Altieri 1999).

Crop biodiversity can improve resilience in a variety of ways, and crop diversification, within agroecosystems, can occur in many forms and with many levels of complexity, over different scales. Diversification on field–crop scale may refer to changes in crop structural diversity or crop vegetation management strategies (i.e., plant mixing, discontinuity of monoculture in time through rotations, or allowing noncrop vegetation within monoculture). At landscape scale, diversification may be achieved by combining multiple production systems, such as complex landscapes that have areas of woodlands, or agroforestry management with cropping, livestock, and fallow areas, to create highly diverse agricultural land (Altieri 1999; Gurr et al. 2003). There is evidence that crop biodiversity can affect soil conditions and soil biodiversity. Palmu et al. (2014) conclude that increasing crop diversity is associated with ground-beetle activity and diversity in arable land, and this beneficial effect may be particularly important in areas of intensive farming. The results of a field experiment on homogeneous nitrogen-limited soil plots revealed that the sustainability of soil nutrient cycles and thus of soil fertility depends on crop biodiversity, which leads to greater productivity and lower nutrient losses in more diverse ecosystems (Tilman and Downing 1994; Tilman et al. 1996).

Soil characteristics in Italy

The Italy Peninsula has a surface area of nearly 30 1300 km², with a significant coastline (7600 km). The climate is highly diverse from the north to south of Italy due to the mountainous topography, latitudinal extension, and proximity to the sea. In most of the inland northern and central regions, the climate ranges from humid subtropical to humid continental and oceanic with altitude. The coastal plains of central and south Italy, along with the islands, are mainly characterized by Mediterranean, Mediterranean subtropical to subcontinental, and continental climates (Costantini et al. 2004).

The key agroenvironmental problems facing Italy are soil erosion and water pollution. Soil erosion and degradation of soil physical quality (namely compaction) and the chemical condition have been identified in many places in Italy, being attributed to intensive agricultural exploitation and low soil organic matter content (Costantini et al. 2004). Also, as mentioned by Costantini et al. (2004), on many coastal plains, groundwater pollution has occurred due to use of brackish waters, particularly on intensively cultivated plains.

³ Crop biodiversity includes plant varieties defined as agromorphologically distinct by farmers and genetically distinct by plant breeders (Drucker et al. 2005).

Table 1 Descriptive statistics of the data used in the analysis

Variable	Mean	SD	Min.	Max.
Texture	1.94	0.27	0.56	2.7
Available water storage capacity (mm/m)	68.75	31.8	15.46	150
Topsoil organic carbon (%)	1.14	0.74	0.25	20.88
Subsoil organic carbon (%)	0.44	0.72	0.034	20.16
Topsoil pH, measured in soil–water solution	6.64	0.52	2.2	7.5
Subsoil pH, measured in soil–water solution	6.08	1.17	0.54	7.64
Topsoil electrical conductivity	0.13	0.05	0.051	0.35
Subsoil electrical conductivity	0.11	0.076	0.008	1.44

SD, standard deviation

The FAO Harmonized World Soil Database (HWSD) (FAO et al. 2012) provides information about the physicochemical properties of soil, such as the percentage of organic carbon in topsoil and subsoil for each municipality and province in Italy; the data are presented for the nominal year of 2000. Soil characteristics in the HWSD represent data from existing soil profiles at various stages of pedogenic development, land use, land use history, and disturbance history. The HWSD provides information useful for addressing emerging problems of land competition between food production, bioenergy demand, and threats to biodiversity. These data have been used, for example, as inputs to terrestrial biosphere models, such as the Community Land Model (CLM) (see Wieder et al. 2014).

According to the HWSD report (FAO et al. 2012), organic carbon is, together with pH, the best simple indicator of the health status of soil. Data concerning the soil attributes from HWSD were integrated with the farm-level dataset from the Italian Farm Accountancy Data Network (FADN); the data are presented at municipality (*comune*) administrative level for the nominal year of 2000. Table 1 illustrates the descriptive statistics of specific soil attributes. However, in the empirical analysis, soil fertility is described by a categorical variable covering the period 1981–2003 that expresses the degree of fertility (low, medium, high) with reference to the average fertility of the land and agricultural production system.⁴

The map shown in Fig. 1 illustrates the major soil groupings which are used to display main soil types. The main soil type in Italy can be classified as Cambisols, which are weakly to moderately developed soils. Cambisols in a temperate climate are among the most productive soils on Earth, being intensely used for agriculture. For a soil to be categorized as Cambisol, the texture of the

subsurface horizons must be sandy loam or finer with at least 8 % clay by mass and thickness of 15 cm or more (FAO et al. 2012). From Fig. 1, one sees that the main soil type in the northern part of Italy can be classified as Leptosols, which are very shallow soils over hard rock or in unconsolidated, very gravelly material, being used mainly for pasture and grassland.

MATERIALS AND METHODS

Agricultural data description

The EU's Farm Accountancy Data Network (FADN)⁵ provides an annual sample survey of the agricultural sector and holds accountancy data for most EU member states. It has been carried out for over half a century,⁶ using a similar approach in all EU member countries, and is the only source of harmonized microeconomic data on the business operation and economic structural dynamics of companies operating in the agricultural sector. The stratification criteria are geographical location, economic size, and type of farming. The economic aspect is based on the standard gross margin.⁷ The observations consist of commercial⁸ farms and all agricultural holdings of more than one hectare, and those of less than one hectare that produce and provide to the market a specified amount of their

⁴ “Agricultural data description” section presents a description of the data used for the empirical analysis.

⁵ The FADN is an important informative source of microeconomic data for the agricultural sector.

⁶ The FADN is an annual sample survey that was established by the European Economic Commission in 1965 by EEC Regulation 79/56, updated with EC Reg. 1217/2009.

⁷ Standard gross margin (SGM) is used to determine the economic size of farms, expressed in terms of European size units (ESU).

⁸ A commercial farm is defined as a farm which is large enough to provide the main activity for the farmer and a level of income sufficient to support his or her family. To be classified as commercial, a farm must exceed a minimum economic size.

Fig. 1 Soil map of Italy . Source Costantini et al. 2012

output. Data collected from individual farms are treated confidentially; farmers take part in the sample voluntarily and are rewarded by detailed reports on their farm and a comparison with other individual farms.

In this study, we compiled a rich dataset from the Italian Farm Accountancy Data Network (RICA).⁹ The RICA is based on a purposive sample of about 11 000 farms, structured to represent the different types of production and size in the national territory. The farms participating in the

RICA are selected by a sampling plan drawn up for each region and autonomous province. The database contains a significant amount of information at farm level, appropriate for study of economic aspects of farms. Our sample consists of an unbalanced panel dataset of 122 800 farms over the period from 1981 to 2003. However, a high percentage of farms have been followed for more than 4 years¹⁰ each.

From the perspective of number of agricultural activities, the farming pattern in the country appears highly diversified: When categorizing the 122 800 farms in the study sample according to their diversified activity, eight

⁹ The FADN is managed for Italy by the National Institute of Agricultural Economics (Istituto Nazionale di Economia Agraria, INEA).

¹⁰ Nine farms were observed over a 22-year period.

Table 2 Diversified agricultural activities of the farms in the sample

Farming pattern ^a	No. of farms	%	Agricultural land (ha)	%
Vegetables	16 486	5	211 446	3
Horticulture	21 005	6	48 055	1
Permanent crops	85 906	25	820 654	12
Livestock	87 465	25	2 697 391	38
Mixed farm	36 270	11	932 626	13
Field crops	36 802	11	952 043	13
Cereals	36 064	10	1 081 732	15
Mixed crops	25 048	7	384 753	5

^a Analysis by technical–economic orientation (TEO)

Table 3 Descriptive statistics of the variables used in the analysis

Variable	Mean	SD	Min.	Max.
Gross production (euros)	833 723	205 215	0	24 800 000
Land (ha)	20.66	43.2	0	4396
Crop diversification	4.67	2.22	1	22
Soil fertility	1.99	0.3	1	3
Fertilizers (euros)	2879	5918	0	598 940
Plant protection (euros)	1995	7736	0	1 609 241
Irrigation dummy	0.55	0.5	0	1
Livestock dummy	0.36	0.49	0	1
Rainfall (mm year ⁻¹)	68.07	25.53	0.25	299.43
Temperature (°C) (1 March–30 September)	17.58	2.32	3.63	24.1

groups emerged (Table 2). A significant percentage of farms in our sample are predominantly specialized in permanent crops (25 %) or livestock (25 %), while approximately 11 % of the whole sample are reported to have mixed operations. About 21 % of the farms are specialized in field crops—predominantly cereal production—with 7 % of them being reported to have mixed crop operations. According to the geographical breakdown, horticultural and permanent crop production dominates in the south, whereas livestock and cereals are more prominent in the north.

Tables 3 and 4 present the descriptive statistics and the definitions of the variables used in the empirical analysis. We focus on ways to capture the interaction between soil functions, agricultural diversification, and agricultural practices. Gross production is used as the dependent variable in the analysis because it provides the return explicitly linked to farm activity, by measuring the value of the final output and the agricultural land capability. Gross production is defined as the revenues obtained from all products, net of seed and feed reuse within agriculture itself, but inclusive of farmers' domestic consumption. The soil fertility index is used to indicate whether or not a soil's condition is sufficient to meet yield expectations.

Climate characteristics have been shown to play a role in agricultural production. We, therefore, integrated the farm-level dataset with climatic variables: average temperatures for the growing season¹¹ and average annual cumulated precipitation averaged at municipality administrative level¹² from numerous meteorological stations located across the Italian territory. Meteorological time series were collected and elaborated by the Italian Environmental Agency. The benefit from irrigation in terms of yield return is measured by considering an irrigation dummy as a control variable. Ownership of livestock may also affect production, so a dummy variable captures the effect of livestock.

Empirical framework

Agricultural production is intrinsically a dynamic process, linking various inputs to the output, where the influence of time can impact heavily on response efficiency (Chavas

¹¹ We consider as the “growing season” the period from 1 March to 30 September.

¹² When matching at municipality level was not possible, we did so at province administrative level.

Table 4 Definitions of the variables used in the analysis

Variable	Definition
Gross production (euro)	Value of agricultural production expressed as revenues obtained from all products and services
Land	Total used agricultural area (ha)
Crop diversification	Number of crops cultivated on the farm and/or number of livestock activities
Soil fertility	Average soil fertility of farms with similar agricultural orientation in the same region. Expressed as degree of fertility, on the basis of soil texture, generating test results that are grouped into three broad categories describing the relative soil fertility of a given plot: low = 1, medium = 2, and high = 3.
Fertilizers	Total chemical fertilizer expenditure (euros)
Plant protection	Total plant protection expenditure (euros)
Irrigation dummy	Dummy = 1 when farm reports irrigation expenditure and irrigated land, 0 otherwise
Livestock dummy	Dummy = 1 when farm owns some livestock, 0 otherwise
Rainfall (mm)	Average annual cumulated precipitation
Temperature (°C)	Average temperature during growing season (1 March–30 September)

et al. 1985). Current production can be considered the result of choices and decisions made in the past, because of biological lags associated with the growth process and also because of the influences of the time sequence of input availability on output, such as livestock feed or fertilizer application and carryover. This particularly emphasizes the importance of dynamic examination of agroecosystem functioning. The central aim of this paper is to analyze the effect of soil fertility and crop diversification and their interplay with agricultural production by focusing on an agricultural production function.

We postulate that the agricultural production function $f(\cdot)$ is determined by the following set of factors:

$$y_{it} = f_{it}(x_{it}, \cdot), \quad (1)$$

where y_{it} is the projected production of farm i at time t , x_{it} is a vector of characteristics of farm i that also vary across time and space, and “ $\cdot$ ” denotes other factors, i.e., a vector of time-invariant farm characteristics. The vector x_t includes conventional inputs, such as land allocation, plant protection, fertilizers, irrigation, livestock, rainfall, and temperature, along with a soil fertility index and crop diversification.

To introduce dynamics into the analysis, the k -th lagged production $y_{i,t-k}$ enters the production function up to lag $k = p$, where $p \geq 0$. After taking the natural logarithms of all variables, a first-order approximation of the production function gives

$$\ln(y_{it}) = \alpha \ln(x_{it}) + \sum_{k=1}^p \beta_k \ln(y_{i,t-k}). \quad (2)$$

As we are particularly interested in the effects of soil fertility and crop diversification on productivity, we introduce the additional interaction term $[\ln(\text{soil}$

fertility) $\times \ln(\text{crop diversification})]$ in Eq. (2). As a result, we consider the following functional specification, representing dynamics as well as interaction effects:

$$\begin{aligned} \ln(y_{it}) &= \alpha \ln(x_{it}) + \sum_{k=1}^p \beta_k \ln(y_{i,t-k}) + \gamma \ln(z_{it}) \\ &\quad + \delta_0 \{ \ln(\text{crop diversification}_{it}) \\ &\quad \times \ln(\text{soil fertility}_{it}) \} + u_{it}, \\ u_{it} &= \mu_i + v_{it} \\ E(\mu_i) &= E(v_{it}) = E(\mu_i v_{it}) = 0. \end{aligned} \quad (3)$$

The disturbance term has two orthogonal components, independently distributed, namely μ_i and v_{it} , each with mean zero and finite variance. The term μ_i measures farm-specific effects, while the term v_{it} denotes the remainder disturbance that can vary over time as well as across farms. The vector x_{it} is a vector of exogenous¹³ and predetermined¹⁴ covariates, and z_{it} is a vector of predetermined and endogenous¹⁵ covariates as well as the vector for the lag of y , all of which may be correlated with the μ_i . Predetermined variables are potentially correlated with past errors, and endogenous variables are potentially correlated with past and present errors. Several econometric problems may arise when estimating Eq. (3). However, the panel nature of the analysis could help to overcome these problems by controlling for cross-sectional heterogeneity and unobservable or missing values (Baltagi 2001). Panel data analysis also provides a basis to study estimation of short- as well as long-run effects of

¹³ If x_{it} is exogenous, $E(x_{it}v_{it}) = 0$.

¹⁴ If x_{it} is predetermined, $E(x_{it}v_{it}) \neq 0$ but $E(x_{i,t-1}v_{i,t-1}) = 0$. Valid instruments are therefore x_{is} , with $s = 1, \dots, t-1$.

¹⁵ If z_{it} is endogenous, $E(z_{it}v_{it}) \neq 0$ but $E(z_{i,t-1}v_{i,t-1}) \neq 0$. Valid instruments are therefore z_{is} , with $s = 1, \dots, t-2$ as $E(z_{i,t-2}v_{it}) = 0$.

explanatory variables. Thus, an Arellano–Bond two-step dynamic panel data GMM estimator is recommended to obtain parameter estimates more efficiently.

First-differencing Eq. (3) removes the specific effect μ_i , thus eliminating a potential source of omitted variable bias in the estimation. However, differencing variables that are predetermined but not strictly exogenous makes them endogenous, since the z_{it} in some $\Delta z_{it} = z_{it} - z_{i,t-1}$ is correlated with the $v_{i,t-1}$ in Δv_{it} . Following Holtz-Eakin et al. (1988), Arellano and Bond (1991) implemented the generalized method of moments estimator that instruments the differenced variables that are not exogenous with all the available lags in levels. Arellano and Bond also developed an appropriate test for autocorrelation, which is applied to the differenced residuals to purge the unobserved and perfectly autocorrelated μ_i . A first-order autocorrelation AR(1) is expected because $\Delta v_{it} = v_{it} - v_{i,t-1}$ should correlate with $\Delta v_{it-1} = v_{i,t-1} - v_{i,t-2}$. Applying the transform to Eq. (3) gives

$$\begin{aligned} \Delta \ln(x_{it}) &= \alpha \Delta \ln(x_{it}) + \sum_{k=1}^p \beta_k \Delta \ln(y_{i,t-k}) + \gamma \Delta \ln(z_{it}) \\ &\quad + \delta_0 \Delta \{ \ln(\text{crop diversification}_{it}) \\ &\quad \times \ln(\text{soil fertility}_{it}) \} + \Delta u_{it}, \\ \Delta u_{it} &= \Delta v_{it} = v_{it} - v_{i,t-1}. \end{aligned} \quad (4)$$

Finally, the Arellano–Bond estimator was designed for small- T large- N panels. By choosing an appropriate set of instruments, the Arellano–Bond GMM estimator can provide consistent estimators. Table 5 reports the associated econometric results.

RESULTS

By choosing an appropriate set of instruments, the Arellano–Bond GMM estimator can provide consistent estimators for the model (4). Among the regressors, two lags are included for the dependent variable ($p = 2$); all variables are taken in natural logarithms. We use the lags of the endogenous variables as instruments (restricting the maximum lag to 5 periods), and for the exogenous and predetermined variables, the variable itself. Climatic variables are considered strictly exogenous; conventional inputs and soil fertility¹⁶ factors are considered as predetermined variables, and the lagged values of the dependent variable and the variable crop diversification are considered endogenous; the main results of the regression are reported in Table 5. We estimate the two-step “difference GMM”

¹⁶ Soil heterogeneity determines crop yield variability not only through soil services, but also by influencing farmers’ management decisions, which in turn feed back to reinforce the soil fertility patterns within farms (Tittonell et al. 2008).

Table 5 Estimation results

Variable	Arellano–Bond dynamic two-step GMM estimation of log gross saleable production per farm
y_{t-1}	0.23*** (0.01)
y_{t-2}	0.054*** (0.006)
Crop diversification _{<i>t</i>}	12.09*** (3.46)
Soil fertility index _{<i>t</i>}	19.30*** (5.55)
Crop diversification _{<i>t</i>} × soil fertility _{<i>t</i>}	−12.00*** (3.46)
Land _{<i>t</i>}	0.37*** (0.2)
Fertilizers expenditure _{<i>t</i>}	0.08*** (0.003)
Plant protection expenditure _{<i>t</i>}	0.14*** (0.004)
Irrigation dummy _{<i>t</i>}	0.019* (0.009)
Livestock dummy _{<i>t</i>}	0.12*** (0.01)
Rainfall _{<i>t</i>}	0.093*** (0.026)
Rainfall squared _{<i>t</i>}	−0.023*** (0.003)
Temperature _{<i>t</i>}	3.17*** (0.6)
Temperature squared _{<i>t</i>}	−0.63*** (0.1)

All variables are in logs. GMM results are two-step estimates with heteroskedasticity-consistent standard errors. Clustered standard errors are in parentheses. Wald test of jointly zero coefficients $\chi^2(13) = 6.368$. p value < 0.000. No. of observations 70,823

Significance levels: *** = 1 %, ** = 5 %, * = 10 %

Arellano–Bond test, H0 of no first-order serial correlation in the residuals: $z = -33.22$ Pr > $z = 0.000$

Arellano–Bond test, H0 of no second-order serial correlation in the residuals: $z = -0.18$, Pr > $z = 0.851$

form of the model. We include a large set of controls besides crop biodiversity, soil fertility, and their interaction.

In the Arellano–Bond approach, a first-order autocorrelation AR(1) is expected in first differences,¹⁷ while higher-order autocorrelation indicates that some lags of the dependent variable, which might be used as instruments, are in fact endogenous and thus considered inadequate instruments. The tests for the AR(1) process in first differences reject the null hypothesis of no serial correlation in v_{it} in both specifications. The test for second-order serial correlation of the residuals AR(2) in first differences is also important because it detects autocorrelation in levels. Under the null hypothesis of no second-order serial correlation in v_{it} , we accept the null hypothesis in both specifications.

In terms of productivity, the dependent variable in the model is the logarithm of gross production per farm. The results show that agriculture depends on its past

¹⁷ Arellano and Bond (1991) note that, whenever this condition holds, the first-differenced residuals should display negative first-order serial correlation but no second-order serial correlation.

realizations; both $y_{i,t-1}$ and $y_{i,t-2}$ coefficients are positive and highly statistically significant. The estimation results support the dynamic specification of the production function. The current level of crop diversification is positively related to production. This positive effect indicates that keeping more varieties or developing different agricultural activities in farmers' fields can enhance production in agroecosystems. Used land fertility level has a positive impact on the yield when the land is of high fertility.

To investigate the role of crop biodiversity in possibly mitigating the effects of land degradation on productivity, we introduced an interaction term between crop diversification and soil fertility. The results of the econometric analysis show evidence of an individually positive effect of diversification and soil fertility on agricultural productivity. However, the coefficient of the interaction term is negative and significant. This means that the effects of diversification on productivity are relatively larger when there is land degradation. This effect also provides evidence for a positive relationship between diversity, resilience, and production in agroecosystems. The two variables can be considered substitutes, and this fact indicates that diversification ensures that the agroecosystem remains productive when facing lower levels of soil fertility.

Because of the interaction term, the effect of soil fertility level on agricultural revenues is different for different values of diversification. In other words, the slopes of the regression lines between agricultural production and soil fertility are different for the various levels of diversification. The coefficient of the interaction term indicates how different those slopes are. The partial derivative of gross production with respect to diversification,¹⁸ evaluated at the three different degree levels of soil fertility, indicates that soil fertility is less important for agricultural revenues when diversification is high. The partial derivative of gross production with respect to diversification is positive (0.09) when soil is less fertile but negative when it is of medium or high fertility. Likewise, the effect of soil fertility is greater when crop diversification is low.

Regarding the other conventional inputs, most of the estimated coefficients are statistically different from zero at the 1 % significance level and have a positive effect on the production process, as expected. Yield is shown to increase significantly with fertilizer and plant protection application, demonstrating that fertilizers and pesticides can be a potential substitute for services generated by soil organisms, hence the necessity to increase the rate of fertilizer and pesticide input to achieve a particular level of yield at lower levels of soil fertility. The effects of land on production are found to be statistically significant, and as expected, the estimated impact of land is relatively large.

The coefficient of the livestock activity dummy suggests that, when a farmer chooses to specialize in livestock or joint operations, productivity is higher. This indicates a possibility of increasing farm income and resource use by integrating crop and livestock activities.

Rainfall positively affects agriculture output and is significant with negative marginal, which is consistent with general beliefs. Excessive rainfall during harvesting and planting seasons might cause loss in production and, consequently, profit losses to farmers. In addition, we observe positive effects of temperature during the growing season, while effects of excessive temperature (marginal effect) are negative; very high temperature during the growing season can have an adverse impact on plants.

Another determinant that might increase farmers' efficiency in generating profits is use of irrigation. In our regression, the coefficient of the irrigation dummy variable estimates by how much irrigating a plot increases productivity, although the significance of the estimated coefficient is small.

DISCUSSION

Agriculture will continue to be a key sector for nearly all major economies in the world. Agricultural expansion and intensification cause adverse environmental impacts, and introduction of different land-use planning, mechanisms, and policies is crucial to mitigate some effects of these impacts. There has been growing concern about the effectiveness of agricultural performance and its relation to natural resources. This study was initiated to measure the efficiency of mixed crop and livestock production systems in terms of soil fertility in the study area.

By means of an Arellano–Bond dynamic panel data study of Italian farms over the period 1981–2003, it is concluded that agricultural production depends on its past realization in both the short and long run. The analysis shows evidence of positive effects of crop biodiversity and soil fertility on agroecosystem production. Furthermore, it indicates that crop diversification ensures that the agroecosystem remains productive when facing lower levels of soil fertility. These results demonstrate a positive relationship between diversity, resilience, and production in agroecosystems.

Furthermore, it suggests that diversification can be a potential strategy for maintaining agricultural productivity on less fertile soil. Farm size, livestock ownership, and fertilizer and pesticide availability affect production efficiency. This implies that a more diversified agroecosystem, especially combining crops and livestock, can ultimately improve agricultural productivity by improving production efficiency. Therefore, more diverse agroecosystems seem more able to cope with environmental risks such as land degradation.

¹⁸ All variables are taken in natural logarithms.

CONCLUSION

This study provides insight into the estimation of current and future agricultural productivity concerning potential risks of land degradation and could also be of interest for consulting purposes in farming development and adaptation perspectives, as it could contribute to policy-making related to future management of land resources. Future extension of the present study will include the type of farming, not only to highlight differences between the main technical economic orientations, but also to capture volatility in agricultural commodity markets. Due to a lack of data over time, we consider degree of fertility as the only soil quality indicator, while other indicators such as soil organic matter and nitrogen could better describe soil conditions. In further extension of this study, we aim to raise awareness amongst agriculturists and environmentalists as well as policy-makers regarding misuse of natural resources and disregard of the roles of natural systems.

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AUTHOR BIOGRAPHIES

Salvatore Di Falco (✉) is a professor at Geneva School of Economics and Management. Salvatore's research focuses on the intersection between environmental and development economics using econometric models. He has analyzed the contribution of natural resources such as biodiversity to agricultural productivity, food security, and weather risk in arid environments. His work also focuses on the role of institutional structures (common property forests) in natural resource conservation, rural development, and poverty reduction. More recent work includes the impact of social capital and traditional sharing norms on consumption, saving accumulation, investment decisions, and adaptation to climate change.
 Address: The Institute of Economics and Econometrics, The University of Geneva, UNIMAIL Boulevard du Pont d'Arve 40, Geneva 1211, Switzerland.
 e-mail: salvatore.difalco@unige.ch

Elisavet Zoupanidou is a Marie-Curie fellow and doctoral student at the Faculty of Social Sciences of the University of Geneva. Her research focuses on environment and agriculture.
 Address: University of Geneva, Geneva, Switzerland.