Adaptation of European crop production to climate: a structural econometric multi-output approach

Abstract

The objective of this paper is shed some light on adaptation mechanisms of European agriculture and to propose a quantitative assessment of climate-induced changes in farmers' choices using an original structural econometric multi-output framework. We estimate a multi-output model and analyse how weather can impact production output, input use and land allocations. Our model is used to estimate weather impacts on European agriculture at the regional NUTS2 level observed during the period 2004-2012. We compare different estimators (within, between, pooled) and calculate the elasticities of wheat and maize production, fertilizer use and land allocation with respect to output prices, input price and weather variables in different seasons. Our preliminary results show that wheat output is more dependent on climate variations than maize output, also, that climate in different seasons plays the inverse role to land allocation between wheat and maize.

Keywords: climate change, production function, European agriculture, structural modelling.
JEL Codes: Q54, C23, Q10.

1 Introduction

Agriculture is one of the most affected sectors by climate change in a context where Food and Agriculture Organization (FAO) forecasts the doubling of world population by 2050 (FAO, 2017). Agriculture could also play an important role in the fight against climate change even if this sector did not figure initially in the COP (conference of the parties) negotiations aiming at tackling climate change.The signing of the Paris Agreement during COP 21, held in 2015, represented an important step and introduced food security as an important principle which puts the agricultural sector to the COP agenda. The COP 23, which was held in November 2017 in Bonn, Germany, was a milestone in agriculture negotiations. The signing of the Koronivia Joint Work on Agriculture, represented a new opportunity to examine the ways that climate change affects agricultural production and is threatening global food security. One of the main issues addressed by the *Koronivia Joint Work on Agriculture* is the development of "Methods and approaches for assessing adaptation, adaptation co-benefits and resilience". The FAO described this outcome for agriculture as a "major step" to address the need to adapt agriculture to climate change and to meet the growing global demand for food[1].

Agriculture accounts for a major proportion of the land area in Europe, accounting for 48%, on

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[1] `http://www.fao.org/news/story/en/item/1068313/icode/`

average, of the total EU surface (EU, 2016), and 11 million farms. However, agriculture is a vulnerable sector in the EU. The European Environment Agency (EEA) “Climate change, impacts and vulnerability in Europe 2016” report, published in 2017, suggests that projected climate change impacts will modify European agro-climatic regions, affecting agricultural practices and outputs. EEA (2017) underlines that negative climate impacts have already been observed for European agriculture and, more precisely, that the EU agricultural sector has been affected by extreme weather events resulting in reduced yields. In order to be able to address climate in the future Common Agricultural Policy (CAP), we need to have a clear idea on how this sector could adapt to climate change (Pe'Er et al., 2019). The main aim of this paper is shed some light on adaptation mechanisms of European agriculture and to propose a quantitative assessment of climate-induced changes in farmers' choices using an original structural econometric multi-output framework.

From a scientific point of view, during recent decades, researchers in diverse disciplines have shown increasing interest in the relation between agriculture and climate and have provided evidence that agriculture is highly dependent on climate (see Hulme (1996) and Kurukulasuriya and Rosenthal (2003)). The literature uses multiple approaches to measure the impacts of climate impacts on agriculture. Mendelsohn and Dinar (2009) proposes to distinguish five approaches: 1) agronomic crop simulation models (Rosenzweig et al., 1994); 2) cross-sectional and intertemporal analyses of yields (Lobell et al.); 3) general equilibrium modelling (Nelson et al., 2014); 4) cross-sectional and panel analyses in a Ricardian approach (Mendelsohn et al., 1994); and 5) an intertemporal net revenue approach (Deschenes and Greenstone, 2007).
The first two approaches are based on agronomic science and do not make assumptions about farmers' behaviors and possible adaptation of their behavior. Computable general equilibrium models, as their name suggests, take account of the fact that if changes induced by climate change are sufficiently large, they may affect input and output prices across the entire economy. The advantage of these models is that they are exhaustive, but are not sufficiently precise, for example, Europe is usually represented as a single region or a small number of regions.
The last two approaches are based on econometric models of net revenues (revenue approach) or land values (Ricardian approach), and take account of climate, soil and other control variables. Even if they give important responses in terms of climate impacts on agricultural economics, these econometric methods do not detail the precise mechanism linking climate and agricultural activity adaptation. These approaches considers usually adaptation as a black box while farmers' behaviour for crop choice, land allocation or inputs use is driven by numerous factors, as market prices and environmental conditions. Previous methods were not able to provide detailed indications about the way climate affects these decisions and hence about adaptation possibilities. However, the literature in agricultural production economics provides interesting basis to investigate such questions.
This papers makes two contributions to the growing literature on the impacts of climate change on agriculture. The first contribution is to provide a method of climate impacts measurement

on agriculture based on agricultural production economics framework which allows to explore the underlying mechanisms of adaptation.

We depart from the literature estimating multi-output models. The main aim of the seminal paper of Chambers and Just (1989) is to measure how crop prices affect farmers' production decisions with respect of crop choice, land allocation or input use. The production decision linked to land allocation to a specific crop is the more challenging because of the quasi-fixity of this specific input. To deal with this issue, some authors use national agricultural subsidies of each crop ((Bayramoglu and Chakir, 2016; Lacroix and Thomas, 2011; Laukkanen and Nauges, 2014)). Despite the fact that this solution is completely rational with the short-term dimension of multi-output models, it is not operational for subsidy decoupled from areas as it is now the case in Europe for instance. Arnade and Kelch (2007) proposes a method to estimate individual crop areas and output response to a change in prices, by including in the estimations shadow price equations for each crop area allocation. Such a strategy relies on the availability of land prices which is not always so easy to obtain. Furthermore, it constitutes a mix between long-term and short-term approaches.

We will rather concentrate on a pure short-term approach, following Gorddard (2013) who introduces a constraint on the total land area which is estimated through a closed-form equation. Such a closed-form equation estimation is also a strategy adopted by Fezzi and Bateman (2011) to appraise agro-environmental policy with a multi-output model or by Moore and Negri (1994) to appraise the response of irrigated agriculture to water price.

Climate is quasi-absent from the literature previously quoted. An exception is the paper from Fezzi and Bateman (2011) who incorporated it in the estimations as a control variable without any detailed investigation of its impact on farmers' choices of production. To the best of our knowledge, Ortiz-Bobea and Just (2012) is the only work focusing on the modelization of the structure of adaptation in climate impact assessment, on the basis of a multi-output model. They theoretically highligh the different channels through which climate can impact production decisions and investigate into more details the yield impact channel in an empirical application based on a unique closed-form equation estimation. We rather estimate a multi-output model with full structural equations for inputs and output choices and a closed-form equation for land-use choices. We then apply this framework to the measurement of climate impacts on European agriculture and to the investigation of European farmers adaptation to climate. It is our second contribution.

There exist only few studies on the impacts of climate change en European agriculture with very limited insights on how this sector will adapt to future climate. Vaitkeviciute et al. (2019); Vanschoenwinkel et al. (2016); Van Passel et al. (2017); Vanschoenwinkel and Van Passel (2018); Iglesias et al. (2012) show that the simulated agro-climate regions will be clearly affected by future climate conditions, with increasing crop productivity in Northern Europe and decreasing production in Southern regions. Nevertheless, the state of knowledge on the adaptation mechanisms of European agriculture and climate-induced changes in farmers' choices remains incomplete. More work is needed to provide information for decision makers to be able to support adaptation strategies.

More particularly, our preliminary results show that temperature variables could have a strong influence on wheat output. Moreover, weather variables are also estimated to have significant effect on maize output, and seems to have effects contrary to those for wheat output. Finally, we found that warmer summers and winters would lead farmers to increase land allocation to wheat production, and to reduce drastically land surface to irrigated and non-irrigated maize. In contrary, warmer mid seasons, spring and autumn, would play in favour with land allocation to maize, decreasing the one for the wheat.

2 Theoretical modelling

2.1 Modelling weather in agricultural profit maximizing program

The theoretical framework is built following the agricultural production modelling developed by Chambers and Just (1989), and based on the farm multi-crop profit maximization problem with a joint input technology. Ortiz-Bobea and Just (2012) propose a rewriting of the model by integrating the climate as an exogenous factor. The theoretical framework is based on profit maximizing producer behaviour where a farmer makes optimal weather-depending choices of agriculture system, crop choices, technology and input levels.

Consider a profit maximization problem with the multi-output technology. Let denote $\mathbf{q}$ the vector of c outputs, with $q \in Y$, where Y denotes multi-output combination, and $\mathbf{x(.)}$ the vector of k farmer's choice variables and weather dependent inputs. Also, indicate with $\mathbf{p}$ the vector of strictly positive output prices and $\mathbf{w}$ the vector of strictly positive input prices. Finally, denote $\mathbf{z}$ the vector of environmental climatic factors that crop c is exposed to. Therefore, the multi-output profit function is:

$$\pi^*(x(.), z, p, w) = max\{p(Q(z)).q(z, x(z)) - w(z).x(z)\}, \tag{1}$$

where Q represents the total output available on the market. Thought, this model suggests that weather impacts directly and indirectly farmer's output, his input choices, including land allocation, input prices, the total crop production available on the market and output prices.

Applying the envelope theorem we can decompose the changes in profits due to weather variations:

$$\frac{\partial \pi^*}{\partial z_c} = \frac{\partial p}{\partial Q}.\frac{\partial Q}{\partial z}.q(z, x^*(z)) + (\frac{\partial q}{\partial z} + \frac{\partial q}{\partial x^*}.\frac{\partial x^*}{\partial z})p(Q(z)) - (\frac{\partial w}{\partial z}.x^*(z) + w(z).\frac{\partial x^*}{\partial z}), \tag{2}$$

where x^* is the optimal level of input x. Following Ortiz-Bobea and Just (2012), we can identify few different channels through which weather affects farmer profits. The first term of equation

2 represents the effect of output prices, that are affected by weather variations impact of global production, on profits. The second term of this equation represents the weather variation impacts on profit through its effects on the individual farmer's output. The third term of equation 2 measures the cost effect of weather variation associated with changes in input prices and input use.

This structural model being complex to estimate, Ortiz-Bobea and Just (2012) suggest to focus on one of identified channels in order to analyse weather variation impacts on farmer profits. In the context of this study, we assume the short-term partial equilibrium and the case of weather that affects the production technology and, thus, enters in our modelling through individual farmer's output.

2.2 Multi-output multi-factor short-term production function model

Due to the complexity of model estimation when suggesting that weather impacts all of model factors, we can release some of restrictions on the model. We use the approach to profit maximization detailed in **?**, adapted to agriculture by Chambers and Just (1989) and completed by Arnade and Kelch (2007). Lets assume that climate is a fixed non-allocable input that enters in the production function, $y = f(\mathbf{x}, \mathbf{l}, \mathbf{z})$, where y denotes the output, $\mathbf{x}$ is a vector of i variable inputs, $\mathbf{l}$ is a vector of quasi-fixed but allocable input land, and $\mathbf{z}$ is a vector of other fixed but not allocable environmental inputs as weather. We can write producer maximizing problem as fallows:

$$\pi(\mathbf{p}, \mathbf{w}, \mathbf{z}, \mathbf{l}) = \max_{y_j, x_i} \{\sum_j p_j y_j - \sum_i w_i x_i : y_j \in Y(\mathbf{x}, \mathbf{l}, \mathbf{z}); \sum l_s = L\}, \tag{3}$$

where $\mathbf{p}$ is a vector of j output prices, $\mathbf{w}$ is a vector of i input prices, and Y describes the total producible output set by a farmer, subject to a production function and technology choice that can be denoted F:

$$Y = F(y_1, ..., y_m; x_1, ..., x_n; l_1, ..., l_s; z_1, ..., z_u), \tag{4}$$

The first step of of maximization program consists to consider that producer maximize profits. The first order conditions (F.O.C.) for profit maximization, $\partial\pi^*/\partial x^* = 0$ and $\partial\pi^*/\partial y^* = 0$, in the multi-output program gives :

$$p_j + \phi \frac{\partial F}{\partial y_j^*} = 0, \ j = 1, ..., m;$$

$$-w_i + \phi \frac{\partial F}{\partial x_i^*} = 0, \ i = 1, ..., n \tag{5}$$

Lets denote y^* and x^* the optimal output and input levels that both are dependent of input and output prices, and quasi-fixed inputs. Then we can write an indirect profit function evaluated at x_i^* and y_j^*:

$$\pi^*(\mathbf{p}, \mathbf{w}, \mathbf{z}, \mathbf{l}) = \sum_{j=1}^{m} p_j . y_j^* - \sum_{i=1}^{n} w_i . x_i^* . \tag{6}$$

In order to find the optimal supply function, lets consider the change in optimal profit when the kth output price changes. With y^* and x^* differentiable functions of prices, yields:

$$\frac{\partial \pi^*}{\partial p_k} = y_k^* + \sum_{j=1}^{m} p_j \frac{\partial y_j^*}{\partial p_k} - \sum_{i=1}^{n} w_i \frac{\partial x_i^*}{\partial p_k}. \tag{7}$$

Substituting (5) in (7) for p_j and w_i gives:

$$\frac{\partial \pi^*}{\partial p_k} \;=\; y_k^* - (\phi \sum_{j=1}^{m} \frac{\partial F}{\partial y_j^*}\frac{\partial y_j^*}{\partial p_k} + \phi \sum_{i=1}^{n} \frac{\partial F}{\partial x_i^*}\frac{\partial x_i^*}{\partial p_k}) \;=\; y_k^* - \phi(\sum_{j=1}^{m} \frac{\partial F}{\partial y_j^*}\frac{\partial y_j^*}{\partial p_k} + \sum_{i=1}^{n} \frac{\partial F}{\partial x_i^*}\frac{\partial x_i^*}{\partial p_k}). \tag{8}$$

Considering the production function associated with profit maximizing output and input levels $F(\mathbf{y}^*, \mathbf{x}^*, \mathbf{z}, \mathbf{l}) = 0$, then we have:

$$\frac{\partial F(\mathbf{y}^*, \mathbf{x}^*, \mathbf{z}, \mathbf{l})}{\partial p_k} = \sum_{j=1}^{m} \frac{\partial F}{\partial y_j^*}\frac{\partial y_j^*}{\partial p_k} + \sum_{i=1}^{n} \frac{\partial F}{\partial x_i^*}\frac{\partial x_i^*}{\partial p_k} = 0 \tag{9}$$

Substituting (9) into (8) gives:

$$\frac{\partial \pi^*}{\partial p_k} = y_k^* - \phi(0) = y_k^*(\mathbf{p}, \mathbf{w}, \mathbf{l}, \mathbf{z}). \tag{10}$$

Noting that from direct profit function π we have $\partial \pi / \partial p_k = y_k$, and from envelope theorem $\partial \pi^* / \partial p_k = \partial \pi / \partial p_k$ yields:

$$\frac{\partial \pi^*}{\partial p_k} = y_k^*(p_1, ..., p_m; w_1, ..., w_n; l_1, ..., l_s; z_1, ..., z_u) = y_k. \tag{11}$$

A similar method is used to calculate the optimal rth input demand function x_r^*, that yields:

$$\frac{\partial \pi^*}{\partial w_r} = -x_r^*(p_1, ..., p_m; w_1, ..., w_n; l_1, ..., l_s; z_1, ..., z_u) = -x_r. \tag{12}$$

Finally, producer maximizes his profit associated to each land allocation, with the constraint of total land available L. This constraint leads to say that marginal values of each land use are equal, and yields to:

$$\frac{\partial \pi(p, w, z, l)}{\partial l_1} = \frac{\partial \pi(p, w, z, l)}{\partial l_s} = \mu, \;\; s = 1, ..., S \tag{13}$$

were μ is the Lagrangian of land constraint that also can be interpreted as shadow price of land use s. Arnade and Kelch (2007) underlines that in an ideal world the shadow price must be equal to the price of land.

3 Empirical model specification

Following Chambers and Just (1989), we consider that the multi-crop profit function for a joint input technology with land as a fixed allocable factor. We specify the profit function as a normalized quadratic function. This functional form has been used widely in agricultural economics to model multi-output production (Bayramoglu and Chakir, 2016; Lacroix and Thomas, 2011; Fezzi and Bateman, 2011). The quadratic normalized profit function is locally flexible and self-dual (Lacroix and Thomas, 2011). This form allows negative profits which cannot be included in other specifications. The normalized quadratic profit function can be written as:

$$\begin{aligned}\bar{\Pi} = \alpha_0 &+ \sum_{c=1}^{C}\alpha_c\bar{p}_c + \sum_{k=1}^{K-1}\beta_k\bar{w}_k + \sum_{u=1}^{U}\theta_u z_u + \sum_{c=1}^{C}\gamma_c l_c + \frac{1}{2}\sum_{c=1}^{C}\sum_{c'=1}^{C}\alpha_{cc'}\bar{p}_c\bar{p}_{c'} + \frac{1}{2}\sum_{k=1}^{K-1}\sum_{k'=1}^{K-1}\beta_{kk'}\bar{w}_k\bar{w}_{k'} \\ &+ \frac{1}{2}\sum_{u=1}^{U}\sum_{u'=1}^{U}\theta_{uu'}z_u z_{u'} + \frac{1}{2}\sum_{c=1}^{C}\sum_{c'=1}^{C}\gamma_{cc'}l_c l_{c'} + \sum_{k=1}^{K-1}\sum_{c=1}^{C}\delta_{kc}^{pw}\bar{p}_c\bar{w}_k + \sum_{c=1}^{C}\sum_{u=1}^{U}\delta_{cu}^{pz}\bar{p}_c z_u \\ &+ \sum_{c=1}^{C}\sum_{c'=1}^{C}\delta_{cc'}^{pl}\bar{p}_c l_{c'} + \sum_{k=1}^{K-1}\sum_{c=1}^{C}\delta_{ck}^{wl}l_c\bar{w}_k + \sum_{k=1}^{K-1}\sum_{u=1}^{U}\delta_{uk}^{wz}z_u\bar{w}_k + \sum_{c=1}^{C}\sum_{u=1}^{U}\delta_{cu}^{lz}l_c z_u \\ &+ \lambda_c^{pL}\bar{p}_c L + \lambda_k^{wL}\bar{w}_c L + \lambda_u^{zL}z_u L + \lambda_s^{lL}l_s L,\end{aligned} \tag{14}$$

where $\bar{\Pi} = \Pi/w_k$, $\bar{p}_c = p_c/w_k$, $\bar{w}_k = w_k/w_k$, indicates respectively normalized profit, output price, input price, w_k is the price of the numeraire good, and z_c is the climate variables expressed as a squared relation. The normalized specification implies that the condition of linear homogeneity is automatically satisfied, and the symmetry is ensured by imposing $\alpha_{cc'} = \alpha_{c'c}$, $\beta_{kk'} = \beta_{k'k}$, $\theta_{cc'} = \theta_{c'c}$, and $\gamma_{cc'} = \gamma_{c'c}$ (Fezzi and Bateman, 2011). The profit function properties imply that the profit function is non-decreasing in the output prices p, non-increasing in the input prices w, homogeneous at degree 1 in the prices (p, w), convex in the prices (p, w), and continuous in the prices (p, w).

Differentiating the profit in equation (14) with respect to the output prices $\bar{p}_c$, the optimal output supply level for crop c can be expressed as follows:

$$y_c = \frac{\partial\bar{\Pi}}{\partial\bar{p}_c} = \alpha_c + \sum_{c'=1}^{C}\alpha_{cc'}\bar{p}_c + \sum_{k=1}^{K-1}\delta_{kc}^{pw}\bar{w}_k + \sum_{c'=1}^{C}\delta_{cc'}^{pz}z_{c'} + \lambda_c^{pL}L; \tag{15}$$

While differentiating the profit with respect to the input prices $\bar{w}_k$ yields the variable input demand equation:

$$-\ x_k = \frac{\partial\bar{\Pi}}{\partial\bar{w}_k} = \beta_k + \sum_{k'=1}^{K-1}\beta_{kk'}\bar{w}_k + \sum_{c=1}^{C}\delta_{ck}^{pw}\bar{p}_c + \sum_{c=1}^{C}\delta_{kc}^{wz}z_c + \lambda_k^{wL}L; \tag{16}$$

where only $K-1$ equations will appear in input's the demand function, because one of the inputs were utilized as a numeraire in the profit normalization process.

Optimal land use allocation could be derived by solving the following equations

$$\frac{\partial\bar{\Pi}}{\partial l_c} = \gamma_c + \sum_{c'=1}^{C}\gamma_{cc'}\bar{l}_{c'} + \sum_{c=1}^{C}\delta_{cc'}^{pr}\bar{p}_c + \sum_{k=1}^{K-1}\delta_{ck}^{wr}\bar{w}_c + \sum_{c'=1}^{C}\delta_{cc'}^{rz}z_{c'} + \lambda_s^{lL}L; \qquad \forall c = 1, ..., C \tag{17}$$

which lead to the following reduced form equations :

$$l_c = \Gamma_c + \sum_{c=1}^{C} \Delta_{cc'}^{pr} \bar{p}_c + \sum_{k=1}^{K-1} \Delta_{ck}^{wr} \bar{w}_c + \sum_{c'=1}^{C} \Delta_{cc'}^{rz} z_{c'} + \Lambda_s^{lL} L;$$

$$\forall c = 1, ..., C \quad (18)$$

with Γ, Δ, and Λ are the vectors of the parameters to be estimated, which are nonlinear combinations of the structural parameters in equation 17.

We need to impose the land adding-up condition $\sum_{c=1}^{C} l_c = L$, which imposes the following conditions on the parameters:

$$\sum_{c'=1}^{C} \gamma_{cc'} = \sum_{c=1}^{C} \delta_{cc'}^{pr} = \sum_{k=1}^{K-1} \delta_{ck}^{wr} = \sum_{c'=1}^{C} \delta_{cc'}^{rz} = 0 \quad (19)$$

$$\sum_{c=1}^{C} \lambda_c^{rL} = 1 \quad (20)$$

Elasticities can be calculated for the inputs, the outputs, and the land allocation with respect to prices, and in our case, the climate variables. For example, the elasticities associated to the output supply can be written as:

$$\varepsilon_{y_c \bar{p}_c} = \frac{\partial \bar{y}_c}{\partial \bar{p}_c} * \frac{\bar{p}_c}{\bar{y}_c} = \alpha_{cc'} * \frac{\bar{p}_c}{\bar{y}_c} \quad (21)$$

$$\varepsilon_{y_c \bar{w}_k} = \frac{\partial \bar{y}_c}{\partial \bar{w}_k} * \frac{\bar{w}_k}{\bar{y}_c} = \delta_{ck}^{pw} * \frac{\bar{w}_k}{\bar{y}_c} \quad (22)$$

While due to the squared variables, the elasticity of the climate variables can be written as:

$$\varepsilon_{y_c z_c} = \frac{\partial \bar{y}_c}{\partial z_c} * \frac{z_c}{\bar{y}_c} = (\delta_{cc'}^{pz} + 2 * \delta_{cc'}^{pz^2} * z_c) * \frac{z_c}{\bar{y}_c} \quad (23)$$

The elasticities of input demand and land allocation are calculated using the same principle.

4 Data description

The study is conducted on a sample of European farmers at the FADN region scale. The agricultural data are mainly from the FADN database for the time period 2004-2012. This study considers the two most common cultivated crops in Europe, wheat and maize. The FADN database provides information that can be associated directly to each of the two crops considered – wheat and corn output, and their surfaces. This information is aggregated directly, and applied at the FADN region level. The FADN database provides other data not associated specifically to wheat and maize production: the utilized agriculture land under irrigation, land rents, and total seed, and fertilizer at the individual farm level. We calculate seed costs per hectare to obtain an approximative seed input price used for prices normalization.

Data on fertilizer use and irrigated surface area are augmented by other information to provide more detailed data. First, the share of irrigated land associated to wheat and maize is re-estimated where possible based on information from the FADN database (e.g. if only maize is grown on the farm, the irrigated surface is associated directly to maize agriculture), otherwise we determine the approximative share of irrigated surface devoted to maize and wheat using AQUASTAT (FAO) data.

As already mentioned, the FADN database provides the total cost of fertilizers used by farmers. This input is important for our analysis, and to retain the variability in fertilizer use provided by the FADN database, we use these data to calculate fertilizer amounts. This requires data on fertilizer prices. We exploit EUROSTAT data on the prices of the three main macronutrients: Nitrogen (N), Phosphorus (P) and Potassium (K). Most fertilizers contain combinations of NPK. We calculate the average price by macronutrient and by country. Then, we use FAO data to calculate the proportional use of each macronutrient by country and by year (over our sample period 2004-2012), and estimate the fertilizer price by country and year. We uses these data on fertilizer price in our study. We divide total fertilizer cost provided in the FADN database by the fertilizer price obtained, to indicate the quantity of fertilizer used in each FADN region.

We use FAO data for information on wheat and maize prices by country and by year.

Finally, climate data are taken from the JRC database for the period 2004-2012. We consider the annual weather fluctuations in this study for following variables: winter, spring, summer, and autumn average temperature and precipitation.

5 Preliminary estimation results

We estimate the system of equations (15), (16) and (17) presented previously. We have seven equations estimated simultaneously: wheat output, maize output, fertilizer demand, irrigated wheat surface, irrigated maize surface, non-irrigated wheat area, and non-irrigated maize area. Five estimators are used to verify the robustness of the estimations: two Ordinary Least Squares (OLS) estimators based on cross-sectional data for 2004 and 2012, Pooled OLS estimator for the period 2004-2012, and two panel-data estimators which account for unobservable individual heterogeneity for the period 2004-2012: between estimator which takes away the temporal dimension of the panel data and captures long-term relations, and within estimator which takes away the individual dimension and estimates more short-run relations. We use the estimation results to calculate the elasticities of crop output supply, input demand, and the land allocation and irrigation decision, with respect to output and input prices, and weather conditions.

5.1 Output supply and input demand elasticities

The preliminary results in table 1 show the elasticities of wheat and maize output supply calculated at the sample mean and for all five estimators.

Table 1: Elasticities of output calculated at the sample mean

With respect to	Wheat output					Maize output				
	2004 OLS	2012 OLS	Pooled OLS	Within	Between	2004 OLS	2012 OLS	Pooled OLS	Within	Between
Wheat price	0.221	0.375	0.001	0.001	0.498	-0.444	0.162	-0.114	-0.133*	-1.045
	(0.527)	(0.842)	(0.112)	(0.036)	(0.545)	(1.158)	(2.372)	(0.273)	(0.080)	(1.451)
Maize price	-0.158	0.062	-0.038	-0.044*	-0.346	0.001	0.001	0.111	0.134*	1.513
	(0.413)	(0.913)	(0.090)	(0.027)	(0.481)	(1.063)	(2.753)	(0.264)	(0.073)	(1.528)
Fertilizer price	0.058	-0.433	0.033	0.060**	-0.160	-0.211	-0.149	-0.154	-0.047	-0.497
	(0.201)	(0.294)	(0.055)	(0.025)	(0.246)	(0.415)	(0.652)	(0.118)	(0.050)	(0.514)
Winter temp.	0.534	1.209**	0.353***	-0.022	4.617***	-0.199	-0.595*	-0.267***	0.060***	-0.811
	(0.830)	(0.520)	(0.090)	(0.029)	(0.989)	(0.525)	(0.350)	(0.064)	(0.023)	(0.592)
Spring temp.	-1.811	-1.342	0.241	0.268**	-6.257**	-0.487	-0.628	-0.186	0.032	-0.431
	(3.097)	(3.107)	(0.294)	(0.119)	(2.928)	(1.606)	(1.642)	(0.147)	(0.063)	(1.257)
Summer temp.	-0.217	1.558	0.217	-0.515**	7.652***	0.998	-0.440	-0.300**	0.091	-1.639*
	(1.867)	(1.570)	(0.261)	(0,247)	(2.051)	(0.959)	(0.824)	(0.123)	(0.122)	(0.895)
Autumn temp.	1.528	-1.740	-0.375	-0.008	-7.001**	-1.145	0.685	0.398**	0.032	2.053
	(2.842)	(2.631)	(0.402)	(0.126)	(3.387)	(1.575)	(1.497)	(0.200)	(0.065)	(1.593)
Winter prec.	0.095	0.100	0.060***	-0.004	0.139	-0.017	-0.066*	-0.013	0.003	-0.103**
	(0.095)	(0.066)	(0.019)	(0.006)	(0.113)	(0.053)	(0.037)	(0.010)	(0.003)	(0.054)
Spring prec.	-0.080	0.009	-0.021	0.011**	0.003	0.076	0.052	0.051***	-0.001	0.117
	(0.147)	(0.117)	(0.021)	(0.006)	(0.175)	(0.078)	(0.061)	(0.012)	(0.003)	(0.085)
Summer prec.	0.121*	0.136**	-0.009	-0.009*	0.160	-0.034	0.016	0.037***	-0.001	0.067
	(0.068)	(0.068)	(0.017)	(0.005)	(0.120)	(0.040)	(0.038)	(0.010)	(0.003)	(0.061)
Autumn prec.	-0.072	-0.001	0.034**	0.005	-0.188	0.042	0.049	-0.001	0.004	0.126*
	(0.076)	(0.075)	(0.016)	(0.005)	(0.141)	(0.041)	(0.041)	(0.009)	(0.003)	(0.067)

The results show that most of output-elasticities with respect to output prices are non significant, except the elasticity of maize production with respect to its own price (-0.134) and with respect to the price of wheat (0.133). Wheat production decreases very slightly with maize price (elasticity=-0.044) and increases very slightly with maize price (elasticity=0.060).

Concerning weather variables, some of them have significant impacts on wheat and maize output depending on the estimation method and in most cases the impacts are opposite between the two crops. For example, winter temperature and autumn temperature have negative impacts on wheat and positive impacts on maize production. Summer precipitation and temperature have mixed impacts on wheat production but have respectively positive and negative impacts on maize production.

Table 2 presents fertilizer demand for crops production. Fertilizer demand has a significant negative own-price elasticity that varies between -0.75 and -0.19 depending on estimators. These results are consistent with the literature (Lacroix and Thomas, 2011; Bayramoglu and Chakir, 2016). However, our results show that fertilizer demand is weakly affected by weather conditions and only summer temperature, winter and autumn precipitations have significant impacts in the Pooled OLS model.

5.2 Land allocated to irrigated and non-irrigated crop areas

Table 3 is based on the land allocation equation (17), and present the elasticities of land allocations to irrigated and non-irrigated wheat, and to irrigated and non-irrigated maize.

Our results show that the own-price elasticities of non-irrigated wheat allocation are not significant, and only Pooled OLS estimator suggests significant irrigated land allocation own-elasticity for wheat surface. Therefore, the own-price elasticities are significantly different from 0, and negative, for non-irrigated maize land allocation for the cross-sectional estimator calculated for 2004 and the Pooled-OLS estimator, and highly significantly positive for Pooled-OLS, Within

Table 2: Elasticities of fertilizer demand calculated at the sample mean

	Fertilizer demand				
	2004 OLS	2012 OLS	Pooled OLS	Within	Between
Wheat price	-0.067	0.642	-0.044	-0.079**	0.210
	(0.235)	(0.436)	(0.072)	(0.032)	(0.323)
Maize price	0.088	0.085	0.067	0.020	0.216
	(0.173)	(0.372)	(0.051)	(0.022)	(0.223)
Fertilizer price	-0.457**	-0.755*	-0.186***	-0.040	-0.500**
	(0.220)	(0.422)	(0.065)	(0.120)	(0.243)
Winter temperature	-0.082	0.035	-0.017	-0.052	-0.006
	(0.132)	(0.127)	(0.025)	(0.056)	(0.213)
Spring temperature	0.011	-0.292	-0.057	0.012	-0.177
	(0.200)	(0.229)	(0.04)2	(0.081)	(0.221)
Summer temperature	0.085	0.206	0.101***	0.003	0.149
	(0.135)	(0.180)	(0.032)	(0.080)	(0.208)
Autumn temperature	0.054	0.089	-0.008	-0.012	-0.024
	(0.235)	(0.269)	(0.035)	(0.058)	(0.376)
Winter precipitation	0.011	0.009	0.007***	0.004	0.016
	(0.008)	(0.007)	(0.002)	(0.004)	(0.010)
Spring precipitation	-0.009	0.001	-0.003	0.001	0.003
	(0.009)	(0.009)	(0.002)	(0.004)	(0.016)
Summer precipitation	0.002	0.005	-0.003	-0.002	-0.010
	(0.008)	(0.008)	(0.002)	(0.004)	(0.013)
Autumn precipitation	-0.006	-0.009	-0.003*	-0.003	-0.008
	(0.006)	(0.007)	(0.002)	(0.003)	(0.013)

and Between estimators for land allocation to irrigated maize. This means that, when maize price increases farmers would prefer to allocate more land to irrigated than to non-irrigated maize.

Interesting results are found on land allocation elasticities with respect to fertilizer price. The majority of significant fertilizer price coefficients for land allocation to non-irrigated crops are negative, while for irrigated crops the elasticity coefficients are positive. These results suggest that the increase of fertilizer price will encourage farmers to allocate their land to irrigated crops, and thus, to reduce land allocation to non-irrigated crops. Fertilizer is usually considered as a risk-increasing input since it increases the expected crop yield and its variance.

Most of elasticities associated with irrigated wheat land area with respect to weather variables are not significant. Although, irrigating wheat is less common practice than irrigating maize. In consequence, the irrigated wheat surface in our data represents, in average, only about 3% of non-irrigated wheat surface, leading to a possible underestimation of climate impacts. However, for other land allocations, climate impacts are strongly dependent on the estimated model.

First, the annual cross-sectional models emphasize that weather variables impacts more land allocation for maize than for wheat, as there is less significant coefficients for wheat land allocation than for maize. Except the within estimator, all other estimators show that an increase of average winter temperature affects significantly and negatively non-irrigated maize surface and positively wheat area in the between and pooled OLS estimations. Winter temperature does not seem to have any significant impact on irrigated areas of both maize and wheat which are more sensitive to spring precipitation. Farmers would also be encouraged to irrigate maize if the average summer temperature increases, increasing high heat risk to maize, and reduce land use for irrigated maize if temperature increases in autumn. In contrary, warmer summer would decrease land allocation to non-irrigated maize and to irrigated wheat.

Second, most of Pooled-OLS and between estimators highlights the significant weather im-

Table 3: Elasticities of land allocation calculated at the sample mean

With respect to	Non-irrigated wheat land allocation					Non-irrigated maize land allocation				
	2004 OLS	2012 OLS	Pooled OLS	Within	Between	2004 OLS	2012 OLS	Pooled OLS	Within	Between
Wheat price	-0.089	-0.082	0.039	0.017	0.137	1.973	1.731	0.759**	0.079	2.382
	(0.316)	(1.006)	(0.073)	(0.019)	(0.413)	(1.282)	(4.478)	(0.347)	(0.134)	(2.194)
Maize price	0.175	0.466	-0.002	-0.022	0.024	-1.852*	-3.506	-0.564*	-0.020	-3.554
	(0.282)	(1.102)	(0.068)	(0.017)	(0.417)	(1.126)	(4.922)	(0.324)	(0.114)	(2.239)
Fertilizer price	0.092	-0.362*	-0.006	0.016	-0.157	-0.835*	1.697*	-0.397**	-0.108	1.146
	(0.111)	(0.199)	(0.031)	(0.011)	(0.153)	(0.468)	(0.909)	(0.155)	(0.076)	(0.858)
Winter temp.	0.113	0.807	0.277***	-0.038**	3.515***	-1.272***	-0.991**	-0.350***	0.015	-3.669***
	(0.624)	(0.523)	(0.073)	(0.019)	(0.827)	(0.314)	(0.491)	(0.053)	(0.023)	(0.670)
Spring temp.	0.355	2.172	0.769***	0.002	-2.026	2.031***	0.781	0.270***	-0.013	4.743***
	(2.448)	(3.509)	(0.254)	(0.085)	(2.598)	(0.681)	(2.176)	(0.089)	(0.043)	(0.947)
Summer temp.	-1.088	0.995	0.753***	0.133	7.083***	-0.736*	-1.060	-0.055	-0.124*	-4.145***
	(1.431)	(1.656)	(0.226)	(0.177)	(1.782)	(0.431)	(1.083)	(0.067)	(0.068)	(0.743)
Autumn temp.	1.737	-2.184	-0.770**	-0.139	-7.340**	-0.024	0.938	0.122	0.055	3.818***
	(2.188)	(2.865)	(0.347)	(0.091)	(2.934)	(0.769)	(1.991)	(0.107)	(0.039)	(1.439)
Winter prec.	0.003	0.087	0.026*	-0.001	0.134	-0.002	0.023	-0.001	0.008***	-0.048
	(0.072)	(0.069)	(0.016)	(0.004)	(0.097)	(0.027)	(0.050)	(0.006)	(0.002)	(0.046)
Spring prec.	-0.104	-0.055	-0.066***	-0.002	-0.016	0.064*	-0.003	0.025***	-0.001	-0.134*
	(0.113)	(0.122)	(0.018)	(0.004)	(0.152)	(0.036)	(0.080)	(0.007)	(0.002)	(0.075)
Summer prec.	0.080	0.026	-0.046***	0.002	-0.040	-0.050**	-0.035	0.020***	-0.005**	0.014
	(0.051)	(0.070)	(0.015)	(0.004)	(0.103)	(0.022)	(0.050)	(0.006)	(0.002)	(0.056)
Autumn prec.	-0.042	-0.030	0.007	-0.005	-0.244**	0.032	-0.005	-0.002	0.004*	0.168***
	(0.058)	(0.079)	(0.014)	(0.003)	(0.121)	(0.020)	(0.055)	(0.006)	(0.002)	(0.059)
With respect to	Irrigated wheat land allocation					Irrigated maize land allocation				
	2004 OLS	2012 OLS	Pooled OLS	Within	Between	2004 OLS	2012 OLS	Pooled OLS	Within	Between
Wheat price	-0.705	-3.371	-0.741*	0.080	-2.380	-1.965	-1.873	-1.384***	-0.349*	-4.498**
	(1.558)	(5.129)	(0.400)	(0.235)	(1.999)	(1.817)	(4.614)	(0.409)	(0.198)	(2.162)
Maize price	0.455	3.120	0.122	-0.064	1.821	1.065	2.013	0.913**	0.300*	4.904**
	(1.373)	(5.894)	(0.378)	(0.198)	(2.138)	(1.650)	(5.278)	(0.392)	(0.168)	(2.312)
Fertilizer price	0.227	0.242	0.722***	-0.010	0.562	0.354	-0.196	0.435**	0.004	-0.406
	(0.594)	(1.324)	(0.185)	(0.133)	(0.747)	(0.673)	(1.166)	(0.183)	(0.113)	(0.787)
Winter temp.	-0.204	0.010	-0.022	-0.001	-0.196	0.334	-0.136	-0.040	0.021	0.139
	(0.146)	(0.147)	(0.028)	(0.019)	(0.216)	(0.257)	(0.207)	(0.042)	(0.023)	(0.360)
Spring temp.	1.302	0.260	0.349***	0.081	1.098	-0.122	0.563	0.387***	0.044	0.501
	(1.051)	(1.080)	(0.134)	(0.078)	(0.927)	(0.427)	(0.410)	(0.081)	(0.036)	(0.439)
Summer temp.	-1.351**	-0.736	-0.101	-0.020	-1.316**	0.767***	-0.093	0.264***	0.044	0.203
	(0.586)	(0.546)	(0.123)	(0.163)	(0.659)	(0.276)	(0.308)	(0.067)	(0.045)	(0.394)
Autumn temp.	0.913	-0.101	-0.055	-0.044	0.743	-0.919**	0.108	-0.207***	-0.051*	-0.202
	(0.720)	(0.678)	(0.150)	(0.081)	(0.878)	(0.442)	(0.406)	(0.066)	(0.028)	(0.648)
Winter prec.	0.011	0.014	0.006	0.002	-0.002	-0.007	-0.027**	-0.008***	-0.004***	-0.027*
	(0.021)	(0.014)	(0.004)	(0.002)	(0.021)	(0.015)	(0.010)	(0.003)	(0.001)	(0.014)
Spring prec.	-0.039	-0.026	-0.003	-0.001	-0.069**	0.019	0.041***	0.017***	-0.001	0.074***
	(0.040)	(0.033)	(0.005)	(0.003)	(0.028)	(0.018)	(0.014)	(0.003)	(0.002)	(0.021)
Summer prec.	0.027**	0.006	0.001	-0.002	0.017	-0.015	0.009	0.002	0.001	-0.001
	(0.012)	(0.016)	(0.004)	(0.002)	(0.017)	(0.015)	(0.011)	(0.003)	(0.001)	(0.020)
Autumn prec.	0.007	0.006	0.002	-0.001	0.019	-0.002	-0.002	-0.001	0.001	-0.008
	(0.020)	(0.016)	(0.004)	(0.002)	(0.025)	(0.013)	(0.009)	(0.002)	(0.001)	(0.018)

pacts for all crops suggesting dominant opposite effects for land allocation to wheat and maize. Warmer winter and summer should benefit to wheat, thus farmers would be incited to allocate more land for wheat production, in distress to land allocation for maize production.

6 Discussion and conclusion

In this paper we propose a novel approach to measure how climate affects agriculture, and more precisely different components of agriculture: output supply, input demand, and land allocation with the choice to irrigate or not. To test the suggested method the challenge was taken to test the method at the European level, and matching the FADN region scale.

To summarize our preliminary results, first, we observe an important role of temperature variables to wheat output. This is not surprising as wheat production takes an important place in European agriculture, with it's particularity to be winter or summer crop, and thus being quite

depending on climate conditions all over a year. Moreover, weather variables are shown to have significant effect on maize output, and seems to have effects contrary to those for wheat output. These results supports the spatial distribution of the choices of dominant crops in Europe since their production is very strongly impacted by climatic conditions.
Second, the majority of significant fertilizer price coefficients for land allocation to non-irrigated crops are negative, while for irrigated crops the elasticity coefficients are positive. These results indicates that the increase of fertilizer price will encourage farmers to allocate their land to irrigated crops and to increase the production potential, and thus, to reduce land allocation to non-irrigated crops. This observation confirms the complementary use of fertilizers when crops are irrigated.
Finally, we found that warmer summers would lead farmers to increase non-irrigated and to decrease irrigated wheat areas at the opposite of maize for which it imply an increase in irrigated areas and a decrease in non-irrigated ones. In contrary, warmer autumn, would play in favour with land allocation to non-irrigated maize at the expense of irrigated maize and non-irrigated wheat.

In this paper we suggest a method based on production economics theoretic background developed by Chambers and Just (1989), and we have found some promising preliminary results. The method is complex and can bring important information about climate impacts, as it analyses simultaneously agricultural outputs, but also inputs and land allocation choices. Nevertheless, some improvements could be made for later considerations. First of all, from methodological point of view, the estimations should also be improved by the spatial econometric modelling taking into account spatial autocorrelation.
Secondly, we noted that this method is complex to apply at a large European scale and to aggregated data, thus the method could be more precise and bring important results at small local scale with individual data. Of cause, there is a need to have a global European vision of the future climate change impacts in order to have a reflection on policy implications, but also local ones (Pe'Er et al., 2019). The European territory is large, regrouping multiple agricultural practices, historical and cultural backgrounds, and agro-climatic regions, resulting in a numerous regions with strong local characteristics. Identifying local strengths and vulnerabilities in climate change context can enable consideration of planning adaptation strategies at the local level, through sensitization of farmers and local agents, such as water management agencies. Therefore, this objective is articulated well with our research work to continue study the short term climate effects on agriculture with the method proposed in this paper.
Thirdly, this production approach could permit to consider diversification as a strategy for climate resilience and farms sustainability. We have identified very few studies on the resilience via diversification, based on divers approaches, that could be the point of departure to study European farms diversification as adaptation strategy. For example, Kandulu et al. (2012) model effects of diversification on the sensitivity to climate change and its economic consequences on Australia. They quantify the variability of yields and margins for four systems. Kandulu et al.

(2012) show in their results that diversification is beneficial in rainfed areas, but the effects are less interesting in irrigated areas. **?** suggests a systemic study of a group of farmers in the US who have set up a set of practices to deal with drought, where, among other things, they considered the diversification of their rotation. Finally, Antwi-Agyei et al. (2012) study the resilience of farms in Ghana to climate change. They suggest that the diversity of crops enhances the ability of farms to adapt and therefore their resilience. Their results show that mixed systems are attractive under certain conditions, for example, if the capacity of irrigation and cattle feeding is limiting. Thus, these considerations and our preliminary results show some promising leads in terms of diversification strategies, but also in terms of irrigation as adaptation strategy. The current application is based on two main crops, wheat and maize, and in order to improve the estimation results we are going to consider, in later improvements, other crops in addition to wheat and maize. It should represent a larger European agricultural landscape and more options that farmers are exposed to.

Finally, in current study we consider only one input, fertilizer. However, knowing that irrigation is closely depending on water availability and should also depend on water price, the later work will introduce water as a second input. Indeed, considering water as an input would make it possible to study the sensitivity of outputs, inputs but also the choices of allocation of agricultural land in connection with water and in the context of climate change. The availability of water itself being highly exposed to climatic vagaries would make it possible to have a more precise vision, and to quantify, marginal impacts due to the water scarcity.

References

Antwi-Agyei, P., Fraser, E. D., Dougill, A. J., Stringer, L. C. and Simelton, E. (2012). Mapping the vulnerability of crop production to drought in ghana using rainfall, yield and socioeconomic data. *Applied Geography* 32: 324–334.

Arnade, C. and Kelch, D. (2007). Estimation of area elasticities from a standard profit function. *American Journal of Agricultural Economics 89, 727-737* .

Bayramoglu, B. and Chakir, R. (2016). The impact of high crop prices on the use of agrochemical inputs in france: A structural econometric analysis. *Land Use Policy* 55: 204–211.

Chambers, R. G. and Just, R. E. (1989). Estimating multioutput technologies. *American Journal of Agricultural Economics* 71: 980–995.

Deschenes, O. and Greenstone, M. (2007). The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. *The American Economic Review* : 354–385.

EEA (2017). Climate change, impacts and vulnerability in Europe 2016. Tech. rep., Report No 1/2017.

EU (2016). The European Union Explained: Agriculture. Tech. rep.

FAO (2017). The future of food and agriculture Ű trends and challenges. *Rome* .

Fezzi, C. and Bateman, I. J. (2011). Structural agricultural land use modeling for spatial agro-environmental policy analysis. *American Journal of Agricultural Economics* 93: 1168–1188.

Gorddard, R. (2013). Profit-maximizing land-use revisited: the testable implications of non-joint crop production under land constraint. *American Journal of Agricultural Economics 95(5), 1109-1121* .

Iglesias, A., Garrote, L., Quiroga, S. and Moneo, M. (2012). A regional comparison of the effects of climate change on agricultural crops in europe. *Climatic Change* 112: 29–46.

Kandulu, J. M., Bryan, B. A., King, D. and Connor, J. D. (2012). Mitigating economic risk from climate variability in rain-fed agriculture through enterprise mix diversification. *Ecological economics* 79: 105–112.

Kurukulasuriya, P. and Rosenthal, S. (2003). Climate change and agriculture: A review of impacts and adaptations .

Lacroix, A. and Thomas, A. (2011). Estimating the environmental impact of land and production decisions with multivariate selection rules and panel data. *American Journal of Agricultural Economics 93(3), 784-802* .

Laukkanen, M. and Nauges, C. (2014). Evaluationg greening farm policies: a structural model for assessing agri-environmental subsidies. *Land Economics 90(3), 458-481* .

Lobell, D., Schlenker, W. and Costa-Roberts, J. (????). Trends and global crop production since 1980. *Science, DOI* 2011.

Mendelsohn, R., Nordhaus, W. D. and Shaw, D. (1994). The impact of global warming on agriculture: A Ricardian analysis. *American Economic Review* 84: 753–771.

Mendelsohn, R. O. and Dinar, A. (2009). *Climate change and agriculture: an economic analysis of global impacts, adaptation and distributional effects*. Edward Elgar Publishing.

Moore, R. and Negri, D. (1994). Multicrop production decisions in western irrigated agriculture: the role of water price. *American Journal of Agricultural Economics 76(4), 859-874* .

Nelson, G. C., Valin, H., Sands, R. D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., Von Lampe, M., Lotze-Campen, H., Mason dŠCroz, D., Meijl, H. van, Mensbrugghe, D. van der, Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Schmitz, C., Tabeau, A. and Willenbockel, D. (2014). Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences* 111: 3274–3279, doi:10.1073/pnas.1222465110.

Ortiz-Bobea, A. and Just, R. E. (2012). Modeling the structure of adaptation in climate change impact assessment. *American Journal of Agricultural Economics 95(2), 244-251* .

Pe'Er, G., Zinngrebe, Y., Moreira, F., Sirami, C., Schindler, S., Müller, R., Bontzorlos, V., Clough, D., Bezák, P., Bonn, A. et al. (2019). A greener path for the eu common agricultural policy. *Science* 365: 449–451.

Rosenzweig, C., Parry, M. L. et al. (1994). Potential impact of climate change on world food supply. *Nature* 367: 133–138.

Vaitkeviciute, J., Chakir, R. and Van Passel, S. (2019). Climate variable choice in ricardian studies of european agriculture. *Revue économique* 70.

Van Passel, S., Massetti, E. and Mendelsohn, R. (2017). A ricardian analysis of the impact of climate change on european agriculture. *Environmental and Resource Economics* 67: 725–760.

Vanschoenwinkel, J., Mendelsohn, R. and Van Passel, S. (2016). Do western and eastern europe have the same agricultural climate response? taking adaptive capacity into account. *Global Environmental Change* 41: 74–87.

Vanschoenwinkel, J. and Van Passel, S. (2018). Climate response of rainfed versus irrigated farms: the bias of farm heterogeneity in irrigation. *Climatic Change* : 1–10.