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Impact of climate change on maize's water needs, yields and profitability under various water prices in Spain

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Abstract

Available water resources are expected to diminish in the Iberian Peninsula as a result of climate change (CC). Agricultural water use represents about 70% of all water uses in Spain. This paper uses a combination of an ensemble of climate change and crop models to analyze the impacts on maize's water needs, yields and economic profitability under various water prices. Maize's evapotranspiration (ET), irrigation needs and yield projections under CC are compared with those of current climate in nine sites of Spain. With these simulated data, maize's and water's prices are included in a stochastic model to simulate the crop's net margin, both under CC and current climate conditions. An adaptation strategy potentially useful for maize in Spain is also studied. Results show that such adaptation can reduce negative CC impact on yields. However, decreases in ET and irrigation needs will be lower with than without adaptation. This creates an ambiguous situation which can be affected or solved with water pricing policies. With higher water tariffs, crop's profitability can drop to negative levels, which may result in the abandoning of the crop in many areas. CC and water policies must be closely coordinated to ensure efficient water use and crops' profitability.

Additional key words: adaptation; evapotranspiration; net margin; Regional Climate Models; uncertainty; *Zea mays* L.

Resumen

Impacto del cambio climático en el rendimiento y en las necesidades hídricas del maíz, y su rentabilidad bajo diferentes precios del agua en España

La disponibilidad de recursos hídricos en la Península Ibérica va a disminuir como consecuencia del cambio climático (CC). En España, el regadío representa cerca del 70% de la demanda total de agua. Este trabajo utiliza un conjunto de modelos climáticos y de cultivo para analizar el impacto en las necesidades hídricas del maíz, en su rendimiento, y en su margen neto bajo diferentes tarifas de agua. Las proyecciones de rendimiento, evapotranspiración (ET) y riego del maíz en el clima futuro han sido comparadas con las del clima actual en nueve zonas de España. También se han evaluado los datos relativos a una posible estrategia de adaptación de este cultivo. Los resultados muestran que esta estrategia puede reducir los impactos negativos del CC en el rendimiento del maíz. Sin embargo, la ET y la necesidad de riego serán mayores con adaptación que sin ella. Esto crea un efecto ambiguo, que puede verse afectado o resolverse con políticas de tarifación del agua. Con mayores niveles de tarifas, debido a una mayor escasez de recursos hídricos disponibles consecuencia del CC, la rentabilidad del maíz puede llegar a caer hasta valores negativos, lo que llevaría a su abandono en algunas zonas. Las políticas de CC y de agua deben estar bien coordinadas con el fin de asegurar la eficiencia del uso del agua, y la rentabilidad de los cultivos.

Palabras clave adicionales: adaptación; evapotranspiración; incertidumbre; margen neto; Modelos Regionales de Clima; *Zea mays* L.

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Abbreviations used: CAP (Common Agricultural Policy); CC (Climate Change); CT (Total Costs); DSSAT (Decision Support System for Agrotechnology Transfer); ET (Evapotranspiration); RCM (Regional Climate Model); SB (Subsidy); WFD (Water Framework Directive); WUE (Water Use Efficiency).

Introduction

The water cycle depends on climate. So, CC (Climate Change) will impact all water cycle's elements (Fernández, 2002; Bates *et al.*, 2008). The Mediterranean region will be among the most affected world regions in terms of reduced precipitation and increased frequency of extreme events (Giannakapoulos *et al*., 2005; Bates *et al*., 2008; Iglesias and Quiroga, 2009; Dono and Mazzapicchio, 2010; Kolokytha, 2010). While drought stands among the largest nature catastrophes, irrigation is the major adaptation strategy to combat meteorological droughts, because it increases crop yields and reduces the risk of crop failure (Hoff *et al.*, 2009). But existing irrigated areas are threatened by increasing water scarcity in many regions.

CC is expected to cause a mean reduction of 17% of water resources in the Iberian Peninsula, mainly in the south (Ayala-Carcedo, 1996; Iglesias *et al.*, 2005). In semiarid areas, available water resources decreases may be equivalent to 50% of the potential resources of the region (Iglesias *et al.*, 2005; Moreno, 2005). It is projected that precipitation in Spain will decrease by 30% in the south and 5% in the north (Rodriguez-Puebla and Nieto, 2009). PRUDENCE Project (http://prudence.dmi.dk/) developed different Climate Models in order to project the impacts of CC on different climatic variables in Europe. Here, we use a model ensemble to obtain the impacts of CC on maize's (*Zea mays L.)* yield and water requirements in Spain.

In the future climate, photosynthesis activity will increase and stomatal conductance will be lower. Therefore, crops' water use efficiency will be higher. Changes in crop's water needs will depend on CC, the thermal requirements of each crop, and the period of the year in which the crop grows. It may be necessary to replace high water-demanding crops (rice, maize) in some areas, and to stop the irrigation of inadequate soils (Iglesias *et al.*, 2005).

Crops' ET (Evapotranspiration) rate will increase due to higher temperatures, and this will lead to greater water needs (Moratiel *et al.*, 2010). However, even if traditional varieties and sowing dates are maintained, crops' cycle will be shortened because of higher temperatures, and this has the opposite effect on crops' total water needs. The decrease in maize's ET could be caused by decreases in growing days and in Leaf Area Index due to higher temperatures, and a lower transpiration due to stomata closure caused by a higher concentration of CO_2 (Yano *et al.*, 2007). The development of more resistant varieties to water stress and diversification strategies could reduce vulnerability. However, controversy exists about whether improved yields under drought conditions must come at the expense of yields in the seasons when the rainfall is favorable (Brown and Hansen, 2008). CC is going to have a wide range of impacts on agriculture, and there is a great deal of uncertainty in the implications that this might have for water management and water policy. The uncertainty of CC's projections makes it difficult to develop and implement adaptations strategies. Small changes in agricultural water use can have significant economic and hydrological impacts (Quiroga *et al.*, 2010). Water policy faces the dilemma of ensuring water resources sustainability in the future, while maintaining the strategic targets of agriculture, society and environment (Iglesias *et al.*, 2006; Calzadilla *et al.*, 2008).

In Spain, irrigation is the main water consumer, accounting for about 70% of total water demand (Iglesias *et al.*, 2003; Rodríguez Díaz *et al.*, 2007), so it is the most threatened sector by water scarcity. Many water bodies in Spain are at risk of not being able to comply with the requirements of the Water Framework Directive (WFD). Due to the increasing water scarcity in some basins, the development of water policies to control demand because of the water mismanagement in Spanish irrigated land was needed (Gómez-Limón and Riesgo, 2004). The WFD aims at establishing a common framework for the management of water resources at the European level for the achievement of the good ecological status. One of the most important mechanisms is the reform of water tariffs. However, due to the low elasticity of agriculture water demand, among other factors, pricing policies may not deliver the expected results (Molle and Berkoff, 2007).

According to Gómez-Limón and Riesgo (2004), with higher water tariffs, crops' net margin would fall for two reasons: the payment of tariffs, and the removal of crops with high water demand. As in other countries, in Spain farmers pay a price for water that hardly covers the supply costs. In fact, with current tariffs only operating and maintenance costs are covered (Gómez-Limón and Riesgo, 2004; Calatrava and Garrido, 2010; Kolokytha, 2010).

Future crops' net margin will be affected by CC impacts on crops' water needs, water productivity, yield and water pricing, among other factors. It is impossible to know exactly the magnitude of the change due to the joint uncertainties of all variables affecting crops' net margin (Challinor, 2009). Changes in water needs will affect maize's profitability if more water is needed for irrigation. Also, as water will be scarcer in the future, prices are expected to rise, increasing farmer's costs. New policies and instruments will have to be developed to face the problem of water scarcity in Spain. Knowing how CC could affect Spanish agriculture is the first step to fight against the negative impacts of new climatic conditions. These results could be applied to other Mediterranean countries, where water availability is facing the same problems than in Spain. The results anticipate the role that water pricing, coupled with CC impacts, may have on farmers' incentives to adapt their cropping systems.

The aim of this paper was to analyze CC impacts on maize's water needs and yield in Spain and how it may threaten the profitability of this crop. Comparing the projections of yield and water needs for maize in different sites of the Iberian Peninsula between two periods (1961-1990 and 2071-2100), some conclusions about CC impacts on maize's profitability can be advanced. The analysis of the CC impacts on maize's yield and water needs enables to obtain a general idea of how CC will impact water needs of summer crops in Spain. Irrigated maize is considered as a reference crop. This crop was chosen because it works well with the climate models, it is a very important crop in Spain, and adaptation strategies have been developed for maize for the future climate in this country. This permits analyzing the effects of adaptation on maize's yield, ET and irrigation needs. Also, analyzing the projections obtained by the 10 RCMs (Regional Climate Models), the performance of each RCM applied onto the Iberian Peninsula and the uncertainty associated to the projections are studied.

Material and methods

The analyses focus on projections of yield, ET and irrigation needs of maize, obtained from the climate projections provided by 10 Regional Climate Models[1] (RCMs, PRUDENCE Project) applied onto Spain. These data were introduced in the crop model CERES-Maize (DSSAT[2]; Jones *et al.*, 2003), which provide data of maize's yield, ET and irrigation requirements. Through the comparison between control period data (29 years, 1961-1990) and future climate data (29 years, 2071-2100, A2 scenario; IPCC, 2000), it is possible to estimate changes in maize's ET, water needs and yield because of CC, in nine sites of Spain. These sites are shown in Figure 1.

RCMs, with a resolution of 50 × 50 km to 20 × 20 km, have been calibrated and validated with historical data (Jacob *et al.*, 2007). They enable to analyse CC impacts in a specific area and thus achieve a description of the effects linked to the features of each site under study.

Simulations with irrigation were done with no limiting water. The automatic irrigation option was set with 0.85 irrigation efficiency and 300 mm irrigation depth. Watering was done when soil water content reached a threshold of allowable depletion of 90% (Ruiz-Ramos and Mínguez, 2010). The simulations were done in such a way that the crop was not suffering water stress in any moment of the cycle. So, irrigation requirements' values used in this work could be higher than those observed in reality.

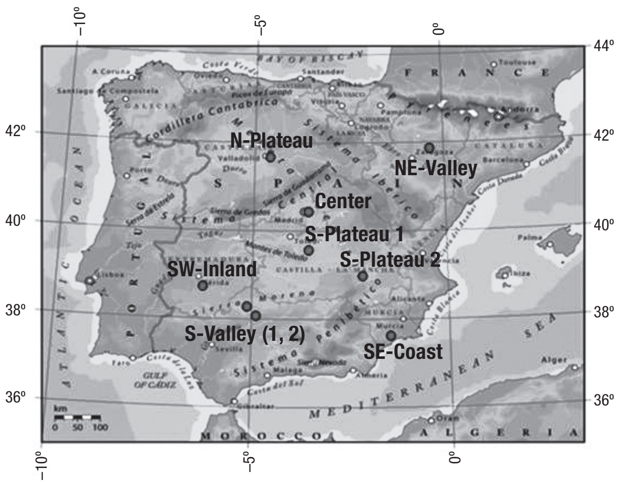

Figure 1. Iberian Peninsula. Sites under study: Albacete (S-Plateau 2), Badajoz (SW-Inland), Córdoba (S-Valley 1 and 2, two sites with different soil type), Valladolid (N-Plateau), Zaragoza (NE- Valley), Toledo (S-Plateau 1), Madrid (Center) and Murcia (SE-Coast).

[1] The 10 RCMs that make up the climate ensemble are: HIRHAM (DMI), ARPEGE (CNRM), HadRM3H (HC), CHRM (ETH), CLM (GKSS), REMO (MPI), RCAO (SMHI), PROMES (UCLM), RegCM (ICTP) and RACMO (KNMI). Eight RCMs were nested in the HadAM3H while two RCMs, ARPEGE and RCAO, used the boundary conditions of the AOGCMs ARPÈGE/OPA and ECHAM/OPYC4, respectively (Christensen and Christensen, 2007).

[2] Decision Support System for Agrotechnology Transfer.

Comparison between RCMs: cluster analysis

A very important issue in studies of CC is the analysis of projections' uncertainty. Iglesias *et al.* (2010) evaluated the potential impacts of CC in different crops and sites of Spain, using several climatic models, scenarios and crops, to analyze the uncertainty associated with them. Ruiz-Ramos and Mínguez (2010) also evaluated the uncertainty in CC impacts on yield of maize and wheat in the Iberian Peninsula. To evaluate this issue in this work, a cluster analysis has been performed to highlight the differences between projections obtained from each RCM.

For each site, a cluster analysis has been made using ET data of the future climate. The target of this analysis is to classify the ten ensemble members in different groups or categories according to the annual ET values that were estimated for maize in this period (28 years between 2071-2100). Then, it can be analyzed how ensemble members spread in these clusters.

The selection of the appropriate number of clusters for each site has been carried out using various statistical tests. The value of the adjusted R^2 for each instance was the main factor taken into account in the selection of the number of clusters. Thus, starting from an initial number of clusters (k = 3), this number has been increased until the difference between the adjusted R^2 for n and for $n + 1$ clusters is negligible. At this point, n clusters for a particular site were chosen, because the other statistical tests (ANOVA, discriminate analysis and Mahalanobis distances) support this decision. The same cluster analysis described above was conducted using yield projections of the future period, to study the uncertainty associated with these data.

Means and variance comparison tests for maize's ET, yield and irrigation needs

These analyses test if the difference of yield, ET and irrigation needs between the two periods [control (1961-1990) and future climate (2071-2100)] is significant. With the analysis of the variance we know whether the variability of ET, yield or irrigation requirements in the future climate will be higher or lower than in the control period (Levene's test helps us determine whether the difference is significant or not). In these tests, the set of values of ET (or yield or irrigation needs) obtained by the ten ensemble members in a given site for the control period (290 data) is compared with the set of data for the same site corresponding to the 29 years of the future period (290 data).

Also, an adaptation strategy for maize in Spain is included in the analysis. This adaptation strategy consists in changing the current variety (PRU001, 700 FAO cycle) with another variety better adapted to the new climatic conditions (PRUAD1 long season AD) and in sowing earlier, *ca.* 2.5 months. PRUAD1 has longer growth duration, smaller photoperiod sensitivity, larger thermal period for leaf appearance, and a longer grain filling duration. Kernel growth and cob kernel number are kept the same. This adaptation strategy aims to reduce the negative impacts of CC on maize's yield.

Means-comparison and variance tests were also used to compare the yield, ET and irrigation needs in the control period, and in the future climate, with the data related to the adaptation strategy. Thus, the effects of this adaptation strategy are evaluated.

Maize's water use efficiency

A crucial element for agricultural water policy is to know how is going to change water use efficiency (WUE) due to new climatic conditions. The ratio yield/ET for each site for two periods, control and future climate is calculated.

$$\mathrm{WUE}_{i,j,m,n} = \frac{\mathrm{Yield}_{i,j,m,n}}{\mathrm{ET}_{i,j,m,n}} \qquad [1]$$

where i denotes site (1,…, 9); j period (0,1,2) control, A2 or A2 with adaptation; the year (1,…,29), and n the RCM (1,…10). Comparing this ratio between two periods, it is possible to determine whether maize could become more water efficient because of CC than under current conditions. In those sites in which the decrease of yield is less marked than ET's decrease because of CC, WUE will improve. The impact of adaptation in maize's WUE is also studied.

Economic analysis

This analysis aims to evaluate how maize's net margin would be affected by different water tariffs, which are likely to increase due to higher water shortages in future climate, and also because of the revision of water tariffs in application of the full cost recovery principle of the WFD. Yield and irrigation requirements data projected by the ten ensemble members for each site and period were used for the analysis (290 data in total, per site and climate assumption). For each case, the distribution function that provided the best fit with the data was identified[3]. The distribution function for maize's price[4] (Log logistic, p value = 0.8810) was obtained using annual data related to the period 1991-2008, in € kg^{-1}.

Knowing the distribution function for yield, irrigation needs and price of maize, and establishing six different water tariffs, between € 0.05 and 0.20 m^{-3}, Monte Carlo simulations were performed. Results show maize's net margin could change depending on the period and the water price in each case, from a simple formula:

$$\text{Net margin}_{i,j,k} = \left(\tilde{R}_{i,j} \times \widetilde{Pm}\right) - \left(\tilde{W}_{i,j} \times Pw_k\right) - CT + SB \quad [2]$$

where $\widetilde{Pm}$ denotes maize's stochastic price; $\tilde{R}$ stochastic yield; $\tilde{W}$ irrigation stochastic needs; i site (1,…, 9); j period (0,1,2): control (1961-1990), A2 or A2 with adaptation (2071-2100); and Pw_k the water price level, which can take six different values in the simulations (in € m^{-3}): 0.05 (Pw_1), 0.07 (Pw_2), 0.10 (Pw_3), 0.12 (Pw_4), 0.15 (Pw_5) and 0.20 (Pw_6). Thus, the impact of different water's tariff levels on maize's net margin is studied. CT represents crop's total costs; and SB the CAP subsidy for maize[5].

Results

Uncertainty analysis. Differences between RCMs

Table 1a shows the number of clusters for each site (5 clusters, except in S-Plateau 2 and SE-Coast, in which the adequate number of clusters is 4, based on previous statistical tests). Highest ET values are in cluster 1, ranging in descending order up to cluster 5, which contain lowest ET values obtained by the ten ensemble members. Table 1 shows those ensemble members which appear in every cluster with a frequency higher than 15 of 28 years (the frequency is shown in brackets). The ensemble members with the superscript "*" are those that we consider assigned to a particular cluster, as more than 21 of the 28 years belong to a single cluster. Clusters 3 and 4 are those which contain more quantity of data in all sites, so middle values of ET are the most frequent in the database.

Results from cluster analysis applied to yield data are very different to those obtained from ET data. As shown in Table 1b, there is hardly any case in which an ensemble member can be considered assigned to a particular cluster. In general, yield projections obtained by an ensemble member are distributed by all clusters related to a site, so it cannot be established whether a given RCM is systematically generating higher or lower yields than the rest.

Despite the number and magnitude of discrepancies among ensemble members, it cannot be said in any way that any ensemble member is mistaken, since nobody knows with accuracy what is going to happen in the future. Differences between projections obtained by all ensemble members give an idea of the uncertainty associated with these data used in this work. So, the results will be affected by this uncertainty too, but they can be used to estimate how CC will affect crops' water needs.

Figure 2 represents ET's variation due to CC, obtained by each ensemble member. All of them agree on the negative sign of the impact caused by new climatic conditions. However, the magnitude of this change is different depending on the ensemble member used, which provides an idea of the uncertainty of the results. Ensemble member RegCM is the one that predicts a smaller impact on ET for maize. HadRM3P and HIRHAM usually predict similar variations between them for all sites. PROMES predicts higher decreases of ET in most sites. Differences between ensemble members can be very marked, like in S-Plateau 1, where the difference between the results of RegCM and ARPEGE is around 21%.

Adaptation *vs*. no adaptation: analysis of its effects on yield and water needs

Effects of CC on yield, ET and irrigation

With the results from the means comparison tests, the variation in yield, ET and irrigation was obtained. It can be concluded that ET and irrigation requirements

[3] 27 fitted distributions for yield data: 21 Beta General (min. p value = 0.0745), 3 Log logistic (min. p value = 0.5822), 1 Inv. Gauss (p value = 0.4778), 2 Weibull (p value = 0.3074); 27 fitted distributions for irrigation data:13 Log logistic (min. p value = 0.0000), 5 Beta General (min. p value = 0.2317), 4 Pearson5 (min. p value = 0.2555), 2 Gamma (min. p value = 0.5283), 2 Inv. Gauss (min. p value = 0.8469), 1 Pearson6 (min. p value = 0.6404).

[4] FAOSTAT: http://faostat.fao.org/site/570/DesktopDefault.aspx?PageID=570#ancor.

[5] Information obtained from farmers in S-Plateau 2 area. TC = € 1693,85 ha^{-1}; SB = € 491 ha^{-1}.

Table 1. Analysis cluster for ET (Evapotranspiration) data (a) and yield data (b) for the future climate. Ensemble members [ARPEGE (1), CHRM (2), CLM (3), HadRM3P (4), HIRHAM (5), RegCM (6), RACMO (7), REMO (8), PROMES (9) and RCAO (10)] which appear more frequently in each site. The frequency is shown in brackets

Site	Cluster				
	1	2	3	4	5
	a) ET data				
NE-Valley	9*(27/28)	4 (19/28)	10* (22/28), 8 (20/28), 7 (16/28), 6(15/28)	3 (20/28), 5 (16/28)	1 (20/28)
N-Plateau	9* (26/28)	4* (23/28), 8 (20/28), 5 (18/28)	10 (19/28)	6 (20/28), 3 (18/28)	1* (23/28)
Center	9* (23/28)	4 (16/28)	6 (15/28)	3 (15/28)	1* (28/28)
S-Plateau 1	9* (28/28)	4* (22/28), 5 (20/28), 8 (16/28)	10 (19/28), 7 (17/28)	6 (18/28)	1* (28/28)
S-Plateau 2	9* (27/28)	4* (25/28)	10 (20/28), 7 (19/28), 8 (17/28), 5 (17/28), 2 (16/28), 3 (16/28)	1* (26/28) , 6 (19/28)	—
SW-Inland	9 (21/28)	4* (23/28), 5 (16/28)		7 (19/28), 6 (17/28), 3 (15/28)	1* (23/28)
SE-Coast	9* (28/28)	4* (25/28)	8* (24/28), 10* (23/28), 5* (22/28), 3 (21/28), 6 (18/28)	2* (26/28), 7 (16/28), 1 (15/28)	—
S-Valley 1	9* (24/28)	4 (20/28)	8 (15/28)	3 (18/28), 7 (17/28), 6 (16/28)	1* (24/28)
S-Valley 2	9* (23/28)	4 (17/28)	10 (16/28), 8 (16/28), 5 (16/28), 2 (15/28)	6 (19/28), 3 (17/28), 7 (16/28)	
	b) Yield data				
NE-Valley		1 (18/28), 3 (15/28)			
N-Plateau					
Center	1 (18/28)				—
S-Plateau 1				8 (15/28)	
S-Plateau 2	9* (23/28)				
SW-Inland		2 (16/28)		8 (16/28)	—
SE-Coast	2*(26/28)			7 (16/28)	
S-Valley 1				5 (15/28)	8 (15/28)
S-Valley 2					8 (15/28)

—: In a) for S-Plateau 2 and SE-Coast the number of clusters is 4; the same in b) for SW-Inland and Center.* Ensemble member considered assigned to a particular cluster, as more than 21 of the 28 years belong to a single cluster.

are expected to decrease in all sites studied in the future climate (Figure 3). Maize's yield will be lower in the future climate, mainly because it is a very sensitive crop to high temperatures.

As shown in Figure 3, the decrease in ET is similar in all sites, and always above 25%. Reductions of maize's irrigation needs are lower. Yield decrease is less homogeneous, but significant in all sites. ET reduction will be higher in: S-Plateau 1 and 2, and N-Plateau, all located in the central plateau, with variations about 28%. CC will have very negative impacts on maize's yield in Spain, with decreases exceeding 25% in the central plateau. However, crops' water needs due to new climatic conditions will be lower than under current conditions.

Variability is lower in the future climate for all sites studied, both for ET and for irrigation needs (Table 2). With the adaptation strategy described above, variances of ET and irrigation in the future period are considerable lower, so yield risks will be reduced.

Figure 4 shows the probability density functions of ET for the control period, A2 and A2 with adaptation. Control's function is on the right of the other two (A2, and A2 with adaptation), indicating higher values of ET. Also, it can be seen that variability in this period will be higher. With maize's adaptation, the mean of ET does not differ much from the one of the control period. However, ET's decrease with adaptation is lower than without. Variance with adaptation is the lowest.

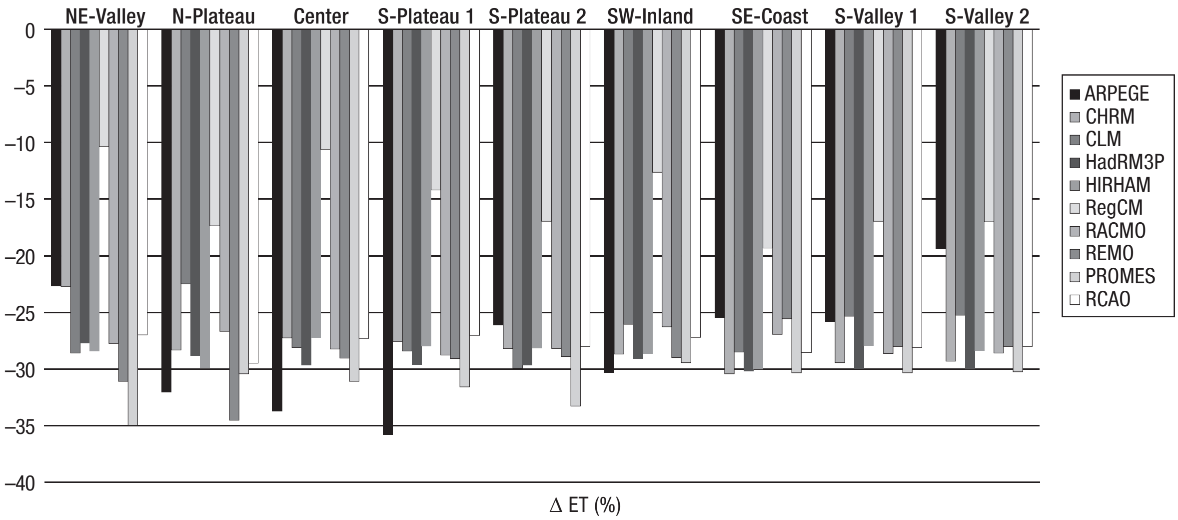

Figure 2. Average differences of maize's ET (evapotranspiration, in %) between the two periods, obtained from climatic data of each Regional Climate Model for each site.

Changes in water use efficiency

The adaptation strategy described above will mitigate to some extent the negative CC impacts on maize's yield. By contrast, the decrease of ET and irrigation will be lower than it would be if maize sowing dates and traditional varieties are kept.

Water resources will become scarcer in the future. Therefore, it is important that crops' WUE improve, so that plant production can take maximum advantage of the available water resources, optimizing irrigation water. Comparing the ratio yield/ET between control period and future climate (Figure 5), results show that this ratio is higher for the period 2071-2100. WUE will increase more in SE-Coast and in the two sites of S-Valley, because yield decrease in these sites is considerable lower, and ET reduction is similar to all sites.

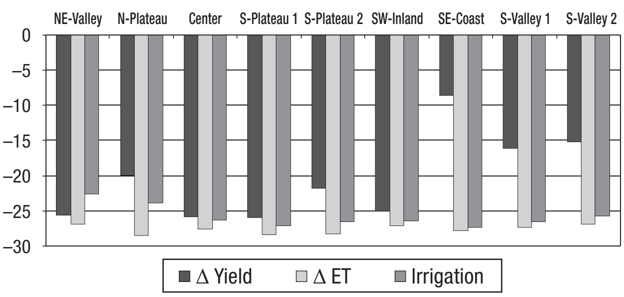

Figure 3. Variations (in %) of yield, ET (evapotranspiration) and irrigation needs of maize between control period and future climate, due to climate change in each site under study.

Decrease in ET, water needs and yield will be lower if an adaptation strategy is implemented (lower panel of Figure 5). In this case, crop's response to new climatic conditions depends on the site. In N-Plateau, NE-Valley, S-Plateau 1 and 2, and Center, WUE will be lower in the future climate as yield reduction is greater than ET reduction, especially in NE-Valley. Here, the difference of the variation of ET and yield is higher. However, in SW-Inland and the two sites in S-Valley, WUE will improve considerably, because yield reduction is small compared with the decrease of ET. In SE-Coast the yield will increase 1.4% and ET will decrease

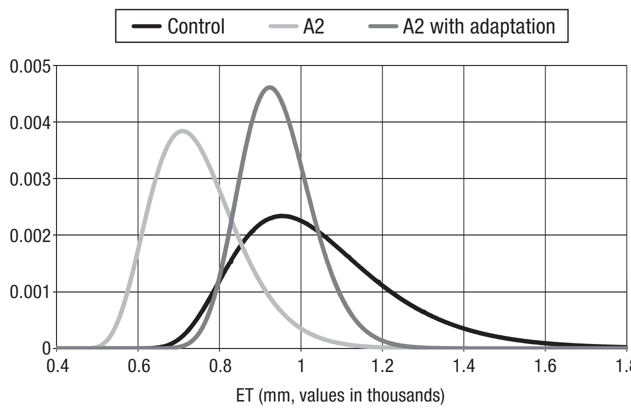

Figure 4. Distribution functions of ET (evapotranspiration) of maize in N-Plateau, obtained from all ensemble members' data for three cases: control period, future climate (A2), and future climate with adaptation. Distribution functions (χ^2 test): Control (Inverse Gauss, p = 0.7107), A2 (Gamma, p = 0.2773) and A2 with adaptation (Pearson 5, p = 0.6871).

Table 2. Means comparison test and variances comparison test[1] for both periods. Comparison between ET (evapotranspiration) and irrigation needs data for control period and future climate (in %), without adaptation (–), and with adaptation (+)

Site	Δ ET				Δ Irrigation needs			
	Means comparison test		Variances comparison test[1]		Means comparison test		Variances comparison test	
	–	+	–	+	–	+	–	+
NE-Valley	–26.9**	–6.4**	–27.7**	–42.5**	–22.6**	–3.0**	–30.5**	–42.5**
N-Plateau	–28.5**	–9.7**	–18.1**	–47.6**	–23.9**	–7.1**	–22.8**	–35.2**
Center	–27.6**	–10.9**	–10.7**	–38.8**	–26.3**	–9.3**	–7.7**	–31.7**
S-Plateau 1	–28.4**	–11.3**	–11.0**	–40.2**	–27.1**	–12.1**	–21.0**	–34.5**
S-Plateau 2	–28.3**	–12.6**	–22.0**	–41.9**	–26.5**	–10.8**	–19.2**	–39.6**
SW-Inland	–27.1**	–16.6**	–12.4**	–32.7**	–26.4**	–17.3**	–12.6**	–23.7**
SE-Coast	–27.8**	–18.7**	–10.4**	–44.3**	–27.3**	–18.5**	–11.4**	–41.4**
S-Valley 1	–27.4**	–17.1**	–17.3**	–29.1**	–26.6**	–16.4**	–17.1**	–24.4**
S-Valley 2	–26.8**	–17.3**	–23.9**	–29.8**	–25.8**	–17.9**	–20.4**	–24.6**

[1] Levene test. ** $p \leq 0.01$.

18.6%. In this site, and the two in S-Valley, WUE will be similar with and without adaptation.

With all that, it can be concluded that adaptation impacts on maize's WUE in Spain will not be homogeneous, but rather site-specific.

Economic analysis

Impacts of CC on maize's water use efficiency raise the question of whether it is better to maintain current yields by adapting this crop, at the expense of using more water (if it were available), or else it would rather be better to get slightly lower yields, and lower crop water requirements.

The previous results do not inform about farmers' incentives to adapt or change crop irrigation strategies. This analysis evaluates how maize's net margin will change under different water tariffs, comparing the net margin in the control period with the net margin in the future climate. With the distribution functions for irrigation needs (total water applied to the crop), maize's yield and price, and for different six water prices (from € 0.05 to 0.20 m^{-3}), Monte Carlo simulations were performed.

Resulting maize's net margin will depend on the site and the tariff level considered. Figure 6 shows the variation of maize's net margin between the control period and the future climate (with and without adaptation) for three different water tariffs. The higher the price of water, the lower maize's net margin variation. As in the future period water requirements will be lower, maize's net margin can be improved in some sites, if the decrease in yield is not very marked. This is the case, for example, of SE-Coast, where maize's

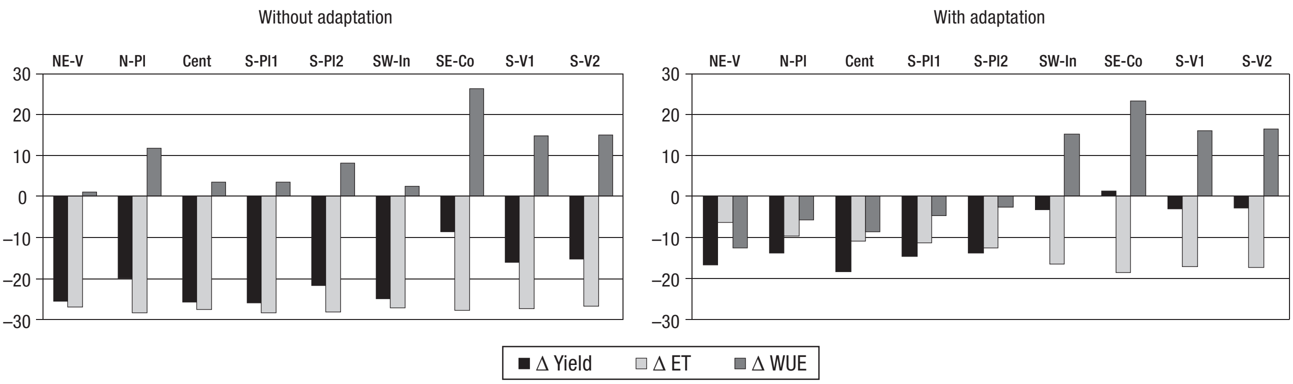

Figure 5. Analysis of the differences (in %) of the water use efficiency (WUE = Yield/ET) of maize due to climate change, between the control period, and the future climate (without adaptation, or with adaptation). Sites: NE-Valley (NE-V), N-Plateau (N-Pl), Center (Cent), S-Plateau 1 (S-Pl 1), S-Plateau 2 (S-Pl 2), SW-Inland (SW-I), SE-Coast (SE-Co), S-Valley 1 (S-V 1), S-Valley 2 (S-V 2).

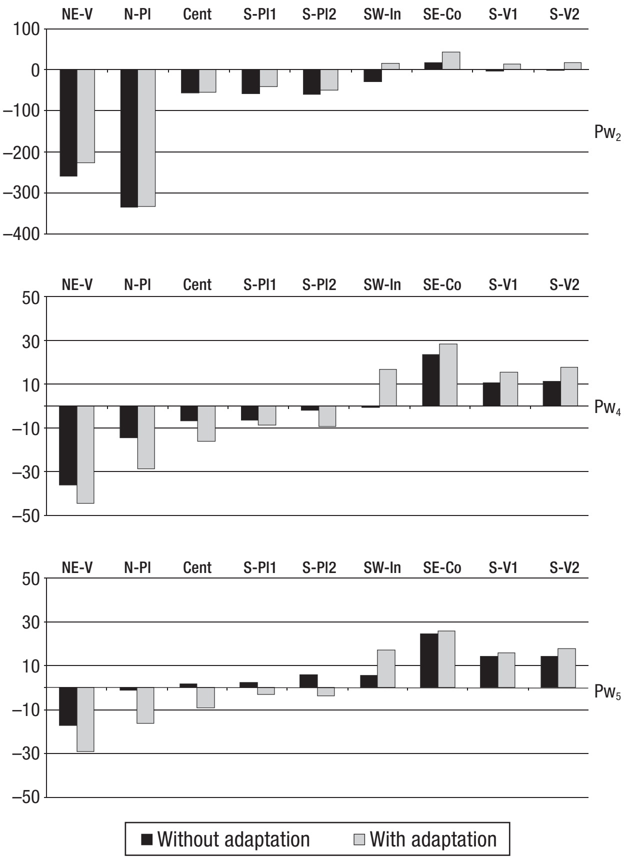

Figure 6. Variation (in %) of maize's mean net margin for different water prices in all sites under study, between the control period and the future climate (with and without adaptation). Sites: NE-Valley (NE-V), N-Plateau (N-Pl), Center (Cent), S-Plateau 1 (S-Pl 1), S-Plateau 2 (S-Pl 2), SW-Inland (SW-I), SE-Coast (SE-Co), S-Valley 1 (S-V 1), S-Valley 2 (S-V 2). Water prices (in € m^{-3}): Pw_2 (0.07), Pw_4 (0.12), Pw_5 (0.15). The axis of the above panel is different from the other two in order to show the variations in N-Plateau and NE-Valley, which are much higher than in other sites.

mean net margin will be higher for all water tariffs considered. And in other sites like NE-Valley the net margin of this crop will be lower in the future period because the yield decrease will be higher than in other sites, and water needs will not be so small. The effects of adaptation in maize's mean net margin depends on the site under study. With maize's adaptation to CC, water needs will not decrease as much as without adaptation, but yields' reduction will be lower. For high water tariffs (Pw_5, Pw_6), maize's net margin will be higher in the future climate than in the control period for most sites, as WUE will improve due to CC.

Cumulative ascending curves of net margin distribution are shown in Figure 7, for two different water tariffs and two sites (NE-Valley and SE-Coast). Attention should be paid to the relative position of the curves in each case (control, A2 and A2 with adaptation). With Pw_6, maize's net margin will be considerably lower than for Pw_1 in both cases for the two periods. In SE-Coast, maize's net margin will be higher in the future period for these two prices. In NE-Valley, net margin will be higher (but also negative) for the future period without adaptation than with adaptation if water tariff rises to € 0.20 m^{-3} (Pw_6), although in both CC scenarios net margin will be much lower than in the control period. Maize's net margin will be higher in NE-Valley than in SE-Coast for both water prices. The effects of adaptation on maize's net margin depend on the site and the water tariff scenario. The adaptation strategy will improve net margin in both sites if water price is Pw_1, but no for Pw_6.

In NE-Valley, CC will have a negative impact in maize's net margin for all water prices considered. If in the future period water prices are low (Pw_1), the adaptation strategy for this crop will improve maize's net margin. However, if water prices are higher than today (Pw_6), the adaptation of this crop will have a negative impact in net margin, as maize's water needs will not decrease as much as without adaptation.

The large volumes of water that have been introduced in the simulations of irrigation to prevent crop suffering from water stress have resulted in lower values of maize's net margin. In real contexts, these quantities of water are smaller, and therefore, net margin would not be as low as those shown here. Furthermore, maize's price distribution (Log logistic, mean = 0.134, sd = 0.0332), fitted on maize's prices for 1991-2008 years, seem rather low for present market conditions (well above € 0.20 kg^{-1}).

Discussion

This paper aims to analyze the potential impacts of CC on maize's water needs, yield of maize and profitability in Spain, through the analysis of the projections obtained from climatic data of 10 RCMs (PRUDENCE Project). The paper's main contribution is doublefold. First, it provides an overview of maize's yields and water demand in a context of climate change, adding new results that complement those reported before only on yields (Ruiz-Ramos and Mínguez, 2010). Secondly, it brings the analysis of crop impacts to the sphere of water policy as well.

Since adaptation strategies can pursue improvements in yields and in water productivity, and these two goals may counteract each other, water prices for irrigation may play fundamental role in helping meet one or the other goal. This issue is addressed with the economic simulation model.

CC will have an important effect on the hydrological cycle (Iglesias *et al.*, 2005; Bates *et al.*, 2008), compromising water supply for all sectors, among which irrigation will suffer the greater impacts. Crops grown presently must be adapted to new climatic conditions in order to compensate for the negative impacts of CC on yields. From the point of view of water conservation, this kind of adaptation may not be the most convenient for maize, taking into account that the decrease in water requirements of this crop will be lower than without adaptation (as we have seen with the results of this work), and water resources in the future climate will be considerably scarcer than today.

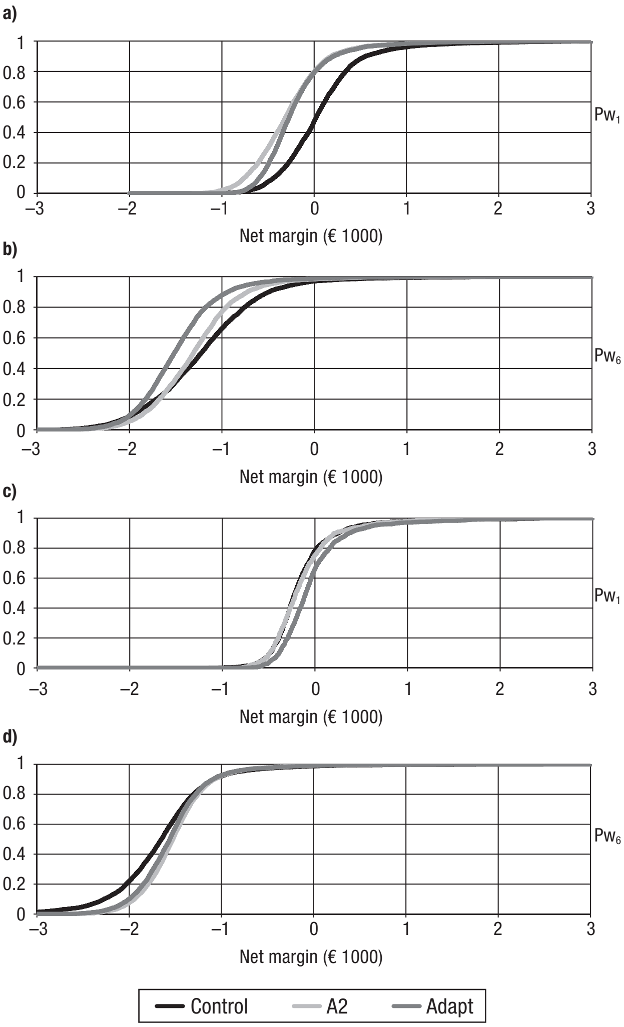

Figure 7. Cumulative ascending curves of net margin (€ 1000) for the two periods: control, and future climate, with and without adaptation. Comparison between two water prices for NE-Valley (a and b) and SE-Coast (c and d). Water prices (in € m^{-3}): Pw$_1$ (0.05), Pw$_6$ (0.20).

The cluster analyses carried out show the uncertainty associated to the projections of CC impact in the coming decades with the 10 RCMs. It shows differences of ET or yield values predicted by the different members of the ensemble. It can be concluded that in general PROMES (9) estimates higher values of ET than the others, so this ensemble member is in cluster 1 in all cases. On the contrary, ensemble member ARPEGE (1) provides lower values of ET in most cases. Despite these differences and its associated uncertainty, the projections unambiguously indicate that water needs of maize in Spain will decrease in the future climate due to CC.

CC has a dual effect in average water irrigation needs in the long term for each irrigation unit. On the one side, the optimal cropping patterns and the growing season will be different from the control period; on the other side, water irrigation needs of a certain crop in a particular day of the year will change (Döll, 2002). If we keep traditional varieties and sowing dates, because of the shorter cycle resulting from CC, water needs of summer crops (maize) in Spain will be lower, falling more than 20% in all studied sites. However, yields will be affected in most sites. The results show that the decrease of ET in this period is greater than the reduction of maize's yield, coinciding with previous studies concerning the Mediterranean area (Meza *et al.*, 2008).

Adaptation as a measure to reduce the negative impacts of CC on maize's yield will generate a lower decrease of ET and irrigation needs in the future climate. However, the variance of both ET and irrigation needs for this period will be lower than if no adaptation takes place. The simulations were done in such a way that the crop would not suffer water stress in any moment of the cycle. So, the irrigation requirements' values used in this work could be higher than those actually applied in irrigation farms.

Water use efficiency of maize will be greater in the future climate in all sites. If adaptation is implemented, the effects on this efficiency will depend on the site studied, improving in some regions, and decreasing in others. A higher crops' WUE is important in the future climate because water availability will be lower.

In a drier climate, as it is expected for the end of the century, irrigation water demand will increase in the entire Mediterranean region, and water resources will be scarcer (Giannakapoulos *et al.*, 2005; Fischer *et al.*, 2007; Iglesias and Quiroga, 2009; Dono and Mazzapicchio, 2010; Kolokytha, 2010). Therefore, it is likely that water tariffs or opportunity cost rise significantly, threatening the profitability of this crop. Although Spain is the EU country with the highest maize's margin because of the low production costs (EC, 2010), in some areas, like S-Plateau, where maize is a traditional crop, currently it is being replaced by more profitable ones due to high maize's water needs and the price of water. In the event that water tariffs were raised, irrigation cost would become the main source of instability of maize's net margin. The adaptation of maize to new climatic conditions could reduce the impact in maize's net margin in some sites under study, but in others the effect could be the opposite. If water prices remain low, adaptation can be positive for maize's net margin. But if water prices are high in the future period, the adaptation strategy can reduce net margin in some sites of Spain. Adaptative responses will be implemented only if farmers' profits increase, and that will depend on the combination of CC impact on yields, water needs and water prices.

The high volume of irrigated water for maize used in the simulations, and the maize's price considered (the distribution function of this price has a mean of € 0.134 kg^{-1}, while nowadays this price is near € 0.22 kg^{-1}), make maize's net margin values low and negative in many cases.

In four decades, world population will be above 9 billion people. World agriculture will face the challenge of feeding them all. Because agriculture is so dependent on climate, it is very important to know how climate change will affect the future climate, including the availability of water resources. Improving crops' yield and water use efficiency is crucial to produce all food needed to feed the world. Studying climate change impact is the first step to develop and implement different kind of policies to make the most of water.

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