Crop insurance valuation in response to climate change

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Abstract

Purpose

In this work, we studied the effect of a warmer climate on crop yield distribution of durum wheat (*Triticum turgidum* L. subsp *durum*) in order to assess the economic significance of climatic change in a risk decision context.

Methods

The outputs of 5 regional Circulation Models (RCMs) were statistically downscaled by a stochastic weather generator over eight sites across the Mediterranean basin and used to feed a crop growth model. Two time slices were considered i) the present period PP (average of the period 1975-1990, [CO2]=350 ppm and 2040 (average of the period 2030-2050, SRES scenario A1b, [CO2]=480 ppm). Simulated yield data were fitted to the most appropriate probability density function (PDF) and then used to estimate the expected payout per hectare from insurance triggered when yields fall below a specific threshold.

Results

The results generally indicated that yield of durum wheat was best fitted by a weibull distribution and that climate change had a different impact on insurance risk depending on the region.

Conclusions

This study highlight the importance of selecting the appropriate distribution function for the assessment of climatic risk

Keywords: extreme events, climatic risk, crop modelling

Introduction

Since the early ’90, many authors have addressed the issue of yield losses in a warmer climate by coupling mechanistic crop growth models to the outputs of General/Regional Circulation Models (GCMs, RCMs). This integrated tool offer a valuable contribute to evaluate crop responses to climatic change by considering the specific interaction between varieties, soil type, CO2 concentration and management practices. This approach has been extensively used to describe crop yield distribution in response to changes in both mean climate and variability and to test the effectiveness of possible e adaptation options (e.g. Giannakopoulos et al. 2009; Moriondo et al., 2010).

The general response of these simulations was not homogeneous but highly influenced by the considered geographical region (e.g. Southern Mediterranean regions are more affected than the northern ones), the specific growing cycle (e.g. summer crops suffer the most while yield of winter crops may even increase), the crop type (e.g. C4 plants are less responsive to higher CO2 concentration) and environmental conditions (e.g. water and nutrient availability).

The impact of climate change on yield is generally expressed as percentage calculated with respect the baseline period. These values give an immediate response to the question “is climate change beneficial for a particular cropping system?” or “what is the average yield loss?” These average changes in crop yield are used to outline possible areas where a crop become viable for cultivation or should be removed according to its specific performances (e.g. Moriondo et al., 2010). In most cases, no further details than changes in standard deviation (*std*) or Coefficient of Variation (CV=*std*/mean) are provided as indexes to highlight the increased risk for the future of having too low or too high yields with respect to the present period. However, these indexes may be not sufficient alone or even misleading to outline these risks for the future since these vary dramatically depending on the actual shape of the distribution of data. As such, Sherrick et al., (2004), emphasized the economic importance of selecting the most appropriate characterization of crop yield distribution in a risk decision context.

In contrast to this background, a little effort has been spent so far to study the effect of climate change on crop yield distribution and this may results into misleading analysis of the impact due to a warmer climate and selection of not appropriated adaptation options to cope with.

On these premises, in this paper, we setup a framework to routinely select the most appropriate PDF to fit yield distribution to study the impact of climate change and variability on crop yield in a risk analysis context. Crop yield simulations for present and future scenario A1b were provided by a crop growth simulation model (Sirius Quality) calibrated for variety of durum wheat. A crop insurance model was implemented to quantify the economic significance of climatic change in a risk decision context.

The results were discussed in terms of the effect of climatic change in the risk management of crop insurance companies in the next future.

Material and Methods

Sirius quality 4.1

Sirius is a wheat simulation model that calculates biomass production from intercepted photosynthetically active radiation (PAR) and grain growth from simple partitioning rules. A simple soil sub-model is used for the dynamics of water and nitrogen (N) in the ground. The model allows the user to specify soil profile properties (e.g. soil hydrological properties, thickness, water and nitrogen initial content, etc.), cultivar genetic coefficients (e.g. photoperiodic sensitivity, duration of grain filling, minimum and maximum potential leaf number, etc.) and management parameters such as sowing date, fertilizer and irrigation quantity and timing. The effect of increased CO2 is simulated by linearly increasing radiation use efficiency (RUE), so that for a doubling of CO2 air concentration the RUE is increased by 30%.

The model was calibrated for a durum wheat variety with a medium cycle. Observed phenological dates (anthesis and maturation) of this variety, main management practices (sowing date, N fertilization) and final yields obtained in the experimental station of Argelato (Italy, 44.6°N, 11.3°E) were provided by Società Produttori Sementi S.p.A for the period 2003-2010 and used as terms of references during the calibration process.

Meteorological dataset

Gridded observed daily meteorological data (Tmin, Tmax, Rainfall, Global Radiation), spaced 50 km x 50 km where extracted from the MARS-STAT database (available at http://www.mars.jrc.ec.europa.eu/).

The daily outputs of 5 RCMs (Tmin, Tmax, Rainfall, Global Radiation) were extracted from the ENSEMBLE project database (available at http://ensemblesrt3.dmi.dk/) (van der Linden and Mitchell 2009) for the SRES scenario A1b. Three time slices were considered i) the present period PP (1975-1990), ii) 2020 (period 2010-2030), and iii) 2040 (2030-2050).

Downscaling technique

Tmin, Tmax, rainfall and solar radiation simulated by the RCMs were statistically downscaled over the observed meteorological records (MARS-STAT) using LARS-WG procedure (Semenov and Barrow, 1997). In turn, these data were used to feed Sirius Quality.

According to the spatial distribution of its cultivation, this downscaling procedure was performed over 7 sites representing the most important cultivated regions across the basin, namely Andalusia (S Spain), Midi–Pyrenees (S France), Centre districts (N France), Tuscany (C Italy), Apulia (S Italy) and South Aegean (S Greece) and North Greece (N Greece) (Fig. 1).

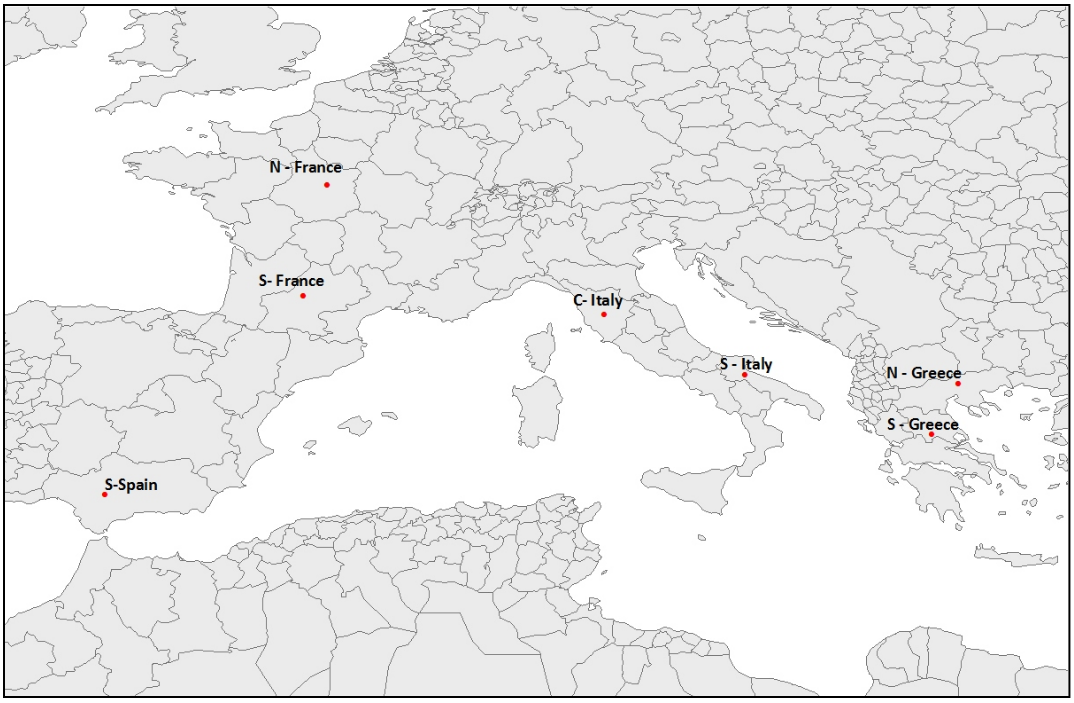

Figure 1. Study sites selected for simulating yield of durum wheat across the Mediterranean basin.

Accordingly, available observed daily weather data for each site (i.e. grid cell of MARS-STAT) were used to determine a set of parameters for probability distributions of weather variables as well as correlations between them (calibration stage). This set of parameters was then used to generate both the synthetic weather time series describing the present period and as a baseline to be perturbed using forcing factors derived from the RCMs.

After calibration, 100 years of synthetic daily weather data (including Tmin, Tmax, rainfall and radiation) were produced for the baseline 1975-2005 and compared to the observed data to provide a general overview of LARS WG performances in simulating the local climate.

The results of 5 RCMs for A1b scenario for 2040 ([CO2] = 490 ppm) were used to derive the forcing factors for the downscaling procedure related to the time slice 2040 (average of 2030-2050). For each site, daily time series for Tmin, Tmax, R and RAD were extracted from the relevant nearest RCM grid cell. The forcing factors for each future period, as required by LARS WG, were computed as monthly average differences of Tmin, Tmax, rainfall and rotation with respect to the reference period (1975-2005). For temperature and rainfall the relative change in standard deviation and in duration of wet and dry spell were also calculated.

Insurance model

Average Production History (APH) insurance approach was used to compare the expected payoff of an insurance company in present and future periods.

According to APH insurance program, an indemnity payment is triggered when final yields fall below a producer selected guaranteed level (Yg) that is function of an expected yield (Y) and an election level as a fraction of the expected yield (h).

$$Yg = Yh \qquad [2]$$

The amount of payment is a function of the difference between Yg and the actual yield at a price (Pg) that is defined at the time of the beginning of the growing season. Accordingly when y falls below YG, the indemnity is given by

$$Pg(Yg - y) \qquad [3]$$

Considering *y* as a stochastic variable, the expected payout (per hectares) may be expressed as:

$$E(g) = \int_0^{Yg} Pg(Yg - y) f(y) dy \qquad [4]$$

Where the appropriate *f(y)* is selected according the goodness of fit as indicated in the next section.

The expected yield was calculated as a simple average of actual yields calculated for each RCM and site. A high coverage level, h=0.85, was chosen aiming at illustrating the economic implications of the use of different varieties and the effect of extreme events on crop yield distribution.

Statistical tests

The yields simulated by Sirius were fitted to different distributions whose performances were compared according to a goodness of fit test. Normal, Lognormal, Weibull and Logistic distributions were considered, each of them having contrasting features to describe yield distribution. The normal distribution is symmetric, has a fixed kurtosis and is not bounded below by zero. The logistic distribution is used as an alternative to the normal, especially in cases where excess kurtosis exists. The lognormal is bounded below by zero and allows for varying degrees of positive skewness and kurtosis. The Weibull distribution has many desirable properties for modeling yields allowing for a wide range of skewed and kurtosis and it can be bounded by zero. Maximum likelihood was used to estimate the parameters of each of the four distributions. Next, the fitting performances of each candidate distribution in representing yield simulated data were

compared using the Anderson-Darling test (AD). The test statistics of AD were used to order each candidate distribution by the number of times they rank from 1st to the fourth place.
The differences in crop insurance with respect to the present period were evaluated highlighting possible effect of different sites. These effects were statistically tested bearing in mind that crop yield distributions may be not normally distributed and therefore Analysis of Variance (ANOVA) may fail the test of significance. Accordingly, the effect of the single factors were tested using Kolmogorov-Smirnov non-parametric test.

Results

Impact of CC on average yield

Climate change, as outlined by the 5 RCMs used in this work, indicated a progressive increase of temperature and decrease in rainfall form the present period to 2040 with a different rate depending on RCM. In average, the impact on Tmin and Tmax was asymmetric with Tmin that increased by 1.5°C in 2040 and Tmax shifting +1.73°C in the same time lapse (data not shown). The highest increase in both Tmin and Tmax were recorded in the southern region of the Mediterranean basin (Tmax up to +2°C in S Spain in 2040) whereas the trend on northern regions (N and S France) was less evident (Tmax up to 1.3° in S France in 2040).
The general picture indicates that these changes, combined to increased CO2 concentration, resulted into a general increase of yield as compared to the present period in all the regions (Table 1), ranging from 1.7% in N Greece to 9% in S. Italy, with a slight decrease only in S Spain (-1%).
The average effect of each RCM on yield ranged from +1.7% of ETHZ to +7% of KNMI yield with respect to the present (data not shown).

Table 1. Yield of durum wheat and expected payout simulated for the present period and relative changes calculated for the future (2040) according to different RCMs. Statistical differences were evaluated according Kolmogorov-Smirnov test where p>0,05 ns; 0,05>p>0,01 *; 0,01>p>0,001 **; p<0,001 ***

Region	Present (kg ha-1)	Payout (€)	Average Change in yield (%)	Average Change in payout (%)
N_FRANCE	8263	14	+4.4**	+0.9
S_FRANCE	8441	11	+5.7**	+40
C_ITALY	8773	30	+2.6**	+40
N_GREECE	6050	31	+1.7**	+42
S_ITALY	6704	97	+9.0**	-20
S_GREECE	6842	44	+8.2**	-8
S_SPAIN	7698	74	-1.1**	-11

Yield distribution and insurance evaluation

The general picture indicates that yields distributions in the present were in average negatively skewed (-0.44) with a slight platykurtic distribution (i.e. with thicker tails with respect to a normal distribution) (2.8). The effect of climatic change resulted in average into a lower skewness (-0.52) and increased kurtosis (3.1) where a significant negative relationships exist between changes in skewness and changes in kurtosis (Fig. 2).

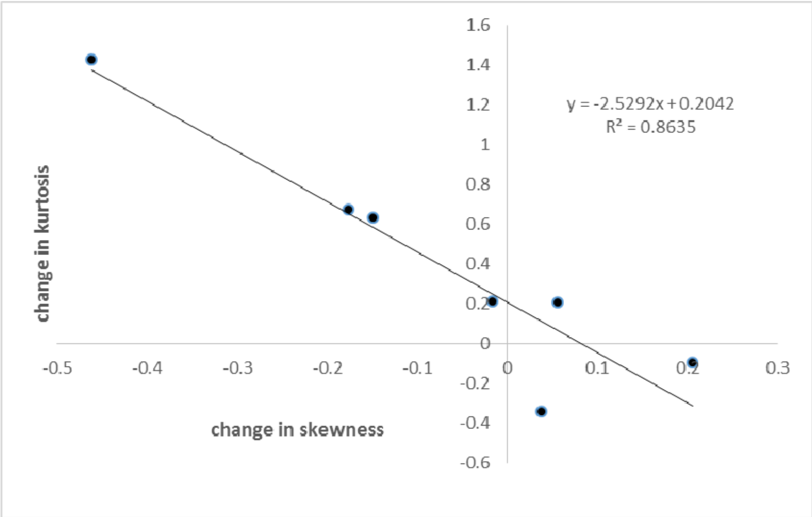

Figure 2. Relationship between average changes in skewness and kurtosis calculated with respect the present period

Amongst the candidate distributions, the ranking analysis indicated that Weibull and Lognormal over-performed the fitting capacity of normal and logistic distributions, irrespective of the site (Table 2), and RCM.

On regional scale, mean climate change resulted into a mixture of increased/decreased premium to be paid with respect to the present period. This was included in a range +42% in N. Greece to -20% in S. Italy, without a clear spatial pattern or trend (Table 1). Not a clear agreement was observed by the analysis of the effect of single RCM, where the impact ranged from -11.4% (MPI) to +11.7% (ETHZ).

Table 2
Rank analysis of the performances of different distributions to fit simulated yield data aggregated per region (present and future data are considered toghether).

	C_ITALY				**N_FRANCE**				**N_GREECE**				**S_FRANCE**				**S_GREECE**				**S_ITALY**				**S_SPAIN**			
rank	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*
nr	0.0	22.2	77.8	0.0	22.2	50.0	27.8	0.0	27.8	55.6	16.7	0.0	11.1	16.7	72.2	0.0	0.0	44.4	55.6	0.0	22.2	66.7	11.1	0.0	0.0	50.0	50.0	0.0
ln	0.0	0.0	0.0	100.0	0.0	0.0	33.3	66.7	0.0	0.0	5.6	94.4	0.0	0.0	11.1	88.9	0.0	0.0	0.0	100.0	0.0	5.6	5.6	88.9	0.0	0.0	0.0	100.0
w	100.0	0.0	0.0	0.0	50.0	5.6	16.7	27.8	72.2	16.7	11.1	0.0	72.2	5.6	11.1	11.1	88.9	11.1	0.0	0.0	77.8	16.7	5.6	0.0	100.0	0.0	0.0	0.0
lg	0.0	77.8	22.2	0.0	27.8	44.4	22.2	5.6	0.0	27.8	66.7	5.6	16.7	77.8	5.6	0.0	11.1	44.4	44.4	0.0	0.0	11.1	77.8	11.1	0.0	50.0	50.0	0.0

Discussion

Many authors indicated agricultural insurance as adaptation option to climate change (Mcleman and Smit, 2006; Schwank et al. 2010) and weather-risk-based insurance products have been proposed since 2000 to reduce agriculture vulnerability (Turvey, 2001).

Since insurance programs are designed to provide compensation for crop losses whose probability is known based on past experience, different tools should be used to predict insurance rate in a future scenario. Accordingly, in this paper we setup a framework to routinely simulate crop yield of durum wheat in a warming climate, fit the data to the most appropriate distribution function and assess the risk according an insurance scheme. This framework took advantage of the use of a weather generator for RCM downscaling that includes the simulation of changes in climate variability. This allowed to reproduce the simulated climate change and variability over 8 sites representative of durum wheat cultivated area for a number of test cases (100 years) suitable for model fitting.

In average, climate change, including increased CO2 concentration, had a positive impact on crop yield over the selected region except than in S Spain. This has been already observed in a number of studies (Moriondo et al., 2010; Moriondo et al., 2011; Ferrise et al., 2013; Supit et al., 2012) with a particular reference to winter crops. While these crops may benefit from increased rainfall rate predicted from the Fall-Winter period, the earlier occurrence of anthesis further reduce the impact of a warmer climate by allowing the grain filling period to avoid extreme hot temperature in Summer. As a result, durum wheat, and generally winter crops are acknowledge as the most promising crops in a warmer climate (Moriondo et al., 2010; Ferrise et al., 2013).

Crop yield distribution, both in present and in future were generally negatively skewed with a various degree of kurtosis. This trend indicates that simulated crop yield are likely not-normal distributed and accordingly, Weibull distribution, allowing for a various degree of skewness-kurtosis, provided the best fitting performances both in present and future scenario. Further, a negative skewness indicates that, depending on the region, crop yield may be close to an upper limit of production (Parker and Sinclair, 1993), i.e. the climate conditions may be particularly favorable for durum wheat and yields are shifted towards an upper bound.

The analysis of momentum indicated that differences exist between present and future scenario.

While climate change had a general positive effect on yield but is S Spain, both kurtosis and skewness resulted into a mix of increase/decrease with respect to the present. In general, as the skewness decreases with respect to the present, as increases the kurtosis revealing that those distributions shifting closer to the upper bound of production tend to have fatter tail with respect to the present. In those regions showing this trend, climatic change would increase the mean and the probability of yields above the mean but distribution still has a long tail towards occasional low yield. As a matter of fact, the thickness and extension of tail in relation to the shift in the insured threshold, is the likely responsible for changes in premium rate under the climatic change one would not expect on the basis of changes in crop yield and momentum. For instance, S France with an increased yield by 5.7% and a distribution with a higher kurtosis more negatively skewed (kurtosis +1.4, skewness -0.46 with respect to the present) showed the highest increase in the premium rate (+41%) (Fig. 3).

Conclusion

The study of the distribution function of crop yield plays a fundamental role in smoothing the effect of adverse climate conditions. Since climate change has the potential to affect crop distribution function, there is the need to estimate the sign and magnitude of these changes. In this work, the coupling of a weather generator to a process based crop growth model allowed the study of the distribution of durum wheat yield over the Mediterranean basin highlighting The results of this work demonstrated that yield distribution of durum wheat is negatively skewed with a various degree of kurtosis. Therefore, Weibull distribution function permitting negative skewness provided the best fitting capacity of simulated yield. The general increase of yield as simulated in the near future did not prevent an increase of expected payout especially in the most productive regions of the Mediterranean belt (C Italy, N Greece, S France).

The examination of possible impact of extreme events on crop yield distribution provides an opportunity for further develop the present framework. Many authors stressed out that a specific impact of whether extremes may be an additional factor creating the possibility of impacts on yield that are larger than predicted using changes in mean climate alone. Accordingly, insurance payout may further be modified by such extremes, leading to a distortion of risk management when the simulation of these events is not considered in crop growth process models.

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