Ecological Economics 152 (2018) 27–39

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

# Climate Change and Agriculture: Do Environmental Preservation and Ecosystem Services Matter?

Alexandre Gori Maia[a], Bruno César Brito Miyamoto[b], Junior Ruiz Garcia[c,*]

[a] Center for Agricultural and Environmental Economics, University of Campinas, R. Pitágoras, 353, Cidade Universitária, Campinas, SP CEP: 13083-857, Brazil
[b] Federal Institute of Rio Grande do Sul (IFRS), R. Princesa Isabel, 60, Feliz, RS CEP: 95770-000, Brazil
[c] Department of Economics, Federal University of Parana (UFPR), Av. Prefeito Lothário Meissner, 632, térreo, Jardim Botânico, Curitiba, PR CEP: 80210-170, Brazil

ARTICLE INFO

*Keywords:*
Extreme Events
Agricultural Production
Environmental Sustainability
Production Practices

ABSTRACT

Climate change is expected to cause several impacts on agriculture. Nonetheless, adaptive strategies and environmental sustainability may affect the ability to cope with these impacts. We analyze how agricultural technologies and the ecosystem diversity represented by the land cover have attenuated the impacts of extreme climate events on agricultural production in the São Paulo state, Brazil. Analyses are based on a panel with information for 568 municipalities between 1990 and 2014. We first use multivariate statistical analysis to define six groups of localities according to their levels of agricultural development and land cover. Secondly, based on fixed effect estimates, we analyze the relationship between the dynamics of extreme climate events and agricultural production in each group of localities. Results highlight that both technological and environmental factors could contribute to increases in agricultural production. More importantly, agriculture practiced with high levels of environmental preservation tends to be more resilient to extreme temperature and precipitation events.

## 1. Introduction

Climate change is expected to cause several impacts on agriculture, primarily through increases in average temperature and in the intensity and frequency of extreme events, such as heavy precipitation and prolonged droughts (IPCC, 2014). Studies have highlighted how less developed regions and more vulnerable farmers tend to be specially affected by climate change, since they lack the basic social and economic capital needed for adaptive strategies, such as access to irrigation and drought-tolerant crops (Mendelsohn and Dinar, 2009; Villamayor-Tomas, 2014; Wreford et al., 2010). South American countries are already suffering the impacts of changes in average rainfall and temperature, increases in the occurrence of warmer nights in tropical regions, and dry spells in semiarid regions (Vergara, 2009; PBMC, 2014; Marengo et al., 2010; Maia et al., 2016).

The patterns of land use and the provision of ecosystem services are also expected to affect the ability to cope with climate change (von Möllendorff and Hirschfeld, 2016). Although humans have appropriated an increasing share of the planet's resources, changes in land use and land cover have potentially undermined the capacity of ecosystems to sustain food production, maintain freshwater and forest resources, regulate climate and air quality, and ameliorate infectious diseases (Foley et al., 2005). The stage in land transition usually encompasses the clearing of natural ecosystems, practices of livestock and agriculture, and finally the expansion of urban areas. Some important consequences of anthropic changes in land use and land cover in South America, mainly through deforestation, extensive livestock and unsustainable agricultural practices, have been hydric degradation, loss of soil fertility, erosion, and desertification (Marengo et al., 2012; The World Bank, 2012).

Changes in the land use and land cover, mainly deforestation and urbanization, have represented one of the main sources of carbon emissions worldwide (IPCC, 2014; The World Bank, 2012; PBMC, 2014). The global consequences of climate change and rising temperature can change the frequency and the intensity of extreme weather events (Hallegatte et al., 2007). In Brazil, for example, the National Institute for Space Research (INPE) projected an increase in average temperature by 2100 from 4 °C to 6 °C in pessimistic scenario, or from 1 °C to 3 °C in optimistic scenario (Marengo, 2007; PBMC, 2014).

The climate change can affect negatively the ecosystem services flow, i.e. the benefits society appropriate from the ecosystem (La Notte et al., 2017), especially through extreme precipitation events (Hallegatte et al., 2007; Millenium Ecosystem Assessment, 2010). Severe droughts contribute to elevate the plant temperature, a regulating

* Corresponding author.
*E-mail addresses:* gori@unicamp.br (A.G. Maia), jrgarcia@ufpr.br (J.R. Garcia).

https://doi.org/10.1016/j.ecolecon.2018.05.013
Received 17 August 2017; Received in revised form 20 April 2018; Accepted 20 May 2018
Available online 02 June 2018
0921-8009/ 

ecosystem service, due to the closure of the stomata and the reduction of transpiration, and to the increase of pests and diseases due to the reduction of the population size of natural enemies (Rosenzweig et al., 2001). Prolonged droughts also increase the risk of soil erosion by winds, a supporting ecosystem service, and, when followed by heavy rains, increase the potential for flooding due to reduced soil water absorption capacity, which creates favorable conditions for fungal infestation in leaves and roots (Knapp et al., 2008). Extreme events can also affect severely the agricultural production, due to both direct and indirect effects of changes in soil moisture conditions (Rosenzweig et al., 2001), by delaying planting and harvesting operations (van der Velde et al., 2012), leaching and erosion in the absence of conservation-oriented soil management (Deelstra et al., 2011; Jørgensen and Termansen, 2016).

Several studies have analyzed the impacts of climate change on agricultural production (Mendelsohn et al., 1994; Mendelsohn and Dinar, 2009; Dai et al., 2015). More recently, studies have also analyzed how the impacts of climate changes may differ depending on the adoption of adaptive strategies (Schlenker et al., 2003). Adaptive strategies can comprise both agronomic adaptations - e.g. changes in crop varieties and species, timing of operations, and land management, including irrigation - and economic adaptations - e.g. investment in new technologies, infrastructure, and labor (Easterling, 1996). Although the effectiveness varies largely across regions and crops, studies suggest that both agronomic and economic strategies can partially or completely offset the losses of productivity caused by climate change (Burney et al., 2014; Maia et al., 2016; Reidsma et al., 2009). These studies tend to include climate variables in a traditional production function, supposing that input and environmental resources as substitute. Adaptive strategies are important components to attenuate the impacts of climate change, but it also depends on the provision of ecosystem services. Intensive agriculture may potentially undermine the capacity of ecosystem to sustain food production in long term (Foley et al., 2005).

While the use of land have provided useful resources for human activities, allowing them to grow crops, raise animals, obtain timber, and build cities – urbanization –, it has altered a range of essentials ecosystem services, such as providing freshwater, regulation of climate and maintenance of soil fertility (Defries et al., 2004). For example, soil water storage capacity is one of the factors that determine how ecosystems will respond to future changes in precipitation regimes. Soil water storage depends on soil and subsurface soil conditions, as well as vegetation characteristics, such as type, density, species composition and root characteristics (Várallyay, 2010). In urban areas, the soil water storage capacity has been almost lost due to impermeabilization. But in forestry areas, the soil water storage capacity can be maxima. Ecosystems, where there is a predominance of deep roots, may present greater resilience to water fluctuations in the soil (Antonija Kustura et al., 2008; Knapp et al., 2008; Nepstad et al., 1994).

The stage of land use transition, from natural forest to urban areas, is also directly related to the biological diversity. The role of biological diversity in the stability of ecosystems due to environmental fluctuations has been an object of intense debate in the ecological research (Hassan et al., 2005). One of the most important themes linked to this debate is "insurance hypothesis" (Mariotte et al., 2013; Naeem and Li, 1997; Yachi and Loreau, 1999). According to this hypothesis, the diversity of species in an ecosystem increases the chance that ecosystem functions will remain stable in the face of an environmental disturbance or extreme climatic event (Mariotte et al., 2015). An ecosystem with greater diversity would be more likely to have species capable of replacing those less adapted to the new environmental conditions and thus guarantee the stability of a given ecosystem service (Borrvall and Ebenman, 2008).

In this context, we analyze how agricultural technologies and environmental preservation practices may attenuate the impacts of extreme climate events on agricultural production in the state of São Paulo, Brazil. Specifically, we analyze how the impacts of extreme events of precipitation and temperature on the agricultural production may differ according to the levels of land cover, proxy for ecosystem diversity, and the adoption of agronomic and economic strategies. Our main hypothesis is that the use agricultural technologies is necessary, but not sufficient, to create climate resilience in the agricultural production. Ecosystem services would play a central role determining the capability of production techniques to mitigate the impacts of extreme climatic events.

São Paulo is the most developed state in Brazil (IBGE, 2018). In 2015, the São Paulo possessed the highest gross value added of agricultural production among Brazilian states (IBGE, 2018), and the state is the leading national producer of sugarcane/ethanol, sugarcane/sugar and orange juice in Brazil (CEPEA, 2017). The cultivation of the main agricultural product in the São Paulo, sugarcane, is based on rainfed irrigation, making it more dependent on environmental and climate conditions, especially rain patterns. Even though São Paulo state is in a region with high levels of precipitation and a rich supply of fresh water, it has experienced critical moments of water shortage in recent years because of both growth in demand and the reduction in regular supply of water resources. Climate change has been pointed as a main factor responsible for the extremely low levels of precipitation observed in the early 2010s (INMET, 2017). Nevertheless, the historical land use in this highly dynamic region has strongly affected the landscape structure and the provision of ecosystem services related to biodiversity, water, and nutrient cycling (Taniwaki et al., 2017; Ferraz et al., 2014).

## 2. Data and Methods

### 2.1. Data Source

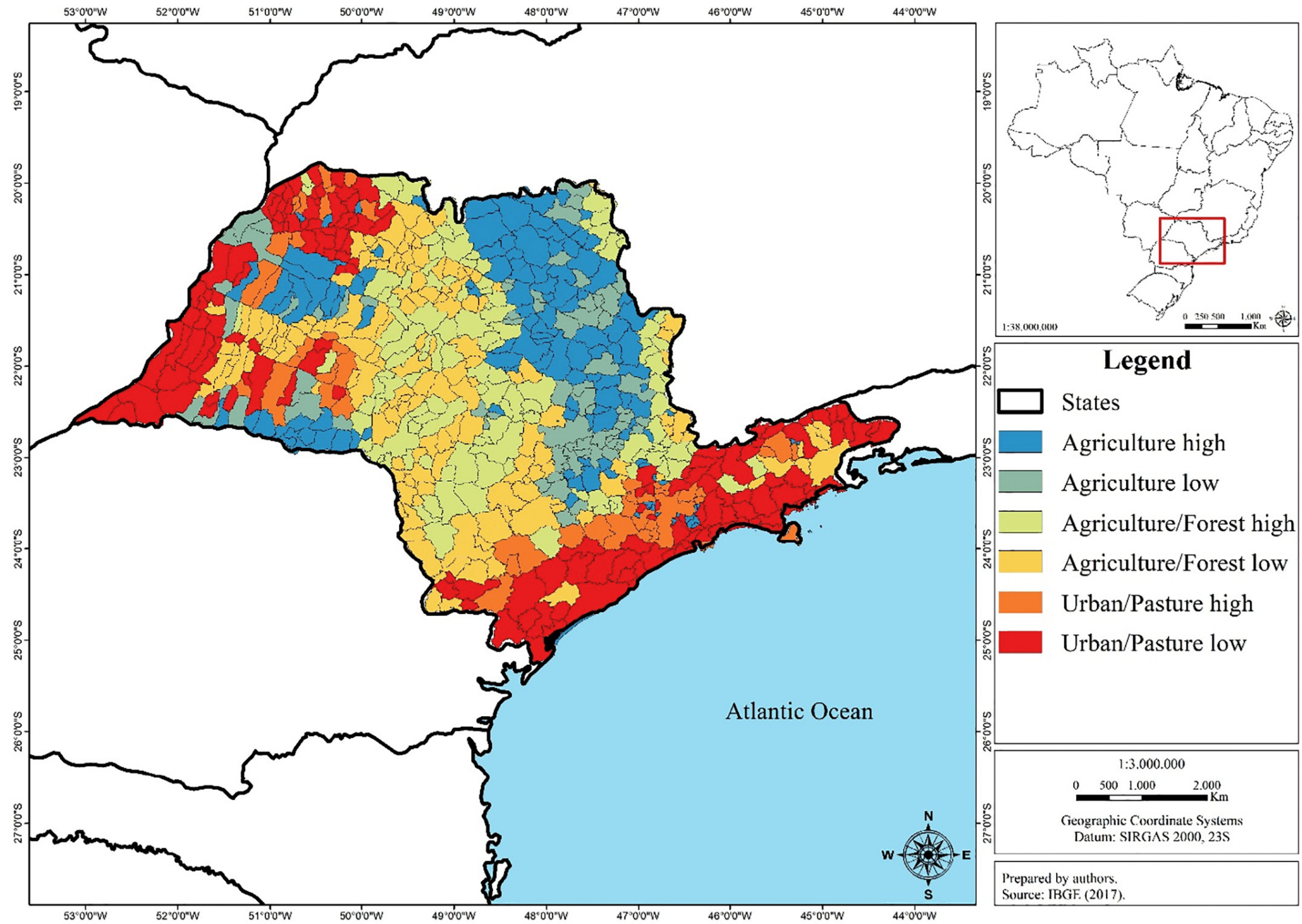
Analyses are based on municipal-level data provided by: (i) the Brazilian Institute of Geography and Statistics (IBGE), for data related to agricultural production; (ii) the Institute of Agricultural Economics (IEA), for data related to agronomic and economic strategies; (iii) the National Meteorological Institute (INMET), for data related to climate variables; and (iv) the INPE, for data related to land cover. We aggregated the information of the São Paulo state into 568 MCAs (Minimum Comparable Areas), which are groups of historically comparable municipalities.

São Paulo state is in the Southeastern Brazil (Map 1). This is the most populous (41 million inhabitants in 2010, or 21.6% of national population) and richest state in Brazil (US$ 789,747 million of GDP in 2014, or 32.2% of the Brazilian GDP) (IBGE, 2018). Although the Gross Value Added of the agricultural production represents only 1.7% of the total in the state (US$ 11,617 million in 2014), the agricultural sector plays an important role in the state and in Brazil, because it is well integrated to the industrial and services sectors, the agribusiness (CEPEA, 2017).

### 2.2. Groups of Land Cover and Production Technologies

The levels of land cover and the adoption of agronomic/economic strategies were defined using multivariate statistical analysis (Morrison, 1990). Cluster analysis was applied to identify three groups of land use/cover. Factor analysis was applied to identify two groups of agronomic/economic strategies. We then joined these two classifications to define 6 groups of *land cover and agronomic/economic technologies*. The flow chart in Fig. 1 summarizes how the groups were defined. The subsections bellow explains more carefully each step.

Based on a panel with 568 MCAs between 1990 and 2014, we then use fixed effect estimates to analyze the relationship between the dynamics of climatic variables and agricultural production in each group of land cover and agronomic/economic technology. We analyze the impacts on the (i) total value of production and (ii) the log of the physical production of sugarcane and orange, the main agricultural




**Map 1.** Spatial location of the São Paulo state and distribution of the groups of land cover and production techniques (High and Low).
Source: Elaborated by the authors using data from INMET (2017) and IBGE (2017).

activities in the region.

### 2.2.1. Clusters of Land Cover

Based on the maps of land cover provided by the IBGE (2017), we identified eight classes in São Paulo: agriculture; urban areas; water and humid forests; mosaic of agriculture and remaining forests (agriculture/forests); mosaic of natural vegetation, forests and agriculture (forest/agriculture); pastures; silviculture; and forests. This information was available for the years 2000, 2010, 2012 and 2014 (Table 1). The main change observed in this period was the shift from forests (declining from 10.7% of the total in 2000 to 9.1% in 2014) and pasture (declining from 12.1% to 10.8%) to agricultural areas (increasing from 26.5% to 31.4%), mainly sugarcane. Most MCAs had less than 10 percentage points of variation in the land cover in the period (486 MCAs). Few exceptions had more 50 percentage point of variation in the land cover (11 MCAs), which was mainly related to the replacement of pasture by

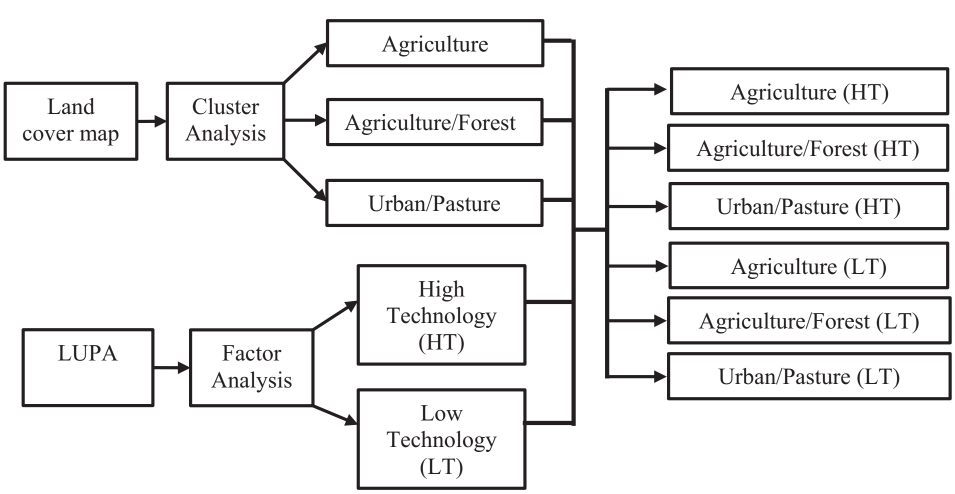



**Fig. 1.** Flow chart for the multivariate analysis.
Note: the types of land cover used in the cluster analysis are agriculture, urban, water, agriculture/forest, forest/agriculture, pasture, silviculture, and forest. The production techniques used in the factor analysis are irrigation, sowing machine, plowing machine, tractor, other machines, soil treatment.
Source: Elaborated by the authors.

**Table 1**
Percentage (%) of the total area according to land cover type, São Paulo: 2000–2014.
Source: Elaborated by the authors using data from the (IBGE, 2017).

| Land cover | Year | | | |
|---|---|---|---|---|
| | 2000 | 2010 | 2012 | 2014 |
| Agriculture | 26.5 | 27.5 | 29.1 | 31.4 |
| Urban | 3.3 | 3.3 | 3.3 | 3.3 |
| Water | 3.5 | 3.5 | 3.5 | 3.5 |
| Agriculture/forest | 33.8 | 33.6 | 32.7 | 32.5 |
| Forest/agriculture | 6.5 | 6.2 | 6.0 | 5.7 |
| Pasture | 12.1 | 12.3 | 12.6 | 10.8 |
| Silviculture | 3.6 | 3.9 | 3.5 | 3.8 |
| Forest | 10.7 | 9.7 | 9.3 | 9.1 |

agricultural areas (mainly sugarcane). These numbers represent only a small share of our sample (2%) and may not affect our estimates. A deeper investigation of the multiple relations between the dynamics of land cover, climate variability, adaptive strategies and agricultural production would rely on the availability of long-term historical data for these variables.

We computed the average percentage value of each MCA's total area covered by each one of the eight classes in the whole period. These average values were used to classify the municipalities in *clusters of land use and land cover* by the method of cluster analysis. Cluster analysis defines hierarchical groups of observations with similar values within the groups and heterogeneous values between the groups (Crivisqui, 1999). There are several methods that may be employed in this process, but all are based on the same principle of hierarchical clustering. Initially, each observation is considered as a cluster. The two closest clusters are then joined to form a new cluster, and so on until the method forms a maximum number of clusters predetermined by the researcher. The difference between alternative clustering methods is basically the way in which the distance (or dissimilarity) between clusters is calculated.

The clustering method employed in this study is the Ward method, an aggregation strategy based on the analysis of variance within and between the groups formed. The aim of this method is to create hierarchical groups in such a way that the variance within groups is minimal and the variance between groups is maximal. The aggregation criterion consists of finding the next group that minimizes the variability within the newly-formed group. To facilitate the understanding of the variability within groups, they are usually divided by the total variance to represent a ratio of the maximum achieved variability (semi partial $R^2$).

### 2.2.2. Factors of Production Techniques in Agriculture

Variables relating to the use production technologies (agronomic and economic strategies) in agriculture were obtained from the Survey of Agricultural Production Units from 2007/2008 (LUPA, *Levantamento Censitário de Unidades de Produção Agrícola*), provided by the Institute of Agricultural Economics (IEA, *Instituto de Economia Agrícola*). These variables refer to ratios between the number of units of systems and the number of farms in each municipality (Table 2): irrigation, sowing machines, plowing machines; tractors; other machines; and adoption of soil treatment.

Next, factor analysis was applied to identify a common factor of production practices that was strongly and positively correlated with these variables. The method assumes that observable variables related to production practices can be expressed by linear combinations of unobservable and uncorrelated factors (Kim and Mueller, 1978). These factors are also called common factors since they contribute to explain the variability of the group of observable variables.

In the factor analysis, commonality represents the share of the total variability of the *i*-th observable variable explained by the common factor. The total variability explained by each common factor represents the discriminatory power of the respective factor over all observable variables. It is also typically expressed in relative terms, i.e., as a percentage of the total variability of the observed variables. In turn, the factor loadings are used to interpret the factors' meaning, considering their linear relation and their relevance in predicting each observable variable.

**Table 2**
Ratio between number of units and farms, São Paulo 2007/2008.
Source: Elaborated by the authors using data from the LUPA.

| Technique | Units/farm |
|---|---|
| Irrigation | 0.082 |
| Sowing machine | 0.076 |
| Plowing machine | 0.259 |
| Tractor | 0.484 |
| Other machines | 0.123 |
| Soil treatment | 0.954 |

To obtain the common factor, we use principal-component factor analysis due to its operational simplicity and the analytical consistency of its results in our case. This technique provides the factor that contributes most to explaining the variability of observable variables. Since the common factor has an average value of 0 (and standard deviation equal to 1), we divide the MCAs into two *groups of production practices*: (i) positive factor scores were classified into a high-technology group; and (ii) those with negative factor scores were classified into a low-technology group.

## 2.3. Climate Variables

Climate variables for the MCAs were obtained by interpolating point data from conventional weather stations of the National Meteorological Institute (INMET, 2017). Daily data on temperature and precipitation were interpolated for all MCAs located in the São Paulo state. The interpolation was performed by the Inverse Distance Weighted method, which is based on the weighted linear combination of the data collected in each meteorological station, using the inverse of the distance as a weighting factor (Kurtzman and Kadmon, 1999). After interpolation, we computed the average values of temperature and precipitation in each season (spring, summer, autumn, and winter) for each MCA (average values presented in Fig. 2). The most striking changes were the decline in precipitation during summer and spring in the 2010's, and the overall trend of rising temperature in the winter.

Extreme temperature and precipitation events were analyzed by 16 dummy variables identifying the seasons of the year $t$ ($p$, for spring, $s$ for summer, $a$ for autumn and $w$ for winter) with average temperature ($T_{kt}$, where $k = p, s, a$ or $w$) and total precipitation ($P_{kt}$) lower or higher than a historical threshold. Historical thresholds are defined by one standard deviation ($\sigma_{T_k}$ for temperature and $\sigma_{P_k}$ for precipitation) from the average value ($\overline{T}_k$ Or $\overline{P}_k$) in season $k$. In other words, we have for temperature:

$$T_k + =\{1 if\ T_{kt} > \overline{T}_k + \sigma_{T_k};\ 0\ otherwise\} \text{ and } T_k - =\{1 if\ T_{kt} < \overline{T}_k - \sigma_{T_k};\ 0\ otherwise\}$$

And for precipitation we have:

$$P_k + =\{1 if\ P_{kt} > \overline{P}_k + \sigma_{P_k};\ 0\ otherwise\} \text{ and } P_k - =\{1 if\ P_{kt} < \overline{P}_k - \sigma_{P_k};\ 0\ otherwise\}$$

## 2.4. Production Model

Information on agricultural production was obtained from the

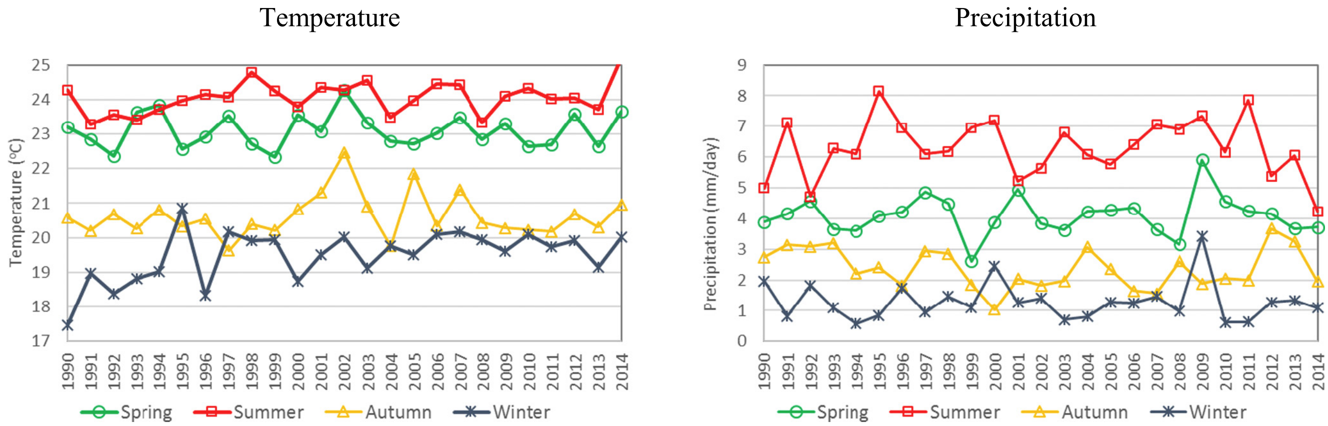



**Fig. 2.** Average values of temperature (°C) and precipitation (mm/day) by season, São Paulo.
Source: Elaborated by the authors using data from (INMET, 2017).

Brazilian Institute of Geography and Statistics (IBGE, 2018), and refers to the Municipal Agricultural Survey (PAM, *Pesquisa Agrícola Municipal*). We analyze the total value of production in each MCA (in constant values) and the total physical production (in tons) of the two main crops in the state: sugarcane (58% of the total value) and oranges (10% of the total value).

The relationship between the dynamics of climate variables and agricultural production in each group was analyzed by panel data models. The dependent variables $Y$ are (i) the log of total value of production and (ii) the log of the physical production of sugarcane and orange. The explanatory variables are the binary climate variables defined in topic 2.3 ($T_k+$, $T_k-$, $P_k+$ *and* $P_k-$) and the total harvested area $A$ of each crop. In the case of the total value of production, $A_i$ represents the total harvested area in each MCA $i$. Unobserved regional ($r_i$) and temporal ($c_t$) factors are controlled using the fixed effects approach. This relationship is given by:

$$Y_{it} = \alpha + \delta A_{it} + \sum_{k=p,s,a,w} \beta_k (T_{k_{it}}+) + \sum_{k=p,s,a,w} \theta_k (T_{k_{it}}-) + \sum_{k=p,s,a,w} \varnothing_k (P_{k_{it}}+) + \sum_{k=p,s,a,w} \varphi_k (P_{k_{it}}-) + r_i + c_t + \varepsilon_{it} \tag{1}$$

The coefficients of interest are β, θ, ϕ and φ, which represent the impact of extreme events on agricultural production $Y$, after controlling for area ($A$) and unobserved regional ($r$) and temporal effects ($c$). We adjust Eq. (1) for each group of MCAs, which were defined by the combination of the clusters of land cover (defined in 2.1) and the groups of production practices (defined in 2.2). The idea is to analyze to what extent differing levels of environmental preservation and production techniques can mitigate the impacts of extreme events on agricultural production.

Since we do not have historical values for the levels of environmental preservation and production techniques across the whole period, we assume that changes observed in time ($c_t$) are independent of differences between MCAs ($r_i$). This may not be totally true, given that the dynamics of agricultural advances and land cover may have been more pronounced in some specific regions. In other words, some MCAs may shift between groups of land cover and/or production practices in the period of analysis. Nonetheless, there were no huge differences in the patterns of regional heterogeneity in this period that would justify the use more complete dynamic factor models.

## 3. Results

### 3.1. Groups of Land Cover and Production Technologies

The cluster analysis was applied to identify groups of MCAs with relatively homogeneous percentages of land cover. We selected three clusters, and the differences between the mean values of these clusters accounted for 51% of the total variability (semi partial $R^2$) observed between the annual values of MCAs. The average characteristics of the three clusters are presented in Table 3.

The first cluster (*agriculture*) contains 145 MCAs (26% of the total) and represents predominantly agricultural areas. The largest share of land is covered exclusively by agriculture (70.5%) and by mosaics of agriculture and remaining areas of forest (13.5%). Only 2% of the area is covered by forest or by areas of forest integrated with small areas of agriculture.

Cluster two (*agriculture/forest*), the largest group with 243 MCAs (43% of the total), represents agricultural areas with high share of forests. It is predominantly covered by mosaics of agriculture and forest (59.6%) and by agriculture alone (18.9%). In comparison with the first cluster (*agriculture*), this second group also highlights a larger share of areas covered by forest integrated to agriculture (6.5% compared to 1.6%), silviculture (3.3% compared to 1.5%) and forest (1% compared to 0.4%).

The third cluster, ***urban/pasture***, represented by 180 MCAs (32% of the total), is predominantly urban (10% of the area). Areas covered exclusively by agriculture or by the integration between agriculture and forests represent only 39.4% of the territory, as opposed to 85% in the first two clusters. This cluster is also characterized by the dichotomy between pastures (25.2%) and forest (20.8%).

Next, each cluster of land cover was disaggregated into two groups: low and high technology. The technology groups were defined using scores obtained by factor analysis (see topic 2.2). We selected the first common factor, which represented 46.1% of the total variability of the six observed variables of production techniques (irrigation systems, sowing machines, plowing machines, tractors, other machines, and

**Table 3**
Proportion of each land cover type according to clusters of MCAs, São Paulo.
Source: Elaborated by the authors using data from IBGE (2017).

| Variable | Group of land cover | | | |
|---|---|---|---|---|
| | Agriculture | Agriculture/forest | Urban/pasture | Total |
| N | 145 | 243 | 180 | 568 |
| Agriculture | 0.705 | 0.189 | 0.079 | 0.286 |
| Urban | 0.045 | 0.028 | 0.103 | 0.056 |
| Water | 0.025 | 0.030 | 0.034 | 0.030 |
| Agriculture/forest | 0.135 | 0.596 | 0.226 | 0.361 |
| Forest/agriculture | 0.016 | 0.065 | 0.089 | 0.060 |
| Pasture | 0.055 | 0.050 | 0.252 | 0.115 |
| Silviculture | 0.015 | 0.033 | 0.008 | 0.020 |
| Forest | 0.004 | 0.010 | 0.208 | 0.071 |

**Table 4**
Ratio between the number of technological systems or techniques per farm according to groups of land cover and production techniques (*High* and *Low*), São Paulo.
Source: Elaborated by the authors using data from LUPA.

| Production technique | Agriculture | | Agriculture/forest | | Urban/pasture | |
|---|---|---|---|---|---|---|
| | High | Low | High | Low | High | Low |
| N | 91 | 54 | 107 | 136 | 43 | 137 |
| Irrigation system | 0.068 | 0.022 | 0.115 | 0.040 | 0.318 | 0.054 |
| Sowing machine | 0.158 | 0.048 | 0.107 | 0.040 | 0.095 | 0.033 |
| Plowing machine | 0.396 | 0.167 | 0.379 | 0.175 | 0.359 | 0.148 |
| Tractor | 0.794 | 0.323 | 0.682 | 0.310 | 0.729 | 0.255 |
| Other machines | 0.271 | 0.072 | 0.172 | 0.061 | 0.148 | 0.053 |
| Soil treatment | 1.133 | 0.881 | 1.200 | 0.789 | 1.157 | 0.748 |

adoption of soil treatment). All observed variables presented positive correlations with the selected common factor, with coefficients ranging from 0.40 (irrigation) to 0.87 (tractor). The correlations (factor patterns) and the standardized scoring coefficients of each variable with the common factor are presented in Appendix A. The MCAs with positive factor scores were classified into a group of high technology use (*high-technology*), while those with negative factor scores were classified into a group of low technology use (*low-technology*).

Table 4 characterizes the groups of land cover and production technologies. The use of production technologies differs sharply between the groups *high-* and *low-technology*. For example, within the group of *urban/pasture* land cover, the use of irrigation systems is almost six times higher in the *high-technology* group (31.8/100 farms) than in the *low-technology* group (5.4/100 farms). Differences in the use of irrigation systems are also notable within the *high-technology* groups. The use of irrigation is more pronounced in the group of *urban/pasture* land cover (31.8/100 farms) and rare in the group of *agriculture* land cover (6.8/100 farms). These differences may reflect both the type of crop and environmental needs.

Table 5 presents the average values over the entire period of analysis (1990–2014) for the agricultural production of each group of land cover and production techniques. The groups *agriculture* and *agriculture/forest* concentrate roughly 90% of the total value of production, as well as more than 90% of the total production of sugarcane and oranges. In these two groups of land cover, a higher rate of use of production technologies has a positive effect on the sugarcane yield, where the production per hectare is roughly 5% higher in the high-technology group than in the low-technology group.

Another important finding is that the value of production per hectare is remarkably higher in the group *agriculture/forest* land cover when compared to the group *agriculture* (31% higher between the high-technology groups and 15% higher between the low-technology groups). Since no major differences exist between sugarcane and orange

**Table 5**
Average agricultural production according to groups of land cover and production techniques (High and Low), São Paulo.
Source: Elaborated by the authors using data from IBGE (2017).

| Agricultural production | Agriculture | | Agriculture/forest | | Urban/pasture | |
|---|---|---|---|---|---|---|
| | High | Low | High | Low | High | Low |
| Total value | | | | | | |
| R$/ha | 1893 | 2056 | 2487 | 2364 | 2548 | 2550 |
| % of total | 32.8 | 12.1 | 24.3 | 19.3 | 3.7 | 7.8 |
| Sugarcane | | | | | | |
| ton/ha | 81.1 | 77.6 | 81.8 | 78.2 | 76.5 | 75.6 |
| % total | 41.9 | 16.4 | 19.6 | 15.2 | 2.0 | 4.9 |
| Orange | | | | | | |
| ton/ha | 69.0 | 79.5 | 69.8 | 71.4 | 74.9 | 78.4 |
| % total | 32.1 | 11.8 | 31.1 | 19.4 | 1.4 | 4.2 |

yields, this difference in production value is mainly related to the adoption of more profitable cultures, which are better adapted to local environments.

Municipalities of the groups *agriculture* and *agriculture/forest* are spatially concentrated in the most traditional areas of agricultural development, in the center of the state (Map 1) and are the main interest in the comparative analysis. The municipalities of the group *urban/pasture* are concentrated in the east and west parts of the state and present more heterogeneous patterns of production. The eastern region is characterized by areas of preservation of the tropical forest (*Mata Atlântica*), urban areas in the coast and pastures. In turn, in the western side, the pastures have been recently replaced by sugarcane crops. Thus, this third group (*urban/pasture*) aggregates municipalities that are far different from those presented in the first two groups (*agriculture* and *agriculture/forest*), but that do not necessarily present equal structure of ecosystem biodiversity, adaptive strategies and/or pattern of technological intensity.

### 3.2. The Impacts of Extreme Climate Events

The relationship between the dynamics of extreme climate events and agricultural production in the MCAs is based on estimates of panel data models (Eq. (1)). The aim of this analysis is to understand how extreme events affect differently the groups of land cover and production technologies. Fig. 3 summarizes the net impacts of extreme temperature events ($T_k+$ and $T_k-$) on the total value of production. The whole set estimates and significance levels are presented in Appendix B.

The most startling result is that the marginal effects are more homogeneous and closer to zero in the *agriculture/forest* group. In other words, the total value of production in the group with a larger share of integration between agriculture and forest seems to be less affected by extreme temperature events. In the *agriculture* group, marginal effects are more homogenous and closer to zero within the *high-technology* group. In other words, the group where agriculture is less integrated with forest areas appears to rely more on the adoption of adaptive strategies and production technologies to mitigate the dependency of extreme climate events. In turn, the *urban/pasture* group presents the most heterogenous and irregular pattern of marginal effects.

Similar results are obtained for the marginal effects of precipitation below and above the historical average ($P_k+$ and $P_k-$) on the total value of production (Fig. 4). Nonetheless, in this case, both the *agriculture* and *agriculture/forest* groups present similar marginal effects, which are more homogenous and closer to zero. The *urban/pasture* group is the one depending more strongly on extreme precipitation events to increase the total value of production.

Figs. 5 and 6 present the marginal effects of extreme events of temperature and precipitation, respectively, on sugarcane production. Production is mainly concentrated in the cluster *agriculture*, which tends to be unaffected by extreme temperatures when practiced using high levels of technology. When practiced using low levels of technology, the production of sugarcane in this cluster tends to be negatively affected by extreme low temperatures in the spring (planting season). The same extreme event tends to have a positive impact in the group *agriculture/pasture*. Unsurprisingly, the group *urban/pasture* presents the most unstable impacts from extreme events on sugarcane production.

Sugarcane production appears to be resilient to extreme precipitation events, even in the low technology group, where irrigation is scarce. Most marginal effects are insignificant or close to zero for this group. The group most affected by extreme precipitation events is *urban/pasture*.

Finally, Figs. 7 and 8 present the marginal effects of extreme events on orange production. Production is concentrated in the group *agriculture/forest* and *high-technology*, and tends to be negatively impacted by freezes in the spring. Extreme heat in the summer and spring also tend to negatively affect the production in the *low-technology* group, likely due to lack of irrigation. While the marginal effects in the

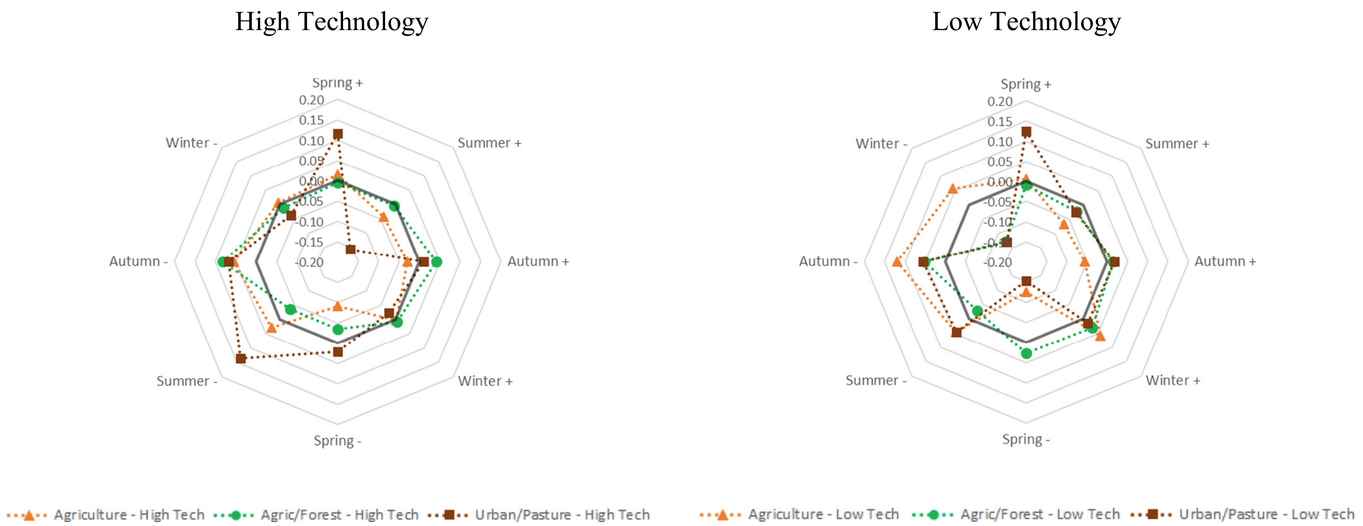



**Fig. 3.** Marginal effects of temperature below (−) and above (+) the historical average on the log of total value of production, São Paulo.
Source: Elaborated by the authors.

*agriculture* and *agriculture/forest* groups present similar levels of heterogeneity, variability is remarkably larger in the *urban/pasture* group.

The net impacts of extreme precipitation events on orange production are roughly null in the *high-technology* groups. In turn, these events exhibit diverse impacts in the *low-technology* groups of *agriculture* and *urban/pasture*. In other words, no matter the adoption of adaptive strategies or production technologies, orange production is more resilient to extreme precipitation events in areas of agriculture that are integrated with forests.

## 4. Discussion and Remarks

Agricultural production will face relevant challenges from the threats imposed by climate change scenarios (IPCC, 2014). On the one hand, the economic literature has emphasized how climate change can affect the agriculture by reducing the provision of ecosystem services that are essential to agriculture, such as nutrient cycling, water provision, pollination, pest and disease control, and climate stabilization (Mendelsohn et al., 1994; Mendelsohn and Dinar, 2009; Dai et al., 2015). On the other hand, it has also evaluated how adaptive strategies, such as agronomic adaptions and investments in new technologies, can improve agricultural productivity and, thus, mitigate the effects of climate change (Schlenker et al., 2003). This study developed an innovative approach to advance in this discussion and provide evidences that: (i) ecosystem services do matter in the agricultural production; and (ii) adaptive strategies is complementary to ecological systems, rather than mere substitutes.

Our analyses were based on municipal-level data of a key state in Brazil, São Paulo, a region in a relative stage of development in the country (IBGE, 2018), which has simultaneously faced pressures to increase agricultural productivity and preserve its rich biodiversity. São Paulo provides a strategic case to analyze the role of ecosystem services on agriculture, presenting a rich variability in the levels of agricultural development and in the provision of ecosystem services. The state is the world's leading producer of sugarcane, a strategic crop to produce sustainable energy (ethanol), and orange, an important commodity in the Brazilian exports (MAPA, 2018). Both crops are strongly dependent on the flow of ecosystem services and São Paulo presents a large diversity of land use and adaptation practices in agriculture (IBGE, 2018). Climate change has also became a main concern in the state, which had historically suffered with recurrent floods in the main metropolitan centers, and recently suffered one of the most extreme droughts in the

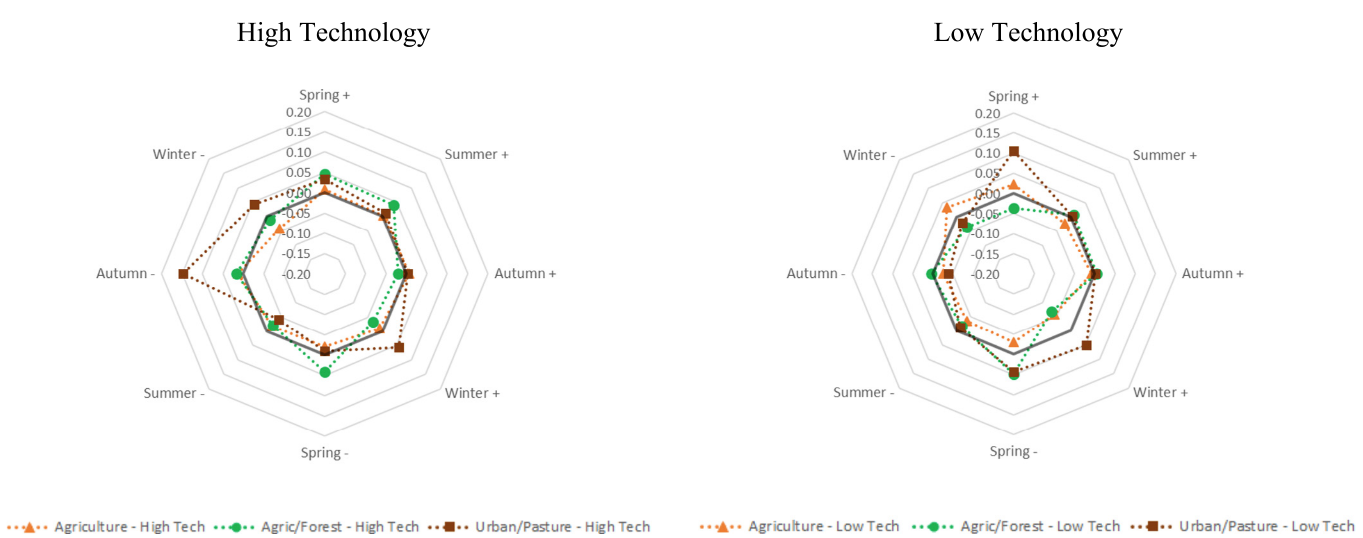



**Fig. 4.** Marginal effects of precipitation below (−) and above (+) the historical average on the log of total value of production, São Paulo.
Source: Elaborated by the authors.

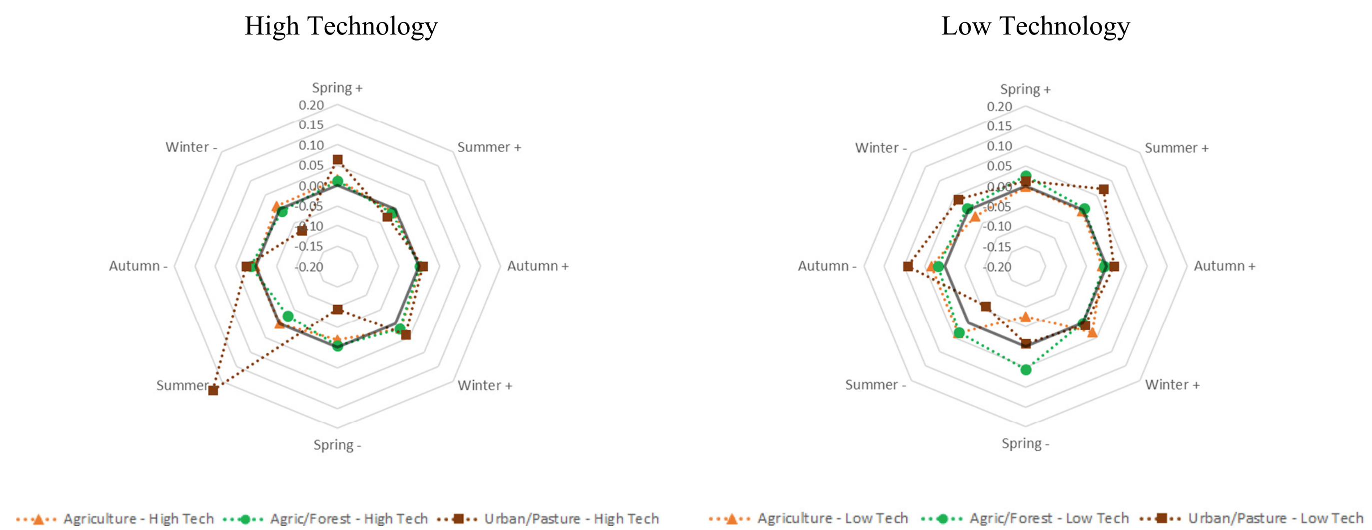



**Fig. 5.** Marginal effects of temperature below (−) and above (+) the historical average on the log of sugarcane production, São Paulo.
Source: Elaborated by the authors.

history (Jacobi et al., 2015).

Roughly 70% of São Paulo's territory is dedicated to agriculture, but municipalities differ substantially in the levels of ecosystem diversity. The group of municipalities with high ecosystem diversity, found in the group of *agriculture/forest* land use, have almost 70% of its territory covered by forests and/or mosaics of forests with croplands. Another group of municipalities (*agriculture*), which feature lower levels of ecosystem diversity, has 70% of its territory covered exclusively by agriculture and just 17% covered by areas of forests (including mosaics). The third group (*urban/pasture*) represents municipalities characterized by the prevalence of urban areas (10%) and by the dichotomy between areas of pasture (25%) and forests (21%). Although the presence of forest areas in a municipality does not necessarily represent the farm's adoption of agroforestry systems, this information provides important elements to a macro-level analysis of how environmental preservation, which is essential to maintain the flow of ecosystem services in a region, is related to local agricultural production.

Several studies have highlighted how adaptation can be a way to increase agriculture productivity and mitigate the loss related to climate change (for example, Burney et al., 2014; Maia et al., 2016; Reidsma et al., 2009). And regions that are highly dependent on natural resources tend to be especially affected by extreme events since many of them lack the economic and social resources necessary to alleviate the impacts of changes in temperature and precipitation distributions (Mendelsohn and Dinar, 2009; Villamayor-Tomas, 2014; Wreford et al., 2010). The average adoption of production technologies in our group of *high-technology* is roughly twice as large as the average in those municipalities of the group of *low-technology*. And the share of municipalities of *high-technology* largely prevails in regions where croplands largely surpass the areas of forests (group *agriculture*). But there is no evidence that the total value of production in the group of *high-technology* is larger than in the group of *low-technology*. Although we cannot directly establish a cause-effect relationship, these results suggest that the adoption of technologies may also be a reaction to ecosystem conditions, in addition to crop needs and other socioeconomic drivers.

A main result of this study is that the benefits of adaptation may differ substantially according to the provision of ecosystem services. In addition to the adoption of production technologies, ecosystem preservation may also play an important role in mitigating the impacts of extreme events. In other words, the environmental preservation and ecosystem services matter to face the extreme events and climate change in the agriculture. Because we initially found evidences that the

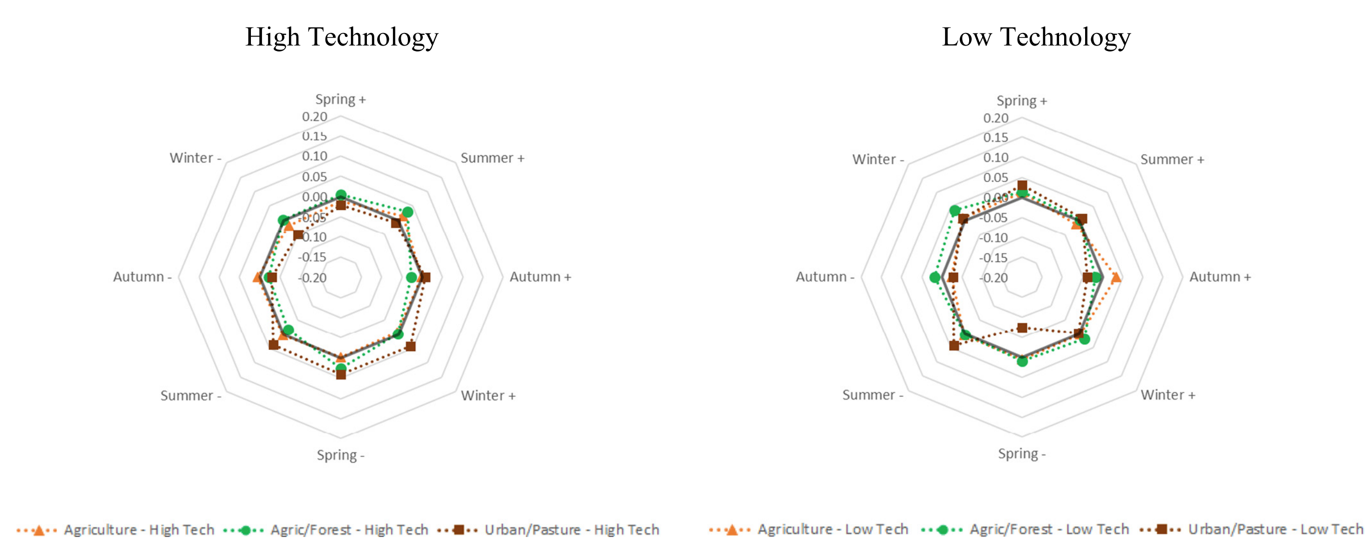



**Fig. 6.** Marginal effects of precipitation below (−) and above (+) the historical average on the log of sugarcane production, São Paulo.
Source: Elaborated by the authors.

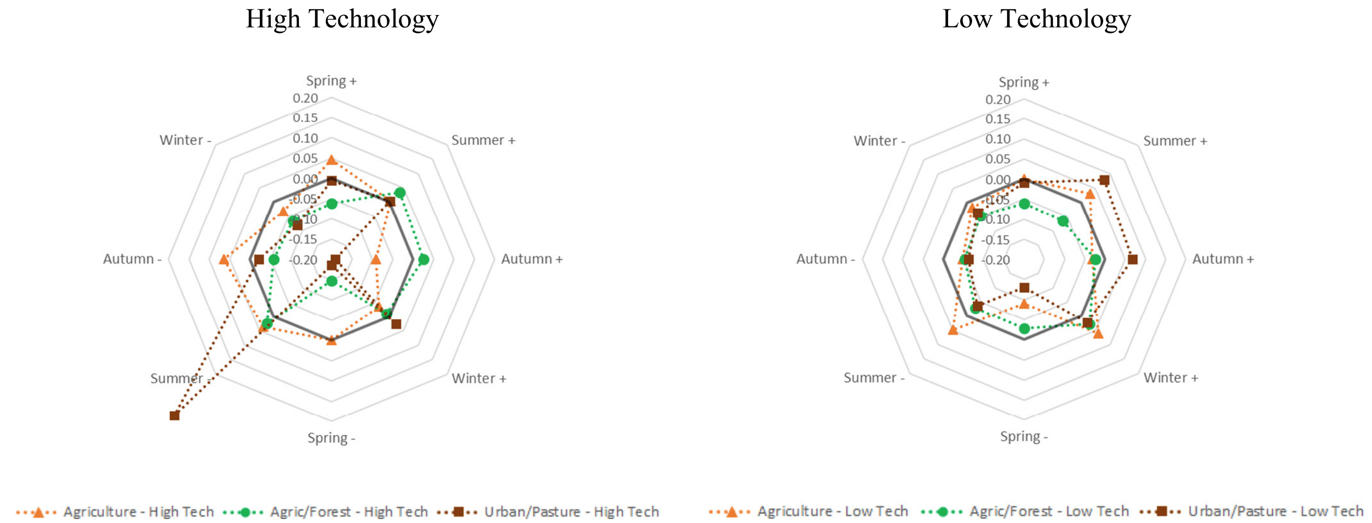



**Fig. 7.** Marginal effects of temperature below (−) and above (+) the historical average on the log of orange production, São Paulo.
Source: Elaborated by the authors.

provision of ecosystem services is positively related to productivity, the total value of production by hectare is between 15% and 31% higher in the group *agriculture/forest* when compared to the group *agriculture*. Since there are no huge differences in the level of land-productivity between these groups for the main crops in the state (sugarcane and orange), a higher average value added in the former group may be particularly due to the choice for more profitable cultures, like fruits and vegetables.

Moreover, ecosystem services have shown to increase agriculture resilience to extreme events. Overall, extreme temperature and precipitation events tend to cause more severe impacts (positive or negative) on the total value of production for those groups that feature lower levels of integration between agriculture and ecosystem diversity (*agriculture* and *urban/pasture*). In other words, the group of agriculture integrated with mosaics of forests tends to be more resilient to extreme events. Since the flow of ecosystem services tend to be higher in preserved forest areas, these results reinforce the hypothesis that agriculture depends on services that are not merely substituted by adaptive strategies, such as nutrient cycling, water provision, pollination, pest and disease control, and climate stabilization (Palm et al., 2014; Parron et al., 2015; Therond et al., 2017).

The impacts of extreme temperature and precipitation events on agricultural production differ across crops and groups of localities. Sugarcane is more resilient to extreme events, while orange production appears to be especially affected by extreme temperatures. The orange production strongly depends on pollination ecosystem services, which can be affected by extreme temperatures. In turn, orange production is more resilient to extreme precipitation events in areas of agriculture integrated with forests. Orange is a permanent crop and tends to retain more water than sugarcane, which is a temporary crop.

One main limitation of our analysis is that they do not account for the diversity of ecosystem services and agricultural practices that may exist among similar groups of land cover and production technologies. For example, areas that still preserve native forests could be considered the maximum and synthetic expression of ecosystem biodiversity (García-Nieto et al., 2013). But our empirical strategy is naturally limited by the provision of geographical and historical data. Geographic data with a finer level of disaggregation would better represent the ecological diversity and the heterogeneity of the agronomic/economic technologies adopted within the same municipality. Similarly, the climatic variables just measure short-term impacts of extreme events and do not account for medium and long impacts that may be caused by

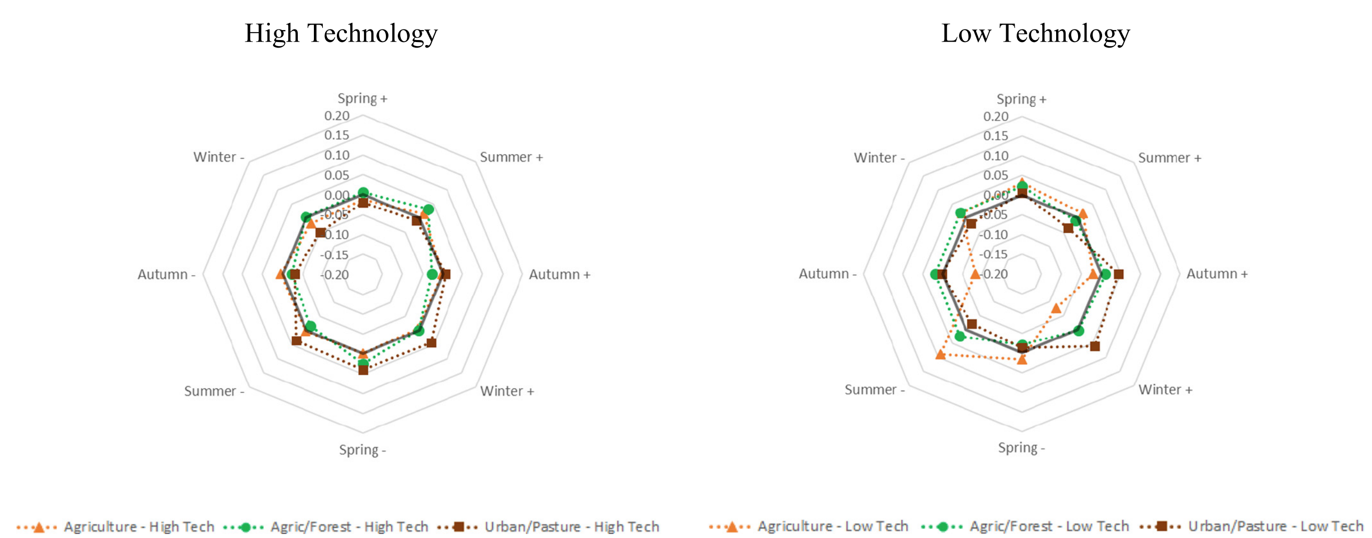



**Fig. 8.** Marginal effects of precipitation below (−) and above (+) the historical average on the log of orange production, São Paulo.
Source: Elaborated by the authors.

extreme droughts.

Other limitation is that the types of land cover change in time, probably also as a response of agricultural production, which imposes additional challenges to the empirical analysis. Even in the face of the high degree of environmental degradation and official efforts to preserve the remnants of natural forests, the share of forest and mosaics of agriculture/forest reduced by 3.7 percentage points between 2000 and 2014. In this sense, the provision of ecosystem services may also have reduced in some areas, undermining the ability to face the climate change and the occurrence of extreme events. On the other hand, areas of pasture have also been replaced by sugarcane, with not yet clearly understood impacts on soil, water and biodiversity (Goldemberg et al., 2008). Unfortunately, the restricted availability of historical land cover data inhibits a longitudinal analysis of the long-term relationship between agricultural production and the provision of ecosystem services.

Despite such empirical challenges still to be overcome in further studies, this paper provides innovative and needed results to understand how regions with the most vulnerable types of land cover may be more affected by the short-term impacts of extreme events due to the environmental preservation, the provision of ecosystem services, and the technological intensity of the agricultural systems. These results allow us to discuss important questions related to the process of agricultural development and environmental protection, which are challenging most developing countries. First, that technologies may be necessary but not sufficient to mitigate the impacts of climate change on agricultural development. This is particularly true because degraded areas can disrupt important ecosystem services, such as the surface water balance, compromising the adoption of irrigation systems. Furthermore, degraded ecosystem conditions may indirectly introduce pests and pathogens, reduce the benefits of natural pollination, and create some warmer and drier local climates. The second challenge is to stimulate the adoption of adaptive strategies in agriculture that are complementary or allied to environmental preservation, rather than mere substitutes. Although farms may introduce technologies and shift to more resilient activities in order to overcome environmental constraints - as sugarcane cultivators have done in São Paulo (Vieira Filho and Gasques, 2016), preserved areas have shown themselves to be related to more profitable and resilient agricultural production. In this sense, sustainable agricultural development policies would, for example, prioritize both: (i) the adoption of technologies to overcome climate change, such as more resistant seeds and improved land management practices, and (ii) programs of preservation and recuperation of ecosystem services, especially in areas that already face high levels of anthropic intervention.

## Funding

This work was supported by the Coordination for the Improvement of Higher Education Personnel (Coordenadoria de Aperfeiçoamento de Pessoal de Nível Superior, Capes), Programa de Apoio à Pós-Graduação e à Pesquisa Científica e Tecnológica em Desenvolvimento Socioeconômico no Brasil (PGPSE), grant numbers 88887.123941/2016-00, Project Abordagem simultânea e inter-relacionada das dimensões de sustentabilidade para a melhoria da gestão de recursos hídricos: o caso da bacia do Rio Jundiaí.

## Appendix A. Factor Pattern and Scoring Coefficient for the First Common Factor

| Production technique | Factor pattern | Scoring coefficient |
|---|---|---|
| Irrigation system | 0.402 | 0.146 |
| Sowing machine | 0.697 | 0.252 |
| Plowing machine | 0.859 | 0.311 |
| Tractor | 0.870 | 0.315 |
| Other machines | 0.610 | 0.221 |
| Soil treatment | 0.500 | 0.181 |

Source Elaborated by the authors using data from LUPA.

## Appendix B. Marginal Effects of the Fixed Effects Model for the log of Total Value of Production, São Paulo

| Variable | Agriculture | | Agriculture/forest | | Urban/pasture | |
|---|---|---|---|---|---|---|
| | High | Low | High | Low | High | Low |
| Intercept | 1.306 | 0.950 | 1.393 | 2.231 | 2.260 | 3.620 |
| | (0.291) | (0.320) | (0.314) | (0.229) | (0.297) | (0.228) |
| Log area | 0.958 | 0.992 | 0.946 | 0.914 | 0.910 | 0.808 |
| | (0.020) | (0.021) | (0.021) | (0.015) | (0.030) | (0.015) |
| Tp + | 0.015+ | 0.005+ | −0.005+ | −0.008+ | 0.117 | 0.125 |
| | (0.018) | (0.025) | (0.021) | (0.018) | (0.047) | (0.026) |
| Ts + | −0.042 | −0.068 | −0.004+ | −0.024+ | −0.156 | −0.026+ |
| | (0.019) | (0.027) | (0.021) | (0.017) | (0.048) | (0.026) |
| Ta + | −0.029+ | −0.055 | 0.041 | 0.013+ | 0.012+ | 0.017+ |
| | (0.023) | (0.033) | (0.025) | (0.022) | (0.056) | (0.032) |
| Tw + | 0.002+ | 0.059 | 0.007+ | 0.031 | −0.023+ | 0.014+ |
| | (0.019) | (0.027) | (0.021) | (0.018) | (0.048) | (0.026) |
| Tp - | −0.092 | −0.125 | −0.035+ | 0.027+ | 0.021+ | −0.153 |
| | (0.043) | (0.056) | (0.049) | (0.041) | (0.169) | (0.084) |
| Ts - | 0.028+ | 0.047+ | −0.037+ | −0.028+ | 0.137+ | 0.045+ |
| | (0.037) | (0.052) | (0.041) | (0.035) | (0.129) | (0.058) |
| Ta - | 0.055 | 0.119 | 0.082 | 0.052+ | 0.067+ | 0.055+ |

| | | | | | | |
|---|---|---|---|---|---|---|
| | (0.029) | (0.046) | (0.039) | (0.037) | (0.142) | (0.062) |
| Tw - | 0.007 + | 0.056 + | −0.013 + | −0.128 | −0.037 + | −0.131 |
| | (0.030) | (0.039) | (0.035) | (0.030) | (0.084) | (0.051) |
| Pp + | 0.007 + | 0.022 + | 0.045 | −0.036 | 0.033 + | 0.105 |
| | (0.020) | (0.027) | (0.026) | (0.022) | (0.047) | (0.029) |
| Ps + | 0.003 + | −0.022 + | 0.038 | 0.009 + | 0.011 + | 0.003 + |
| | (0.016) | (0.023) | (0.020) | (0.018) | (0.041) | (0.024) |
| Pa + | 0.008 + | −0.009 + | −0.019 + | 0.004 + | 0.003 + | 0.002 + |
| | (0.017) | (0.025) | (0.022) | (0.018) | (0.046) | (0.024) |
| Pw + | −0.010 + | −0.059 + | −0.032 + | −0.070 | 0.056 + | 0.052 + |
| | (0.027) | (0.041) | (0.032) | (0.027) | (0.060) | (0.032) |
| Pp - | −0.021 + | −0.031 + | 0.042 | 0.050 | −0.010 + | 0.044 |
| | (0.016) | (0.023) | (0.021) | (0.018) | (0.047) | (0.024) |
| Ps - | −0.017 + | −0.035 + | −0.020 + | −0.017 + | −0.040 + | −0.012 + |
| | (0.018) | (0.030) | (0.023) | (0.020) | (0.054) | (0.027) |
| Pa - | 0.012 + | −0.024 + | 0.016 + | 0.003 + | 0.146 | −0.038 + |
| | (0.021) | (0.031) | (0.027) | (0.022) | (0.060) | (0.030) |
| Pw - | −0.043 | 0.035 + | −0.011 + | −0.037 + | 0.043 + | −0.021 + |
| | (0.026) | (0.039) | (0.029) | (0.025) | (0.071) | (0.036) |
| *n* cross section | 91 | 54 | 107 | 135 | 42 | 124 |
| *n* time series | 25 | 25 | 25 | 25 | 25 | 25 |

Source: Elaborated by the authors using data from IBGE (2017), INMET (2017) and LUPA. Standard deviations between parentheses. + Insignificant at 10% level.

## Appendix C. Marginal Effects of the Fixed Effects Model for the log of Sugarcane Production, São Paulo

| Variable | Agriculture | | Agriculture/forest | | Urban/pasture | |
|---|---|---|---|---|---|---|
| | High | Low | High | Low | High | Low |
| Intercept | 4.583 | 2.803 | 3.965 | 3.643 | 4.411 | 4.430 |
| | (0.070) | (0.112) | (0.112) | (0.094) | (0.136) | (0.209) |
| Log area | 0.981 | 1.100 | 1.026 | 1.045 | 1.003 | 0.980 |
| | (0.004) | (0.007) | (0.007) | (0.006) | (0.010) | (0.014) |
| Tp + | 0.015 | −0.002 + | 0.011 + | 0.025 | 0.065 | 0.013 + |
| | (0.009) | (0.015) | (0.016) | (0.015) | (0.033) | (0.044) |
| Ts + | −0.008 + | −0.004 + | −0.012 + | 0.004 + | −0.027 + | 0.073 |
| | (0.009) | (0.015) | (0.016) | (0.014) | (0.031) | (0.040) |
| Ta + | 0.005 + | −0.010 + | 0.001 + | −0.005 + | 0.009 + | 0.018 + |
| | (0.011) | (0.020) | (0.019) | (0.018) | (0.040) | (0.055) |
| Tw + | 0.018 | 0.033 | 0.017 + | −0.001 + | 0.038 + | 0.008 + |
| | (0.009) | (0.016) | (0.016) | (0.014) | (0.033) | (0.039) |
| Tp - | −0.018 + | −0.076 | −0.004 + | 0.056 | −0.095 + | −0.008 + |
| | (0.020) | (0.032) | (0.036) | (0.033) | (0.174) | (0.196) |
| Ts - | 0.001 + | 0.036 + | −0.028 + | 0.033 + | 0.231 | −0.061 + |
| | (0.018) | (0.030) | (0.030) | (0.029) | (0.088) | (0.092) |
| Ta - | 0.003 + | 0.032 + | 0.013 + | 0.016 + | 0.023 + | 0.091 + |
| | (0.014) | (0.027) | (0.029) | (0.030) | (0.119) | (0.117) |
| Tw - | 0.010 + | −0.024 + | −0.006 + | 0.005 + | −0.076 + | 0.036 + |
| | (0.014) | (0.023) | (0.027) | (0.026) | (0.070) | (0.088) |
| Pp + | −0.012 + | 0.012 + | 0.005 + | 0.013 + | −0.020 + | 0.032 + |
| | (0.010) | (0.016) | (0.019) | (0.017) | (0.030) | (0.044) |
| Ps + | 0.015 | −0.011 + | 0.031 | 0.003 + | −0.010 + | 0.010 + |
| | (0.008) | (0.014) | (0.015) | (0.014) | (0.028) | (0.035) |
| Pa + | −0.002 + | 0.033 | −0.027 + | −0.018 + | 0.008 + | −0.038 + |
| | (0.008) | (0.015) | (0.016) | (0.014) | (0.033) | (0.038) |
| Pw + | −0.006 + | 0.003 + | −0.002 + | 0.020 + | 0.042 + | −0.002 + |
| | (0.013) | (0.024) | (0.026) | (0.023) | (0.045) | (0.055) |
| Pp - | −0.001 + | 0.006 + | 0.025 + | 0.009 + | 0.040 + | −0.076 |
| | (0.008) | (0.014) | (0.016) | (0.013) | (0.030) | (0.038) |
| Ps - | 0.002 + | 0.005 + | −0.016 + | 0.002 + | 0.036 + | 0.041 + |
| | (0.009) | (0.017) | (0.017) | (0.015) | (0.036) | (0.042) |
| Pa - | 0.006 + | −0.024 + | −0.023 + | 0.018 + | −0.029 + | −0.027 + |
| | (0.010) | (0.018) | (0.020) | (0.017) | (0.039) | (0.044) |
| Pw - | −0.019 + | 0.010 + | 0.002 + | 0.037 | −0.050 + | 0.010 + |
| | (0.013) | (0.023) | (0.022) | (0.019) | (0.050) | (0.057) |

| | | | | | | |
|---|---|---|---|---|---|---|
| *n* cross section | 91 | 54 | 107 | 135 | 42 | 124 |
| *n* time series | 25 | 25 | 25 | 25 | 25 | 25 |

Source: Elaborated by the authors using data from IBGE (2017), INMET (2017) and LUPA. Standard deviations between parentheses. + Insignificant at 10% level.

**Appendix D. Marginal Effects of the Fixed Effects Model for the log of Orange Production, São Paulo**

| Variable | Agriculture | | Agriculture/forest | | Urban/pasture | |
|---|---|---|---|---|---|---|
| | High | Low | High | Low | High | Low |
| Intercept | 3.384 | 2.780 | 2.867 | 3.150 | 2.440 | 4.077 |
| | (0.164) | (0.168) | (0.127) | (0.128) | (0.194) | (0.197) |
| Log area | 0.981 | 1.036 | 0.981 | 1.004 | 0.987 | 0.935 |
| | (0.012) | (0.015) | (0.007) | (0.008) | (0.020) | (0.015) |
| Tp + | 0.046 + | 0.000 + | −0.062 | −0.061 | −0.005 + | −0.010 + |
| | (0.030) | (0.038) | (0.022) | (0.024) | (0.057) | (0.034) |
| Ts + | 0.005 + | 0.031 + | 0.035 + | −0.066 | 0.004 + | 0.080 |
| | (0.031) | (0.042) | (0.022) | (0.022) | (0.056) | (0.030) |
| Ta + | −0.092 | −0.031 + | 0.026 + | −0.024 + | −0.191 | 0.068 |
| | (0.035) | (0.047) | (0.026) | (0.028) | (0.069) | (0.038) |
| Tw + | −0.036 + | 0.060 + | −0.009 + | 0.028 + | 0.025 + | 0.021 + |
| | (0.032) | (0.043) | (0.022) | (0.024) | (0.054) | (0.030) |
| Tp - | −0.001 + | −0.090 + | −0.147 | −0.029 + | −0.185 + | −0.132 + |
| | (0.060) | (0.074) | (0.050) | (0.052) | (0.176) | (0.124) |
| Ts - | 0.037 + | 0.049 + | 0.023 + | −0.030 + | 0.344 | −0.038 + |
| | (0.054) | (0.080) | (0.043) | (0.049) | (0.196) | (0.081) |
| Ta - | 0.064 + | −0.048 + | −0.059 + | −0.054 + | −0.021 + | −0.063 + |
| | (0.041) | (0.060) | (0.041) | (0.048) | (0.195) | (0.083) |
| Tw - | −0.032 + | −0.019 + | −0.066 | −0.048 + | −0.081 + | −0.035 + |
| | (0.046) | (0.058) | (0.038) | (0.040) | (0.110) | (0.070) |
| Pp + | 0.010 + | 0.031 + | −0.027 + | 0.023 + | 0.079 + | 0.005 + |
| | (0.031) | (0.039) | (0.027) | (0.028) | (0.059) | (0.033) |
| Ps + | 0.023 + | 0.018 + | 0.013 + | −0.010 + | 0.008 + | −0.035 + |
| | (0.026) | (0.036) | (0.021) | (0.022) | (0.047) | (0.029) |
| Pa + | −0.010 + | −0.021 + | 0.056 | 0.011 + | −0.041 + | 0.043 + |
| | (0.027) | (0.038) | (0.022) | (0.023) | (0.053) | (0.028) |
| Pw + | 0.022 + | −0.077 + | 0.004 + | 0.001 + | −0.021 + | 0.059 + |
| | (0.041) | (0.063) | (0.034) | (0.034) | (0.072) | (0.040) |
| Pp - | −0.059 | 0.017 + | −0.004 + | −0.019 + | −0.056 + | −0.012 + |
| | (0.026) | (0.035) | (0.022) | (0.022) | (0.053) | (0.027) |
| Ps - | −0.062 | 0.090 | −0.014 + | 0.022 + | 0.030 + | −0.022 + |
| | (0.030) | (0.046) | (0.024) | (0.024) | (0.061) | (0.032) |
| Pa - | 0.030 + | −0.083 | 0.066 | 0.019 + | 0.000 + | 0.001 + |
| | (0.034) | (0.048) | (0.029) | (0.029) | (0.071) | (0.035) |
| Pw - | 0.023 + | 0.016 + | 0.023 + | 0.019 + | −0.063 + | −0.020 + |
| | (0.040) | (0.056) | (0.031) | (0.033) | (0.080) | (0.040) |
| *n* cross section | 91 | 54 | 107 | 135 | 42 | 124 |
| *n* time series | 25 | 25 | 25 | 25 | 25 | 25 |

Source: Elaborated by the authors using data from IBGE (2017), INMET (2017) and LUPA. Standard deviations between parentheses. + Insignificant at 10% level.

## References


Borrvall, C., Ebenman, B., 2008. Biodiversity and persistence of ecological communities in variable environments. Ecol. Complex. 5, 99–105. http://dx.doi.org/10.1016/J.ECOCOM.2008.02.004.

Burney, J., Cesano, D., Russell, J., La Rovere, E.L., Corral, T., Coelho, N.S., Santos, L., 2014. Climate change adaptation strategies for smallholder farmers in the Brazilian Serttão. Clim. Chang. 126, 45–59. http://dx.doi.org/10.1007/s10584-014-1186-0.

CEPEA, 2017. Centro de Estudos Avançados em Economia Aplicada - CEPEA-Esalq/USP (WWW Document). https://www.cepea.esalq.usp.br/br, Accessed date: 28 November 2017.

Crivisqui, E., 1999. Presentación de los métodos de clasificación.

Dai, J., Kesternich, M., Löschel, A., Ziegler, A., 2015. Extreme weather experiences and climate change beliefs in China: an econometric analysis. Ecol. Econ. 116, 310–321. http://dx.doi.org/10.1016/j.ecolecon.2015.05.001.

Deelstra, J., Øygarden, L., Blankenberg, A.B., Olav Eggestad, H., 2011. Climate change and runoff from agricultural catchments in Norway. Int. J. Clim. Change Strategies Manage. 3, 345–360. http://dx.doi.org/10.1108/17568691111175641.

Defries, S., Foley, A., Asner, P., 2004. Land-use choices: balancing human needs and ecosystem function. Front. Ecol. Environ. 2, 249–257.

Easterling, W.E., 1996. Adapting North American agriculture to climate change. Agric. For. Meteorol. 80, 1–53. http://dx.doi.org/10.1016/0168-1923(95)02314-3.

Ferraz, S.F.B., Ferraz, K.M.P.M.B., Cassiano, C.C., Brancalion, P.H.S., da Luz, D.T.A., Azevedo, T.N., Tambosi, L.R., Metzger, J.P., 2014. How good are tropical forest patches for ecosystem services provisioning? Landsc. Ecol. 29, 187–200. http://dx.doi.org/10.1007/s10980-014-9988-z.

Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309 (80), 570–574. http://dx.doi.org/10.1126/science.1111772.

García-Nieto, A.P., García-Llorente, M., Iniesta-Arandia, I., Martín-López, B., 2013. Mapping forest ecosystem services: from providing units to beneficiaries. Ecosyst.

Serv. 4, 126–138. http://dx.doi.org/10.1016/j.ecoser.2013.03.003.
Goldemberg, J., Coelho, S.T., Guardabassi, P., 2008. The sustainability of ethanol production from sugarcane. Energy Policy 36, 2086–2097. http://dx.doi.org/10.1016/j.enpol.2008.02.028.
Hallegatte, S., Hourcade, J.-C., Dumas, P., 2007. Why economic dynamics matter in assessing climate change damages: illustration on extreme events. Ecol. Econ. 62, 330–340. http://dx.doi.org/10.1016/j.ecolecon.2006.06.006.
Hassan, R.M., Scholes, R., Ash, N., 2005. Ecosystems and human well-being-current state and trends: findings of the condition and trends working group of the millennium ecosystem assessment. Millenn. Ecosyst. Assess. Ser. 1, 917. http://dx.doi.org/10.1016/j.fm.2010.10.016.
IBGE, 2017. Portal do Instituto Brasileiro de Geografia e Estatística - IBGE (WWW Document). https://www.ibge.gov.br/, Accessed date: 27 November 2017.
IBGE – Instituto Brasileiro de Geografia e Estatística, 2018. Sistema IBGE de Recuperação Automática - SIDRA (WWW Document). https://sidra.ibge.gov.br/home/scnt/brasil, Accessed date: 3 March 2018.
INMET, 2017. Portal do INMET - Instituto Nacional de Meteorologia (WWW Document). http://www.inmet.gov.br/portal/, Accessed date: 28 November 2017.
IPCC, 2014. Climate change 2014: synthesis report. In: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC.
Jacobi, P.R., Cibim, J., Leão, R. de S., Jacobi, P.R., Cibim, J., Leão, R. de S., 2015. Crise hídrica na Macrometrópole Paulista e respostas da sociedade civil. Estud. Avançados. 29. pp. 27–42. http://dx.doi.org/10.1590/S0103-40142015000200003.
Jørgensen, S.L., Termansen, M., 2016. Linking climate change perceptions to adaptation and mitigation action. Clim. Chang. 138, 283–296. http://dx.doi.org/10.1007/s10584-016-1718-x.
Kim, J., Mueller, C.W., 1978. Factor Analysis: Statistical Methods and Practical Issues. SAGE Publications.
Knapp, A.K., Beier, C., Briske, D.D., Classen, A.T., Luo, Y., Reichstein, M., Smith, M.D., Smith, S.D., Bell, J.E., Fay, P.A., Heisler, J.L., Leavitt, S.W., Sherry, R., Smith, B., Weng, E., 2008. Consequences of more extreme precipitation regimes for terrestrial ecosystems. Bioscience 58, 811–821.
Kurtzman, D., Kadmon, R., 1999. Mapping of temperature variables in Israel: a comparison of different interpolation methods. Clim. Res. 13, 33–43. http://dx.doi.org/10.3354/cr013033.
Kustura, Antonija, Kisic, Ivica, Basic, Ferdo, Jurisic, Aleksandra, 2008. Soil erosion by water in perennial plantations of the Ilok region. Agric. Conspec. Sci. 73, 75–83.
La Notte, A., D'Amato, D., Mäkinen, H., Paracchini, M.L., Liquete, C., Egoh, B., Geneletti, D., Crossman, N.D., 2017. Ecosystem services classification: a systems ecology perspective of the cascade framework. Ecol. Indic. 74, 392–402. http://dx.doi.org/10.1016/j.ecolind.2016.11.030.
Maia, A.G., Cesano, D., Miyamoto, B., Eusebio, G., Andrade, P., 2016. Climate change and adaptive strategies in agriculture: assessing the impacts on small farmers in the Brazilian Sertão. In: Agricultural & Applied Economics Association Annual Meeting.
MAPA - Ministério da Agricultura, P. e A, 2018. Estatísticas de Comércio Exterior [WWW Document]. http://www.agricultura.gov.br/assuntos/relacoes-internacionais/estatisticas-de-comercio-exterior, Accessed date: 24 March 2018.
Marengo, J.A., 2007. Mudanças climáticas globais e seus efeitos sobre a biodiversidade, 2ª edição. MMA, Brasília-DF.
Marengo, J.A., Ambrizzi, T., da Rocha, R.P., Alves, L.M., Cuadra, S.V., Valverde, M.C., Torres, R.R., Santos, D.C., Ferraz, S.E.T., 2010. Future change of climate in South America in the late twenty-first century: intercomparison of scenarios from three regional climate models. Clim. Dyn. 35, 1089–1113. http://dx.doi.org/10.1007/s00382-009-0721-6.
Marengo, J.A., Chou, S.C., Kay, G., Alves, L.M., Pesquero, J.F., Soares, W.R., Santos, D.C., Lyra, A.A., Sueiro, G., Betts, R., Chagas, D.J., Gomes, J.L., Bustamante, J.F., Tavares, P., 2012. Development of regional future climate change scenarios in South America using the Eta CPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. Clim. Dyn. 38, 1829–1848. http://dx.doi.org/10.1007/s00382-011-1155-5.
Mariotte, P., Vandenberghe, C., Kardol, P., Hagedorn, F., Buttler, A., 2013. Subordinate plant species enhance community resistance against drought in semi-natural grasslands. J. Ecol. 101, 763–773. http://dx.doi.org/10.1111/1365-2745.12064.
Mariotte, P., Robroek, B.J.M., Jassey, V.E.J., Buttler, A., 2015. Subordinate plants mitigate drought effects on soil ecosystem processes by stimulating fungi. Funct. Ecol. 29, 1578–1586. http://dx.doi.org/10.1111/1365-2435.12467.
Mendelsohn, R., Dinar, A., 2009. Climate Change and Agriculture: an Economic Analysis of Global Impacts, Adaptation and Distributional Effects. Edward Elgar, Cheltenham.
Mendelsohn, R., Nordhaus, W.D., Shaw, D., 1994. The impact of global warming on agriculture: a Ricardian analysis. Am. Econ. Rev. 84, 753–771.
Millenium Ecosystem Assessment, 2010. Ecosystems and Human Well-Being: Biodiversity Synthesis, Ecosystems. http://dx.doi.org/10.1057/9780230625600.
Morrison, D., 1990. Multivariate statistical methods. In: Multivariate Statistical Methods, 3rd ed. McGraw-Hill, New York.
Naeem, S., Li, S., 1997. Biodiversity enhances ecosystem reliability. Nature 390, 507.
Nepstad, D.C., de Carvalho, C.R., Davidson, E.A., Jipp, P.H., Lefebvre, P.A., Negreiros, G.H., da Silva, E.D., Stone, T.A., Trumbore, S.E., Vieira, S., 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. Nature 372, 666.
Palm, C., Blanco-Canqui, H., Declerck, F., Gatere, L., Grace, P., 2014. Conservation agriculture and ecosystem services: an overview. Agric. Ecosyst. Environ. http://dx.doi.org/10.1016/j.agee.2013.10.010.
Parron, L.M., Garcia, J.R., Rachwal, M.F.G., Franchini, J.C., Franciscon, L., Porfírio-Da-Silva, V., Brown, G.G., 2015. Avaliação de serviços ambientais no âmbito do projeto ServiAmbi. In: Parron, L.M., Garcia, J.R., de Oliveira, E.B., Brown, G.G., Prado, R.B. (Eds.), Serviços Ambientais Em Sistemas Agrícolas E Florestais Do Bioma Mata Atlântica. Embrapa, Brasília, pp. 36–46.
PBMC, 2014. Base científica das mudanças climáticas.Base científica das mudanças climáticas. Contribuição do Grupo de Trabalho 1 do Painel Brasileiro de Mudanças Climáticas ao Primeiro Relatório da Avaliação Nacional sobre Mudanças Climáticas. COPPE. Universidade Federal do Rio de Janeiro, Rio de Janeiro. http://dx.doi.org/10.13140/RG.2.1.1641.6883.
Reidsma, P., Oude Lansink, A., Ewert, F., 2009. Economic impacts of climatic variability and subsidies on European agriculture and observed adaptation strategies. Mitig. Adapt. Strateg. Glob. Chang. 14, 35–59. http://dx.doi.org/10.1007/s11027-008-9149-2.
Rosenzweig, C., Iglesius, A., Yang, X.B., Epstein, P.R., Chivian, E., Lincoln Rosenzweig, N., 2001. Climate change and extreme weather events - implications for food production, plant diseases, and pests challenges to food production and nutrition current and future energy use from burning of fossil fuels and clearing of forests for cultivation can have profound effects on the global environment. Glob. Chang. Hum. Heal. 2.
Schlenker, W., Hanemann, W.M., Fisher, A.C., 2003. Will U.S. agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach. Am. Econ. Rev. 95, 395–406.
Taniwaki, R.H., Cassiano, C.C., Filoso, S., Ferraz, S.F. de B., de Camargo, P.B., Martinelli, L.A., 2017. Impacts of converting low-intensity pastureland to high-intensity bioenergy cropland on the water quality of tropical streams in Brazil. Sci. Total Environ. 584–585, 339–347. http://dx.doi.org/10.1016/j.scitotenv.2016.12.150.
The World Bank, 2012. Turn down the heat: why a 4 °C warmer world must be avoided. … rep. World 106.
Therond, O., Duru, M., Roger-Estrade, J., Richard, G., 2017. A new analytical framework of farming system and agriculture model diversities. A review. Agron. Sustain. Dev. 37 (21). http://dx.doi.org/10.1007/s13593-017-0429-7.
van der Velde, M., Tubiello, F.N., Vrieling, A., Bouraoui, F., 2012. Impacts of extreme weather on wheat and maize in France: evaluating regional crop simulations against observed data. Clim. Chang. 113, 751–765. http://dx.doi.org/10.1007/s10584-011-0368-2.
Várallyay, G., 2010. The impact of climate change on soils and on their water management. Agron. Res. 8, 385–396.
Vergara, W., 2009. Assessing the potential consequences of climate destabilization in Latin America (No. 32). In: Latin America and Caribbean Region Sustainable Development Working Paper. Washington, DC.
Vieira Filho, J.E.R., Gasques, J.G., 2016. Agricultura, transformação produtiva e sustentabilidade, 1ª. ed. IPEA, Brasília.
Villamayor-Tomas, S., 2014. Cooperation in common property regimes under extreme drought conditions: empirical evidence from the use of pooled transferable quotas in Spanish irrigation systems. Ecol. Econ. 107, 482–493. http://dx.doi.org/10.1016/j.ecolecon.2014.09.005.
von Möllendorff, C., Hirschfeld, J., 2016. Measuring impacts of extreme weather events using the life satisfaction approach. Ecol. Econ. 121, 108–116. http://dx.doi.org/10.1016/j.ecolecon.2015.11.013.
Wreford, A., Moran, D., Adger, N., 2010. Climate change and agriculture: impacts, adaptation and mitigation. In: Source OECD Agriculture & Food. 9.
Yachi, S., Loreau, M., 1999. Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis. Proc. Natl. Acad. Sci. U. S. A. 96, 1463–1468.