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The impacts of climate change on French agricultural productivity

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Abstract

This paper analyzes the impact of changes in stochastic climatic variables on a sample of French agricultural farms between 1990 and 2008. We quantify the productivity impact by decomposing productivity changes over time via nonparametric productivity accounting. This method provides an empirical nonparametric measure of the impact of climate variables on production, a measure of technological change and a measure of efficiency change.

1. Introduction

The importance of climate and soil inputs has been recently reconsidered in agricultural production. The impacts of climate on agricultural production have been subject to intense study during recent years. If it is true that climate is changing, the estimation of climate change impacts is key to understanding a strategy towards a sustainable future. However, the estimation process has not been clear-cut nor easy.

Two main strands of literature are considered. On one hand, for example, Deschênes and Greenstone (2007) estimate the impacts of climate change in a profit maximization context and then project future impacts along different

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climate scenarios to produce estimates of climate change damages. On the other hand, for example, Schlenker and Roberts (2009) estimate the impacts of climate change by correlating yields of different separate crops and climatic variables. These estimates result in elasticities that, projected in the future with climate change scenarios, produce damage estimates.

Many contributions have treated precipitation and temperature variables as additively separable inputs (Deschênes and Greenstone, 2007; Schlenker and Roberts, 2009). However, as demonstrated in Ortiz-Bobea and Just (2013), precipitation and temperature are not additively separable. Ortiz-Bobea and Just (2013) treat in fact precipitation and temperature variables from different months as different inputs, implying that they have different production impacts. Our intuition goes further. Not only these inputs are different inputs depending on the time of occurrence but also their impact on the production is not structurally separable. By not being structurally separable we mean that this impact cannot be added as in a linear regression framework (additively separable), nor is necessarily just multiplicatively separable (as in multiplication in regression interaction terms). The shape of this interaction with other variables is not assumed nor specified in our framework.

The aim of this study is to consider the impact of change in climatic inputs on the production process. In particular, we consider the impact of changes in the amount of precipitation, in the level of temperature and in the amount of greenhouse gases on the production process. Scientists consider greenhouse gas emissions, and not only carbon dioxide emissions, as the culprit of climate change. However, economic studies of the impact of climate change in agriculture have thus far mainly concentrated on carbon dioxide because its emission is mainly anthropogenic.

It is well recognized that CO₂ is one of the main drivers of climate change. However, its impact on the agricultural production process from an economic point of view has not adequately been considered. Under appropriate climatic conditions, the negative effect of an increase in temperature due to the increase in atmospheric CO₂ could be reversed by a higher input to vegetation growth, such as CO₂. This is what Schlenker and Roberts (2009) refer to as the potential CO₂ cross-fertilization effect, which is not captured in their study. A necessary input to assimilate CO₂ is solar radiation. We also include this input into the agricultural production process.

Another important fact that we consider in our study is that climate change has had an asymmetric impact on the levels of temperatures during

night and day (Easterling et al., 1997). In particular, climate change analyses and forecasts show an increase in the minimum temperatures higher than the increase in maximum temperatures. This is not usually captured in climate change studies if one considers a mean daily temperature. Additionally, biologists (McClung, 2006) have shown that plants have the highest peak of their growth process in the day during early hours in the day, approximately when the minimum temperatures are recorded. Also in this case the aggregation to a mean value of two different inputs may result in erroneous results. This would hint to a positive impact of night warming due to climate change. In other words, it might be that a positive impact is measurable for increases in average daily temperatures in which the increase in temperature has mostly occurred during the night.

Most of the academic literature moreover, focuses on aggregate levels. However, how to adapt to climate change or the mitigation of its impacts depends extensively on the decision maker. The methods used in this study allow one to decompose exactly the changes in productivity for every farm, and not in aggregate terms. This is a critical feature if one is interested in potential diversity of impact on different heterogeneous decision makers. The core of this paper is, in fact, the characterization of a production technology that describes the production of a group of single farmers from 1990 to 2000. We only assume that producers are product maximizers.

This article proposes to study, via nonparametric productivity accounting decomposition methods, the impact of soil and climate on agricultural productivity in France in the period between 1990 and 2000. This is the period in which CO₂ has increased most rapidly in Europe. At the same time France has observed in the 20th century an increase in temperature 30% higher than elsewhere in the world (ONERC, Paris 2009). Additionally, French agricultural production is a sector potentially highly affected from climate change, for example if we consider the earlier grape flowering time and vintage time in grape production occurred since 1987.

2. Methodology

Empirical analyses on the impact of climate change do not usually consider the possibilities of interactions between climatic inputs and other inputs and outputs, nor the cross-fertilization effect of CO₂. This is especially true due to the difficulty in isolating the effect of a change of a single variable on a product increase or decrease. In other words it is difficult to consider analyses

“ceteris paribus”. Moreover, the freedom from functional form assumptions make this method new to the analysis of the issue of climate change.

The present contribution adapts methods developed by Färe et al. (1994) and Kumar and Russell (2002) to accommodate the presence of climatic variable inputs and to show the impact of a change over time of these inputs on agriculture in terms of chain-indexed productivity changes under constant returns to scale.

2.1. Technology

Let $y \in \mathbb{R}_+$ denote an output, $\mathbf{x} \in \mathbb{R}_+^U$ denote the inputs, $\mathbf{c} \in \mathbb{R}_+^D$ denote climatic inputs, and t denote time. The multi-input technology set $T \subset \mathbb{R}_+^{U+D+1}$ is defined:

$$T(t) = \{(\mathbf{x}, \mathbf{c}, y) \in \mathbb{R}_+^{U+D+1} : (\mathbf{x}, \mathbf{c}) \text{ can be used to produce } y \text{ at time } t\}.$$

We assume that T satisfies:

A.1: T is nonempty and closed;

A.2: Weak disposability of output, that is, $(\mathbf{x}, \mathbf{c}, y) \in T \implies (\mathbf{x}, \mathbf{c}, \lambda y) \in T, 0 < \lambda < 1$.

Define the Farrell output-oriented measure of technical efficiency, which is just the reciprocal of a distance function, as $E : \mathbb{R}_+^U \times \mathbb{R}_+^D \times \mathbb{R}_+ \rightarrow \mathbb{R}_+$, by:

$$E(\mathbf{x}, \mathbf{c}, y) \equiv \max \{\lambda > 0 : (\mathbf{x}, \mathbf{c}, \lambda y) \in T\} \quad (1)$$

if there exists $\lambda > 0$ such that $(\mathbf{x}, \mathbf{c}, \lambda y) \in T$ and 0 otherwise, and where, by construction, $E(\mathbf{x}, \mathbf{c}, y)$ is positively homogeneous of degree -1 in y . By weak disposability of outputs,

$$E(\mathbf{x}, \mathbf{c}, y) \geq 1 \Leftrightarrow (\mathbf{x}, \mathbf{c}, y) \in T \quad (2)$$

so that $E(\mathbf{x}, \mathbf{c}, y)$ is a complete function representation of T . One can show that

$$E(\mathbf{x}, \mathbf{c}, y) = \frac{E(\mathbf{x}, \mathbf{c}, 1)}{y}, y > 0. \quad (3)$$

Of interest is the possibility of writing the efficiency measure as the ration between a production function at the numerator $E(\mathbf{x}, \mathbf{c}, 1)$ and observed output y .

2.2. Identifying climate effects

The analysis in this paper is done on productivity chained indexes between two consecutive years (time $t - 1$ against time t). In this methodological part we analyze a generic change between a unit 1 and another unit 0. These two units will typically be in the empirical results in this study the same farm at two consecutive year periods. The output productivity index is simply defined by

$$\frac{y_1}{y_0}.$$

Using (3) yields:

$$\frac{y_1}{y_0} = \frac{E(\mathbf{x}_1, \mathbf{c}_1, 1) E(\mathbf{x}_0, \mathbf{c}_0, y_0)}{E(\mathbf{x}_0, \mathbf{c}_0, 1) E(\mathbf{x}_1, \mathbf{c}_1, y_1)}. \quad (4)$$

Expression (4) naturally breaks into two parts. One,

$$\frac{E(\mathbf{x}_0, \mathbf{c}_0, y_0)}{E(\mathbf{x}_1, \mathbf{c}_1, y_1)},$$

is a measure of technical catch-up between the two observations 0 and 1. The other,

$$\frac{E(\mathbf{x}_1, \mathbf{c}_1, 1)}{E(\mathbf{x}_0, \mathbf{c}_0, 1)}, \quad (5)$$

is interpretable as an index of “maximum products”. By (2), the maximum amount of y obtainable given fixed levels of $(\mathbf{x}, \mathbf{c}, y)$ is

$$\max \{y : E(\mathbf{x}, \mathbf{c}, y) \geq 1\},$$

while applying (3) gives

$$\begin{aligned} \max \{y : E(\mathbf{x}, \mathbf{c}, y) \geq 1\} &= \max \{y : E(\mathbf{x}, \mathbf{c}, 1) \geq y\} \\ &= E(\mathbf{x}, \mathbf{c}, 1), \end{aligned}$$

which is interpretable as the maximum amount of output y that can be produced, for a given amount of (\mathbf{x}, \mathbf{c}) .

To identify climatic effects we need to decompose (5) into different components so that one can ascertain the role that differing values of (\mathbf{x}, \mathbf{c}) play in determining the overall productivity index. To measure explicitly time passing one can rewrite time t as an explicit argument of a generic production function $h(\mathbf{x}, \mathbf{c}, t)$, and then decompose this production function into

three components. By its indicial nature, the observed level of (5) depends upon the choice of both unit 0 and unit 1. That, in turn, means that it is possible to decompose indices such as (5) in multiple ways. To keep the treatment simple, here we illustrate the way of identifying the impact of a climatic input c and a generic input x by considering the generic problem of creating an index using a function of two variables, $g(x, c)$ where $g : \mathbb{R}_+^2 \rightarrow \mathbb{R}_+$, so that the index to be decomposed is

$$\frac{g(x_1, c_1)}{g(x_0, c_0)}.$$

Note that we can rewrite this after a simple manipulation as

$$\frac{g(x_1, c_1)}{g(x_0, c_0)} = \frac{g(x_1, c_1)}{g(x_0, c_1)} \frac{g(x_0, c_1)}{g(x_0, c_0)},$$

and one can interpret $\frac{g(x_1, c_1)}{g(x_0, c_1)}$ as an index measuring the effect that variation in x has on the overall index holding c constant and $\frac{g(x_0, c_1)}{g(x_0, c_0)}$ as an index measuring the effect of variation in c holding x constant. However, it's equally possible to write

$$\frac{g(x_1, c_1)}{g(x_0, c_0)} = \frac{g(x_1, c_1)}{g(x_1, c_0)} \frac{g(x_1, c_0)}{g(x_0, c_0)}.$$

Now $\frac{g(x_1, c_0)}{g(x_0, c_0)}$ is the index measuring the effect that variation in x has on the overall index holding c constant, and $\frac{g(x_1, c_1)}{g(x_1, c_0)}$ is measuring the effect of variation in c holding x constant. Unless g satisfies a specific separability condition, this arbitrariness in the decomposition is unavoidable in constructing an index number.

This problem is well known in the productivity literature and it is referred to as path dependency. To illustrate the path dependency issue, one can consider figure 1. Different paths attribute different measures to changes in x and c . One can determine the paths by changing the variables in different orders. To illustrate, let the comparison be the change between $g(x_1, c_1)$ and $g(x_0, c_0)$. One can either move from point $g(x_1, c_1)$ to point $g(x_1, c_0)$, and then to point $g(x_0, c_0)$ (first path). But one can also move from point $g(x_1, c_1)$, to point $g(x_0, c_1)$, and then to point $g(x_0, c_0)$ (second path). The problem of path dependency arises because, as in this example in the picture, the portions of the change from $g(x_1, c_1)$ to $g(x_0, c_0)$ attributed to each component are different depending on the path followed.

A workable alternative that avoids this arbitrariness is to follow Caves et al. (1982), Färe et al. (1994), Kumar and Russell (2002), and Henderson and Russell (2005) and rely on a “Fisher ideal index” that takes the geometric average of the two decompositions. That is,

$$\begin{aligned} \frac{g(x_1, c_1)}{g(x_0, c_0)} &= \left(\frac{g(x_1, c_1) g(x_0, c_1)}{g(x_0, c_1) g(x_0, c_0)} \right)^{\frac{1}{2}} \left(\frac{g(x_1, c_1) g(x_1, c_0)}{g(x_1, c_0) g(x_0, c_0)} \right)^{\frac{1}{2}} \\ &= \left(\frac{g(x_1, c_1) g(x_1, c_0)}{g(x_0, c_1) g(x_0, c_0)} \right)^{\frac{1}{2}} \left(\frac{g(x_1, c_1) g(x_0, c_1)}{g(x_1, c_0) g(x_0, c_0)} \right)^{\frac{1}{2}}, \end{aligned}$$

where $\left(\frac{g(x_1, c_1) g(x_1, c_0)}{g(x_0, c_1) g(x_0, c_0)} \right)^{\frac{1}{2}}$ indexes the effect that variation in x has on the overall index holding c constant, and $\left(\frac{g(x_1, c_1) g(x_0, c_1)}{g(x_1, c_0) g(x_0, c_0)} \right)^{\frac{1}{2}}$ the effect of variation in c holding x constant. The latter index number is in fact the index number of interest in our case: how much the output productivity index changes given changes in climatic variables. In the empirical results we also consider the passage of time.

2.3. Implementing the productivity decomposition

One can obtain empirical estimates of the three components by applying nonparametric linear programming methods without specific assumptions on returns to scale.

The nonparametric DEA approximation to the technology T is as follows:

$$\hat{T}(t) = \{(\mathbf{x}_t, \mathbf{c}_t, y_t) \in \mathbb{R}_+^{U+D+1} : y_t \leq \sum_{i=1}^n \sum_{t=1}^v \gamma_{it} y_{it} ;$$

$$x_{tu} \geq \sum_{i=1}^n \sum_{t=1}^v \gamma_{it} x_{itu}, u = 1, \dots, U;$$

$$c_{td} = \sum_{i=1}^n \sum_{t=1}^v \gamma_{it} c_{itd}, d = 1, \dots, D;$$

$$\text{for } (\gamma_{1t}, \dots, \gamma_{nt}) \text{ s.t. } \sum_{i=1}^n \gamma_i = 1; \gamma_{it} \geq 0, i = 1, \dots, n, t = 1, \dots, v \} \quad (6)$$

where i indexes decision-making units. The set of constraints on \mathbf{c} allows only convex combinations of the climate variables in the technology. In this manner we consider the possibility of negative marginal products associated with the climatic variables.

The approximation to the function E in the productivity decomposition proposed in this study is done through a Farrell output efficiency score. The function $E(\mathbf{x}, \mathbf{c}, y)$ can be calculated as follows:

$$\begin{aligned} \hat{E}(\mathbf{x}, \mathbf{c}, y) &= \max e \in \mathbb{R}_+ \\ \text{s.t. } ey &\leq \sum_{i=1}^n \sum_{t=1}^v \lambda_{it} y_{it} ; \\ x_{tu} &\geq \sum_{i=1}^n \sum_{t=1}^v \lambda_{it} x_{itu}, \quad u = 1, \dots, U; \\ c_{td} &= \sum_{i=1}^n \sum_{t=1}^v \lambda_{it} c_{itd}, \quad d = 1, \dots, D; \end{aligned}$$

$$\text{for } (\lambda_{1t}, \dots, \lambda_{nt}) \text{ s.t. } \sum_{i=1}^n \lambda_i = 1; \lambda_i \geq 0, i = 1, \dots, n, t = 1, \dots, v. \quad (7)$$

3. Data

We use a balanced panel data set of 66 French farms from the Farm Accountancy Data Network (FADN), observed between 1990 and 2000 for a total of 726 observations. The data from the FADN contain accountancy data for representative farms from a stratified, rotating sample.

Summary statistics of inputs and outputs used in the analysis are in table 1. We use a parsimonious one-output technology with multiple inputs. As inputs we consider family labor, land area utilized, and an aggregate input index including all other inputs. Both the aggregate input and output values are deflated with aggregate price indices from the National Institute of Statistics and Economic Studies (INSEE) with base period 2010. We match these data with a series of different data sources. In particular, we consider soil properties from the data in the GISSOL data base in France. We consider

as crucial soil properties soil organic carbon (in % of soil weight) and soil pH.

Part of the climatic inputs are obtained from the European Climate Assessment and Dataset (van den Besselaar et al., 2011)², which is a gridded dataset with a resolution of 0.25 degree latitude-longitude. From the data provided we use daily minimum and maximum temperature (in degree Celsius), daily average sea level pressure (in hectoPascals), and daily precipitation (in mm). As a proxy for concentration of carbon dioxide (CO₂) available to plants for cross-fertilization, we use gridded CO₂ emission levels (in $kg/m^2/s$) from the Emission Database for Global Atmospheric Research of the Joint Research Centre of the European Union. Finally, monthly net shortwave solar radiation data (in W/m^2) with 0.25 degree resolution is obtained from the Global Land Assimilation System Data (Noah model).

All gridded variables with different definitions and different grid resolutions have been matched to grid points inside the borders of French NUTS 3 regions, which are the smallest administrative units at which the FADN data are categorized. We then averaged all points in each region because we do not have the specific position of farmers in the corresponding NUTS 3 region. We further adapted the data to each farmer by multiplying the solar radiation by the area cultivated and CO₂ by the area and by time, to create cumulative yearly amounts. Finally we multiplied the rainfall rate in each month by the area cultivated to calculate how much water has been used for production on average in a specific farm in a particular year.

4. Results

The results of the productivity indexes are depicted in figure 2. Productivity indexes below 1 signal productivity growth while indexes above 1 signal slowdown. While one can observe many farms with quite high levels in the period 1990-1991, in the period 1995-1996 many of them decrease. Most farms have values concentrated more above 1 in the period 1999-2000. This signals a slowdown in the years 1999-2000 for this sample of farms.

If we decompose these productivity indexes and look at the climate indexes in figure 3, we realize that the first two periods have somewhat similar

²We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (<http://ensembles-eu.metoffice.com>) and the data providers in the ECA& D project (<http://www.ecad.eu>).

distributions. Even though the distributions are similar, there is a progressive “stretching” of the productivity components over time, above 1. If one looks at the histograms, it is possible to notice a general increase in the indexes over the three periods. This signals an increase in the productivity differences explained by climate variables, and a potential worsening of the impact of climatic inputs on the frontier.

The output efficiency indexes in figure 4 show an interesting progress of technological catch-up (efficiency indexes below 1) and falling behind the frontier (efficiency indexes above 1). In the 1990-1991 period when very good climatic conditions pushed further away the frontier, many farms fell behind the frontier with efficiency indexes above 1. In the 1995-1996 period there are both farms lagging behind and farms catching up. However, interestingly, in the 1999-2000 period many farms are shown to be catching up with the frontier. This last phenomenon can also be partly attributed to the fact that the climate has impacted the frontier negatively in that period as one can see from figure 3.

The technological change indexes shown in figure 5 present only values below 1, signaling technological progress. These results are due to the fact that we imposed no technological regress on the frontier. In fact, in agriculture, it is reasonable to imagine that farmers would not forget the availability of techniques over time. It is interesting to notice, however, that there is a concentration of values over time, comparing first the period 1990-1991 to 1995-1996 and then to 1999-2000.

We now concentrate on the climate indexes in the three periods. In figure 6 we show the amounts of carbon dioxide on the horizontal axis and the climate index on the vertical axis. In the period 1990-1991 there seemed to be a positive relationship between carbon dioxide and the index which, in turn, signals a negative contribution from increasing amounts of carbon dioxide. In the period 1995-1996 there seems to be no relationship. However, in the period 1999-2000 there seems to be a negative relationship between carbon dioxide and the climate index. The climate index shows also many values above 1 implying a negative impact of climate on productivity. However, one can also see that at increasing amount of carbon dioxide this negative impact decreases. In figure 7 we present the climate index against rainfall amounts. The behavior seems relatively similar to the behavior of carbon dioxide with respect to the climate index.

In figure 8 we represent the minimum average temperature against the climate index. In this graph one can see that there is a seemingly beneficial

relationship between high minimum temperatures in the period 1990-1991. This beneficial relationship is slowly changing in the 1995-1996 period. Finally, in the 1999-2000 period the relationship is overturned. It appears that high minimum temperatures, as supposed by climate change scientists, become harmful to productivity in the 1999-2000 period.

Finally, in figure 9 we show the maximum average temperature against the climate index. In this graph one can see a shift over time periods in the relationship with respect to productivity. As in the case of minimum temperature a progressive increase of the indexes over time show a more negative impact of maximum temperature over time. It is interesting to notice that in the first two periods a steep increase occurs for average temperatures approaching 14 degree Celsius, signaling a negative impact on productivity from higher temperatures. In the third period instead climate indexes are generally high showing a more negative impact than in previous years. However, in the third period there is instead a steep decrease for increasing average maximum temperatures towards 14 degree Celsius.

5. Conclusions

The methods presented in this study reconsider the impact of climate change from a different perspective. The proposed method accounts for productivity differences of inputs and outputs without assuming production efficiency, nor a parametric form on the technology. The possibility of production inefficiency allows decomposing a ratio of maximum products and not of observed products. Absence of specific technological functional form assumptions (apart from piecewise linearity) allows not imposing, a priori, unrealistic properties among inputs and outputs, and assumptions on the interaction of climatic inputs with other inputs and outputs.

The assumption of weak disposability on the climatic variables allows negative marginal contributions to productivity of certain ranges of temperature or rainfall or carbon dioxide.

The methodology purges out the inefficiency, and directly decomposes the distance among maximum products into three components: efficiency change, technological change, and climate index. The present study proposes to calculate the three components with nonparametric productivity accounting methods.

The results show increases in productivity in the period 1990-1991, and 1995-1996, but a slowdown in the period 1999-2000. The results show an

increase in climate impact on productivity. In particular, this impact is seemingly more negative in the period 1999-2000. This negative impact is higher also for carbon dioxide. However, the negative impact for higher amounts of carbon dioxide is decreasing in the period 1999-2000.

These conclusions are nonetheless only valid for this sample and for these technology assumptions. This is only the first step in reconsidering the impact of climate change at a disaggregated farm level.

Considering the importance of long time series in the evaluation of climate change, this study is moreover only an approximation of the results obtainable if longer data series were available. Once these data were to become available, a generalized version of this study would be possible.

6. Figures and Tables

Figure 1: Graphical representation of the problem of path dependency

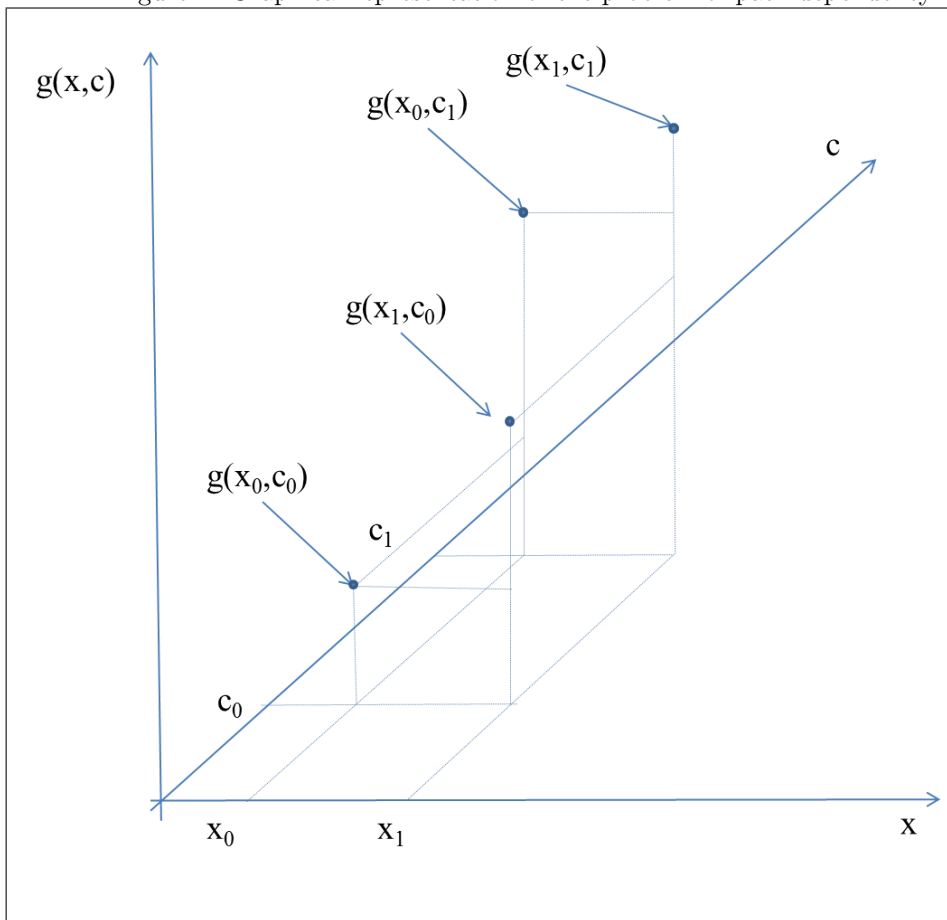


Figure 2: Output productivity indexes

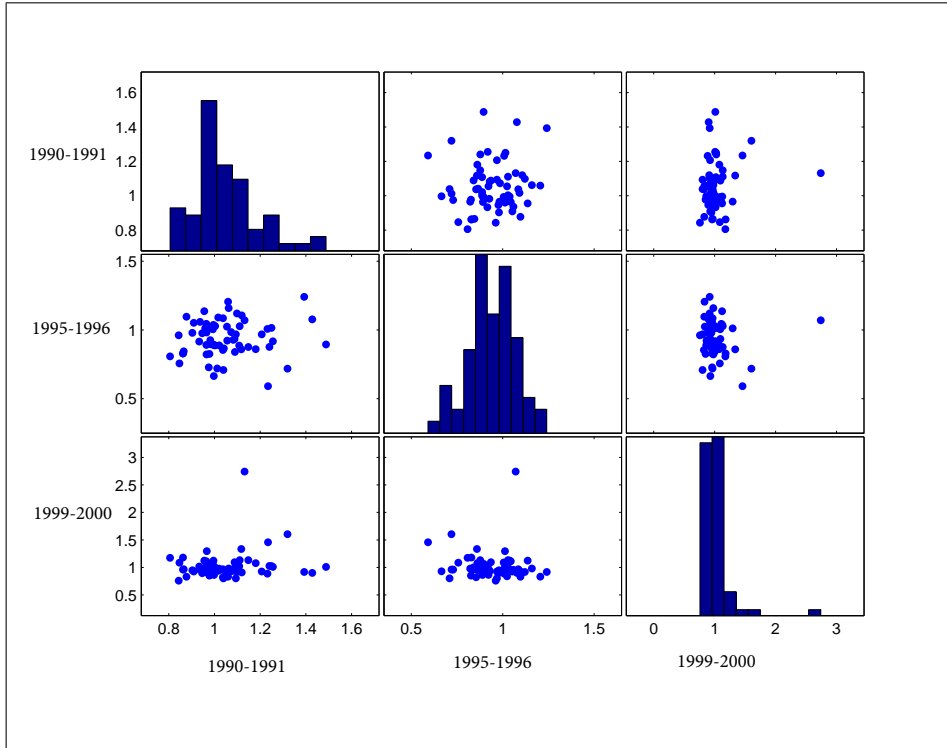


Figure 3: Climate indexes

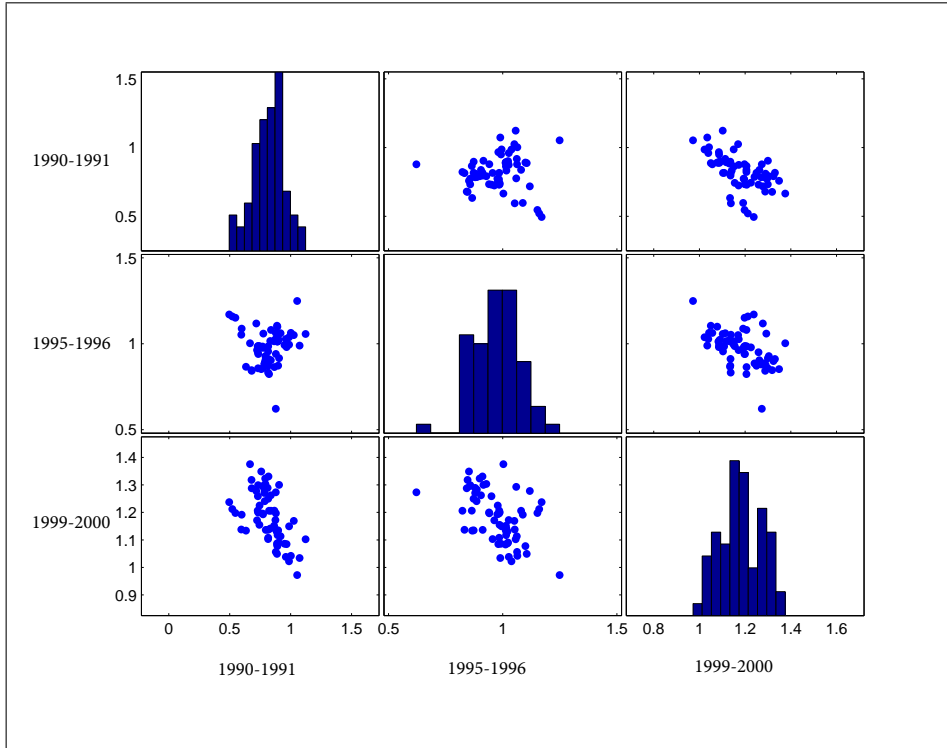


Figure 4: Output efficiency indexes

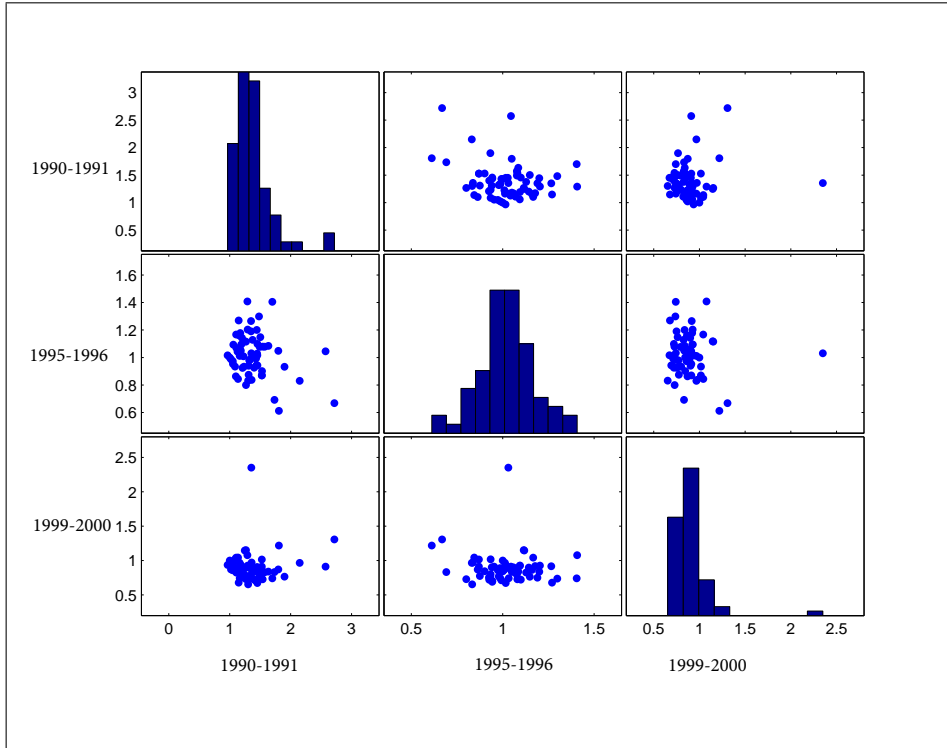


Figure 5: Technological change indexes

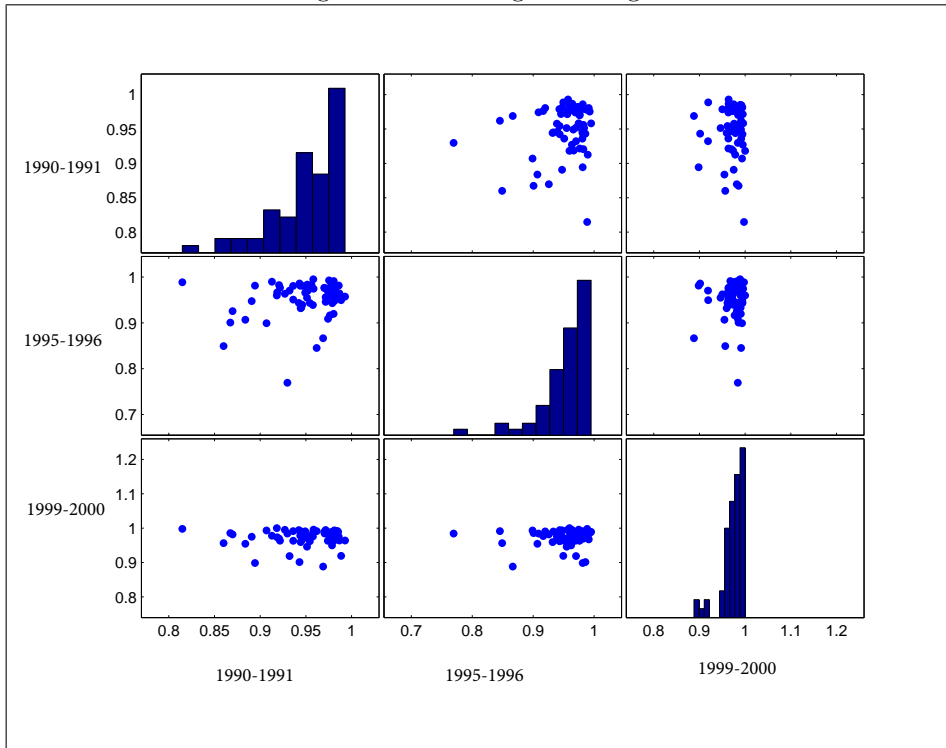


Figure 6: Carbon dioxide and climate index

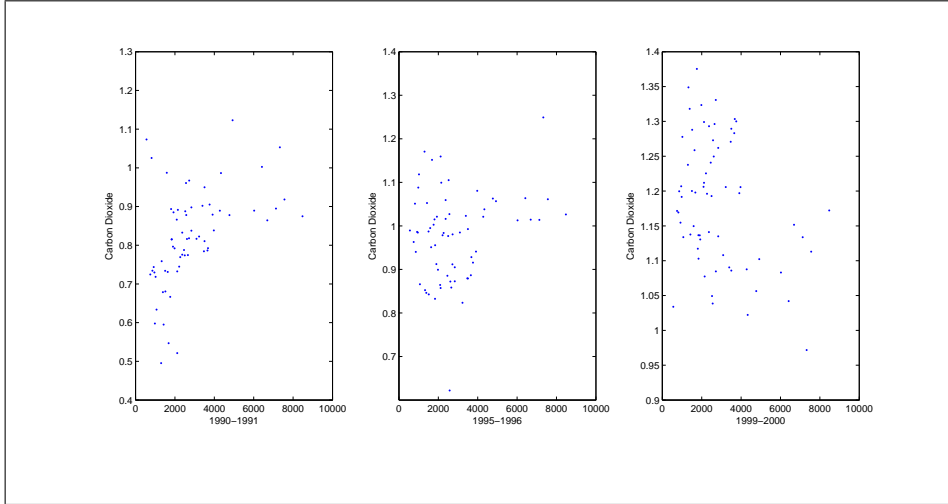


Figure 7: Rainfall and climate index

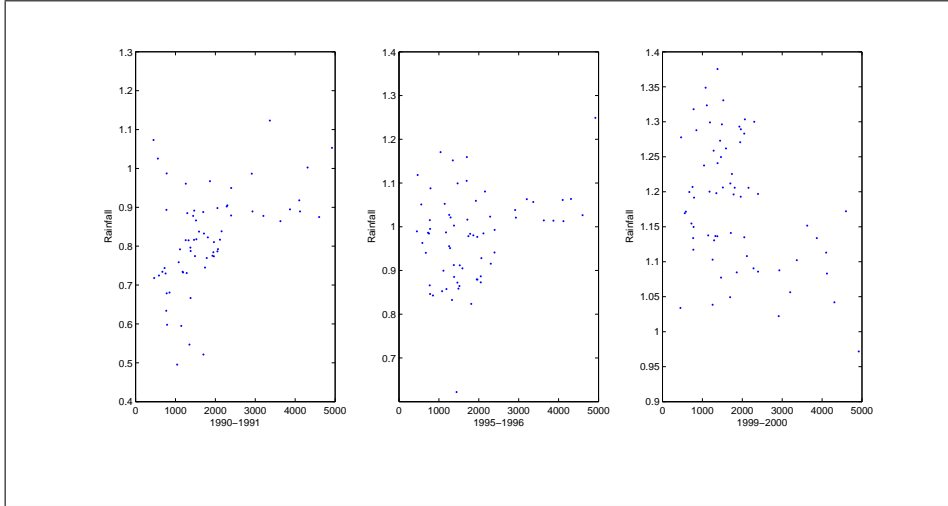


Figure 8: Minimum temperature and climate index

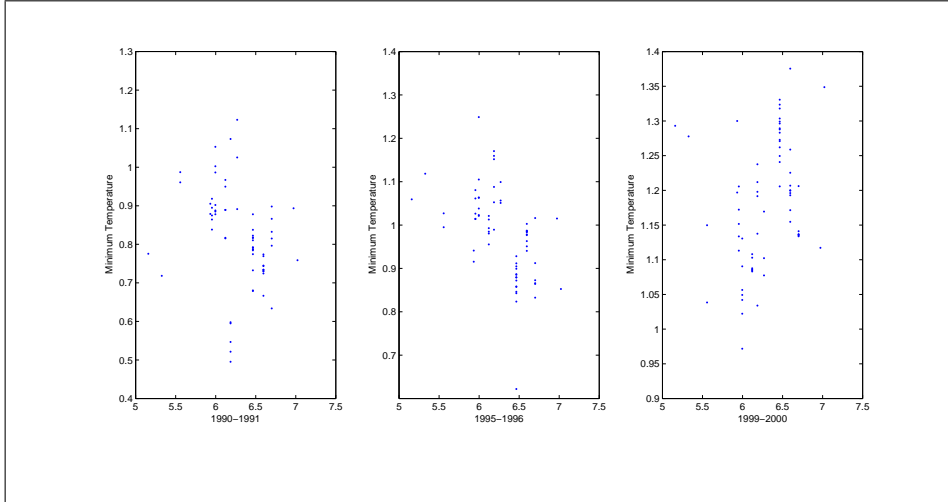


Figure 9: Maximum temperature and climate index

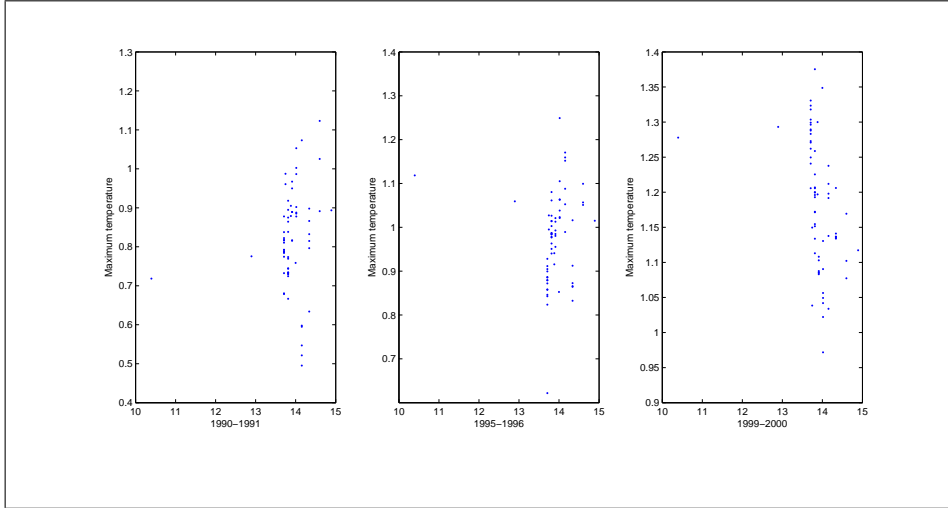


Table 1: Summary statistics of inputs, outputs, and soil-quality physical characteristics

Variable	Mean	Std.Dev.	Min	Max
Inputs				
Family Labor (AWU)	1.724	0.679	0.800	5.000
Land (ha)	92.598	53.354	13.660	293.140
Other Inputs (IQ)	1733.680	961.969	373.285	5213.325
Output				
Output (IQ)	1778.153	1018.796	278.867	6509.240
Climatic inputs				
pH	7.347	0.373	6.005	8.031
Soil Organic Carbon (g/kg)	16.755	3.140	11.960	28.555
Atmospheric Pressure (hPa)	993.473	35.167	725.843	1002.297
Average rainfall (kg)	1930.604	1239.243	299.742	7370.564
Temperature (Maximum)	14.228	0.915	9.872	16.522
Temperature (Minimum)	6.036	0.721	3.453	7.733
Net shortwave solar radiation (in MW)	100.716	58.583	15.434	321.890
Carbon Dioxide (kg)	3624.905	2423.060	560.016	15387.270
Observations: 726			Farms: 66	
IQ= Implicit Quantities				

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