Methods for drought risk analysis in agriculture [Part 1. Components of drought planning. 1.3. Methodological component]

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in

Iglesias A. (ed.), Moneo M. (ed.), López-Francos A. (ed.).
Drought management guidelines technical annex

Zaragoza : CIHEAM / EC MEDA Water
Options Méditerranéennes : Série B. Etudes et Recherches; n. 58

2007
pages 103-113

To cite this article / Pour citer cet article

Quiroga S., Iglesias A. **Methods for drought risk analysis in agriculture [Part 1. Components of drought planning. 1.3. Methodological component].** In : Iglesias A. (ed.), Moneo M. (ed.), López-Francos A. (ed.). *Drought management guidelines technical annex.* Zaragoza : CIHEAM / EC MEDA Water, 2007. p. 103-113 (Options Méditerranéennes : Série B. Etudes et Recherches; n. 58)

Chapter 8. Methods for drought risk analysis in agriculture

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SUMMARY – This Chapter focuses on risk analysis methods aiming to develop a methodological base to understand drought risks in agriculture and formulate conceptual basis that allows rigorous drought impacts attribution. The method integrates both climate and agricultural system's characteristics to measure the rainfed agriculture risk to drought in a way that allows making comparisons between different places with different potential yields. Monte Carlo simulations are used to obtain the probability distributions allowing the characterization of risk. Finally, risk premium has been estimated by using statistical and risk evaluation models for some selected sites in Spain.

Key words: Rainfed agriculture, irrigation, impacts, risk factor, yields.

Risk concept

Unfavourable weather conditions are the main source of risk in subsistence farming systems, especially in marginal land and social conditions. In this case, drought has a direct relationship with farmers' income and risk is relatively simple to analyse evaluating simple variables, such as crop yield. In contrast, farming systems in economically developed regions, are greatly affected by policy, markets, technology and financial instruments, and it is complex to determine the effect of drought in individual farmers and in the aggregated agricultural sector.

Farmers need to manage the year-to-year variability of agricultural production with a range of agronomic and market-based strategies. In many regions a main source of production variability is weather-dependent.

Key issues to be considered in the risk analysis in agriculture:

(i) In general, for a given level of precipitation decrease, the magnitude of drought impacts varies with the type of farming system (subsistence or commercial).

(ii) Drought impacts vary according to location and enterprise type and the effectiveness of risk management practices adopted.

(iii) Inter-annual distribution of precipitations is a key issue in the levels of risk associated to the agricultural systems analyzed.

(iv) Synthetic series of precipitation allow to produce distribution functions of agricultural variables that enhance the risk analysis.

(v) Economic variables need to be included for determining the social risk and evaluating the potential market based and policy measures to mitigate drought.

This chapter focuses on the risk analysis methods aiming to:

(i) Develop a methodological base to understand drought risks in agriculture.

(ii) Formulate a sound conceptual basis that allows rigorous drought impacts attribution.

(iii) Broaden our perception of how drought impacts evolve and spread over space.

(iv) Enrich our understanding of successful drought preparedness practices.

The methods followed highlight the difference between risk (the probabilistic consequences of drought) and uncertainty (the imperfect knowledge of the probabilities of drought). Uncertainty arise from the imperfect knowledge of: (i) climate dynamics; (ii) interaction between meteorological, hydrological and agronomic systems; (iii) the undefined impacts on farm production and income; and (iv) the market-based responses to drought onset, inputs suppliers and financial institutions.

In the case of agricultural drought, the development level of the agricultural systems can influence vulnerability. Table 1 shows the main characteristics of two agricultural systems in the Mediterranean region that may imply different levels of vulnerability to similar levels of drought.

Table 1. Main characteristics of different agricultural systems in the Mediterranean

Characteristics	Subsistence farmers	Commercial farmers
Production strategy	Production stability	Maximize benefits
Main sources of risk	Climate	Climate, market based response
Main consequences of drought	Income reduction, migration and starvation	Financial liability, bankrupt and abandoning activity
Non structural risk management mechanism	In practice non existent	Insurance, credit (interest rate subsidies), taxes reduction, subsidies, laws
Inputs and resources	Very low	Significant
Role of livestock	Strategic resource	Production objectives

Rainfed and irrigated agricultural systems

Risk in irrigated systems is directly related to water scarcity, which differs from drought because it is related to a shortage of water availability to satisfy demands. The shortage results from an unbalance between water supply and demand, which is originated by a meteorological phenomenon, but is also conditioned by other time-varying factors, such as demand development, supply infrastructure and management strategies. The result of the unbalance is demand deficit, which is of concern for water managers. It is usually anti-economical to guarantee 100% all demands in a system, and a risk level has to be adopted in the risk management plan. Theoretical models are used to characterise risk in hydrological systems (Rossi *et al.*, 2003). The acceptable risk level is conditioned by available water resources and infrastructure and depends on demand characteristics and their elasticity.

The distribution of resources in a drought period among multiple demands in hydrological systems is a challenging task requiring careful planning. The operational rules of the system are related to resource sharing criteria, priorities among users, utilization of complementary resources and strategic reserves among others. In large systems, mathematical simulation and optimisation models should be used to obtain quantitative results accounting for all system complexities in an uncertain context. These models provide guidance in identifying critical demands, evaluating the effect of capacity building or water conservation measures, and scheduling available actions within given constraints. All models provide a measure of demands reliability, quantified as the probability that a given demand may suffer water shortages during a given drought.

Groundwater is a strategic water supply source in Mediterranean countries, and its strategic value becomes more relevant during drought conditions. Only prolonged meteorological droughts have and effect on groundwater levels. Critical level of groundwater can be derived form the minimum threshold levels associated with no impacts.

However, the availability of well-calibrated operational models is doubtful in some parts of the MEDROPLAN target area. They require a large investment in information, to evaluate resources, characterise demands, identify optimal management criteria, etc, which may not be readily available in all regions. If these models are available, they should be used in risk analysis, using indicators derived from model results to evaluate relative risks. If they are not, it can be assumed that the system is not very complex, and risk analysis can be carried out with simpler indicators.

The Chapter 9 of this publication ("Methods for risk assessment in water supply systems") makes an in-deep explanation on the ideas that are otulined in the paragraphs above.

Coping with risk in rainfed agricultural systems is a very different task of water management and the following sections focus on the components of the risk analysis within this context.

Components of the Risk Analysis in agriculture

Risk analysis in agriculture consists on identifying the productivity level that affects farmers' income (for commercial farmers) or capacity to maintain its production activity the following year (for subsistence farmers). The acceptable risk level is conditioned by each crop and area and depends on the mechanisms in place to mitigate drought, such as subsidies, policies, etc.

In this context, the risk analysis in agriculture should consider the following aspects:

(i) Probability of failure to reach an acceptable yield level for each crop.

(ii) Severity of failures (magnitude of the deficit for each crop).

(iii) Failure duration (time span when deficits occur, single year or multi-year, for each crop).

(iv) Economic impact of failures (aggregated impact on farm income).

(v) Unexpected climatic events which magnitude or duration is not included in the available time series which has to be considered when setting up the guarantees.

These factors determine also the operational rules for system management during droughts. At the aggregated level (i.e., from farm to region, or national), there are inter-dependent risk management units that implement different risk management alternatives.

The final objective of the risk analysis is to evaluate the level of risk associated with the potential consequences of drought in different systems and their underlying causes. Figure 1 outlines the sequential steps to be taken for the quantification of overall sensitivity to drought of agricultural of systems. The methodology includes the following components:

(i) Potential impacts: Ranking of agricultural impacts in the context of other potential drought impacts.

(ii) Quantification of risk: Identification of the direct consequences of drought (fair inference and attribution). This includes the application of the drought indices to establish risk level.

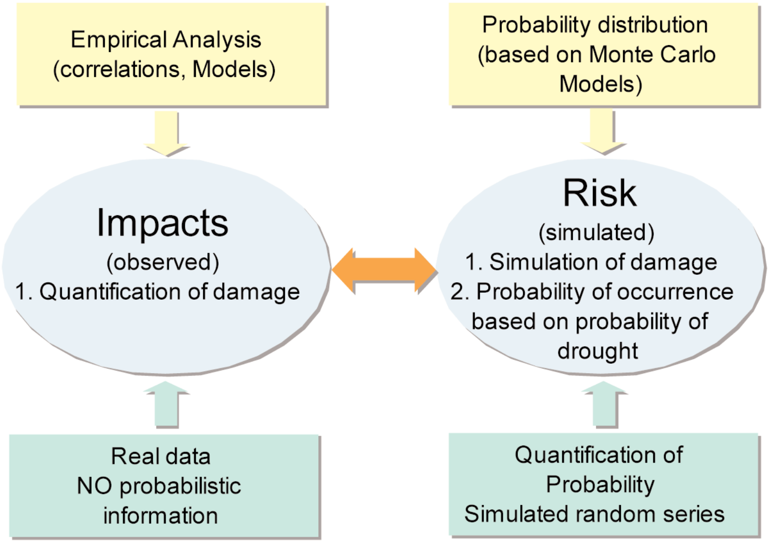

Fig. 1. Technical approach for the risk analysis in agriculture.

Definition of theoretical causal relationships between the agricultural variables and drought in order to establish solid evidence of the drought impact in the agricultural sector is essential to provide the largest possible quantitative information to place management actions or some insurance protection.

The sequential steps to be taken for the quantification of overall sensitivity to drought of agricultural of systems are:

(i) Identification of the agricultural system representative of the geographical unit and definition of the basic cost structures and revenues of the farms. For example, subsistence farmers in dryland areas or commercial irrigated farms, among others.

(ii) Definition of the variables that characterise each agricultural system. For example, crop yield, irrigation water demand, farm income.

(iii) Definition of theoretical causal relationships between the agricultural variables and drought. An empirical model may be used to find the relations between yield, climate and agriculture characteristics, using available data. The statistic tool used is the multilineal regression. The model is to be defined and calibrated for each region studied.

(iv) Statistical analysis of the correlations of drought indices with the selected variables that define the system. This step is essential for the selection and validation of the drought indices as thresholds of the drought risk. The indices that show a larger significant correlation with the impacted variables should be the ones to consider as potential triggers into the management plans. The statistical properties of the yield functions are analysed through Monte Carlo simulations, a statistical tool that allows obtaining large samples of the yield through the generation of synthetic data from the yield functions. With that large size sample, it is possible to analyse the statistical distributions of the yield function in a much more fine and precise manner.

(v) Definition and measure of a risk level. The probability distribution function measures the probability of exceeding or not surpassing a given yield in each region of study.

(vi) Definition of an aggregated measure of sensitivity of the agricultural system to drought based in the combination of the partial impacts.

Aggregation of the local results to provide regional conclusions is always a complex task, but a simple aggregated measure may be constructed by normalizing and scaling the representative variables (or proxy variables) with respect to some common baseline.

Potential impacts

Mediterranean rainfed agricultural systems are especially sensitive to drought episodes that account for large production losses, especially in marginal areas (Iglesias and Moneo, 2005). Recent drought impacts, especially if they are associated with severe to extreme droughts, are ranked more heavily than the impacts of ancient drought, since recent events reflect more accurately current vulnerabilities.

Example of calculation potential impacts in Spain

In Spain, the contribution of rainfall variability to final agricultural production has been evaluated by using empirical data (Iglesias and Quiroga, 2007). The agricultural systems under study are typical Mediterranean rainfed systems based on cereal production. The analysis was carried out in five regions of Spain that represent a range of Mediterranean farming systems.

The objective of the study is to measure the rainfed agriculture risk to drought in a way that allows making comparisons between different places with different potential yields. The method integrates both climate (hazard) and agricultural system’s characteristics (that explain vulnerability and trends of the systems) through yield functions (yield is taken as impact variable). The potential impacts quantification is evaluated by empiric models to find the relations between yield, climate and agriculture characteristics, using available data. The statistic tool used is the multilineal regression. The model is to be defined and calibrated for each region studied.

The agricultural systems under study are typical Mediterranean rainfed systems based on cereal production. The localisation and characteristics of the 5 regions of study are summarized in Table 2. Yearly time series of crop yield (y) of each site for the 1940-2000 period were used to evaluate the potential impact of climate and specially drought effect. In Fig. 2 the important and increasingly variability of the crop yields can be observed for four of the sites.

Table 2. Characteristics of the sites

Site	Lat (°N)	Alt. (m)	Tavg (°C)	Annual precip avg (mm)	Wheat avg yield (t/ha)	Yield CV
Burgos	42.37	894	10.2	630	1.90	1.65
Valladolid	41.65	734	12.1	373	2.03	2.47
Logroño (La Rioja)	42.45	353	13.4	383	2.74	2.18
Cordoba	37.85	92	17.9	674	2.24	2.70
Murcia	38.00	0	17.6	305	0.83	2.45

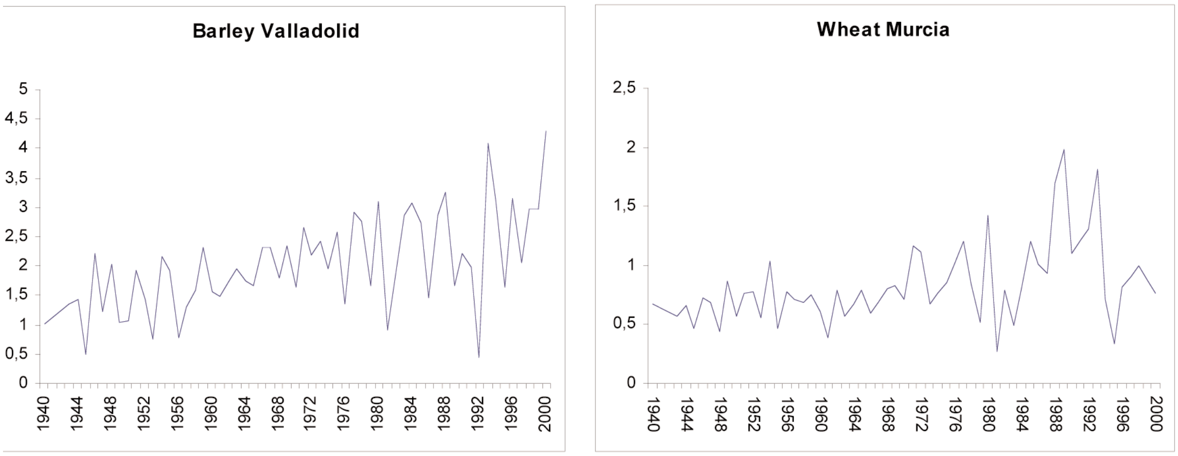

Fig. 2. Crop yield series for two of the studied sites.

The specified model has the following general form:

$$\mathrm{In}\ Y_t = \eta Y_{t-1} + \alpha_0 + \alpha_1\ Mac_t + \alpha_1\ Fert_t + \alpha_1\ Pest_t + \alpha_{2i}\ Tavi_t + \alpha_{3i}\ Fri_t + \alpha_{4i}\ Precipi_t + \alpha_{5i}\ Tmax_t + \alpha_{6i}\ Dr_t + \beta\ t^*\ Impt^*t + \gamma\ t^*\ Stpt^*t + \varepsilon t$$

Where the model output (Y_t) is the crop yield in a site on year t, and the inputs are of two types: management and climate variables. The climate variables are: temperature average (Tav_{it}), total precipitation ($Precip_{it}$), maximum temperature ($Tmax_{it}$), number of days with temperature below 0°C (Fr_{it}), and a dummy variable indicating drought years (Dr_t) based on SPI index. Management variables include farm equipment power (Mac_t), nitrogen fertilizer ($Fert_t$) and pesticide consumption ($Pest_t$), which account for large increases in crop productivity.

The results of the regressions are fully documented in Iglesias and Quiroga (2007). In which climate influence refers, the drought influence appears as a decisive factor. It can be observed, in general, that rainfed yields are affected on a negative way by the high temperature and the low precipitation on early summer time. That is because of the increase of the hydrologic stress.

For the wheat yield in Valladolid, the estimated model is:

$$\text{Ln } Y_t = 2.382126 + 0.0020\text{Mac}_t + 0.0038\text{Precip}_{may} -0.0552\text{Tmax}_{nov} -0.0937\text{Tmax}_{mam} -0.1726\text{Dr}_t -0.9205\text{ Imp}_{1956} -1{,}3424\text{ Imp}_{1992}$$

In this case, the variables that have influence on wheat yields are:

(i) The power of the mechanical equipment (Mac_t).

(ii) The precipitations on May (Precip_{may}), that affect positively to the yields.

(iii) The maximum temperature on November (Tmax_{nov}) and spring time (Tmax_{mam}) which has a negative influence over the yield.

(iv) The drought years causing low yields (Imp). There have been two especially low yield years (1956 and 1992).

The coefficients of the variables can be read as % of yield reduction: for example, a drought year causes a yield decrease of about 17% change in yield with respect to long-term average, being the most important factor of influence. The estimation of production functions can be useful to quantify the potential drought impact over agriculture. The analysis has derived in interesting comparisons of impact levels for future design of drought mamagement guidelines.

Quantification of risk

The methodology is the identification of the direct consequences of drought (fair inference and attribution), such as reduction in crop yield. This includes the application of the drought indices to establish correlations with the variables that represent the affected sectors, such as correlation of the SPI with the crop yields.

Applying the Monte Carlo simulations to the models, the distributions of yields are obtained. Monte Carlo simulation is a statistical tool that allows obtaining large samples of the yield through the generation of synthetic data from the yield functions (Gibbons and Ramsden 2005, Lobell and Ortiz-Monasterio 2006; Limaye et al 2004). With that large size sample, it is possible to analyse the statistical distributions of the yield function in a much more fine and precise manner.

The standardized yields are used to take into account the differences of agrarian production systems and yield potentials between the regions. After that, risk functions based on the simulated yields can be calculated to establish the relations between the drought hazard and the agricultural variables and to to quantify the probability of damage in order to establish the threshold levels of acceptable risk that trigger the operational management actions.

Example of quantification of risk in Spain

In Fig. 3, cumulative distribution functions of real and standarized yields are shown. The interpretation of the graphs is simple. For example, in Córdoba, the selected point C means that the probability of obtaining a yield of less than 4 t/ha is 0.8 (80%). Point C' indicates that a decrease of yield of 0.4 t/ha from the mean yield has a probability of 0.41 (41%).

The probability distribution functions allow the quantification of risk.

Ferreyra *et al.* (2001) propose an approach to quantify outcome risk for each station and climate scenario (ENSO and neutral years) based on comparing the chances of exceeding a given yield in each station with the corresponding chances for a reference station. Based on this approach, Iglesias and Quiroga (2007) develop a risk factor to compare yields variability and risk level across sites. The risk function is defined as:

$$RFi = \log 10 \; (EPCFi/EPCFr)$$

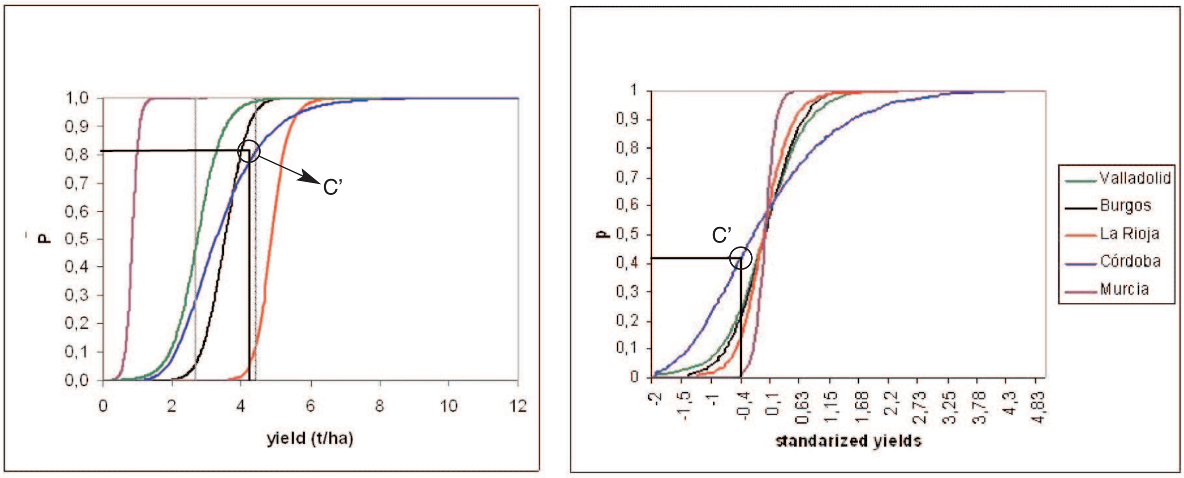

Fig. 3. Yield cumulative distributions: Real yield and standardized yield (Source: Iglesias and Quiroga, 2007).

EPCF denotes cumulative probability distribution of the variable of yield for both, the reference station (EPCFr) and the station of interest (EPCFi). In the present case, reference site is Burgos region, which was taken because it presents a yield distribution near Normal.

The RF for each location is calculated by normalising cumulative yield distributions functions that are previously derived by Monte Carlo simulations. The reference station (RF = 0) is taken as a comparison basis and two yields classes are considered: below the mean and above the mean.

For each location the RF values indicate whether yields in that station are more at risk than in the reference station. In the context of agricultural yield, the areas with highest risk are the ones that have a higher probability of having low yields. Positive RF values when yields are below the mean (lower than 0) indicate that the location has more risk because there is a higher probability of attaining low yields than in the reference station. Negative RF values when yields are above the mean (higher than 0) indicate that the risk is lower because there is a higher probability of reaching yields above the average than in the reference scenario. Figure 4 illustrates the risk factor distribution in selected Spanish locations under rainfed cereal farming systems.

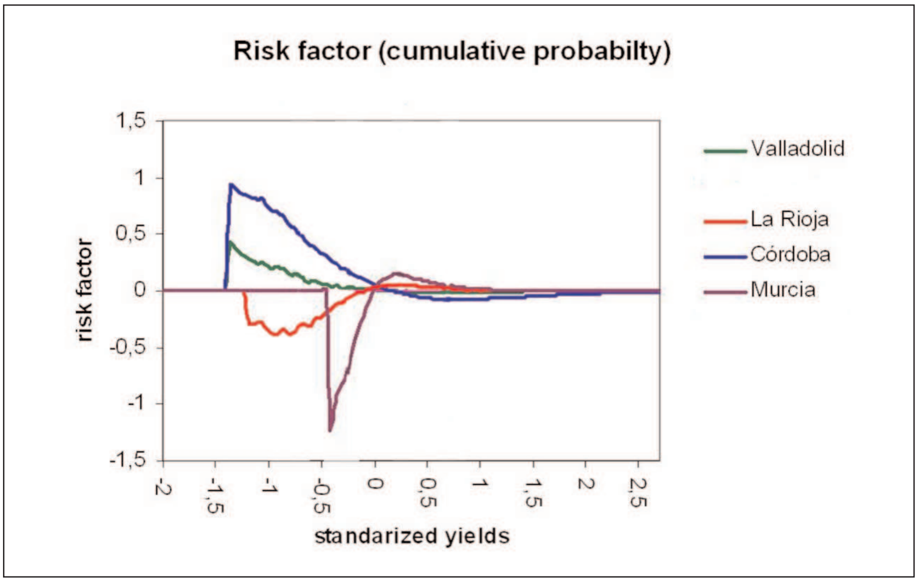

Fig. 4. Risk factor distribution in a range of standardised: below zero are lower than average yields and above zero are higher than average yields.

The risk analysis suggests the following conclusions for the selected sites:

(i) Córdoba: the probability of not exceeding yields lower than the average is much higher than in the reference region. So Córdoba has a high level of risk of having very low yields due to climatic incidences. But in the contrary, Córdoba shows also higher probability than the other regions of the study of exceeding yields above the average. The expected variation of yields in Córdoba is the highest of the 5 sites.

(ii) Valladolid shows a similar situation than Córdoba for the lower yields. Nevertheless, we can not expect exceeding the higher classes of yields.

(iii) Murcia: the risk of having much below normal yields is low. Murcia shows negative risk factors for the below normal yields, so its production has little risk of yield drops. It has also low probabilities of exceeding above normal or much above normal yields. These results mean that yields in Murcia are expected to be the most uniform.

(iv) La Rioja shows a similar distribution of risks than Murcia, although not reaching as negative values as Murcia does for the risk of having low yields.

The estimated models at the district scale detect the effect of climate, technological and management variables over different crop yields and districts, and the simulations of synthetic series of precipitation permit the generation of distribution functions adequate for the risk analysis. Inter-annual distribution of precipitations is a key issue in the levels of risk associated to the agricultural systems analysed.

Risk premium estimation

In all cases the operational risk management cannot guarantee full prevention of drought damage, and a risk level has to be adopted in the drought management plan. For example, in Spain, the drought insurance system (ENESA) has an operational drought insurance plan that establishes a risk level defined by the probability of suffering a reduction in crop yield below a pre-established threshold (acceptable risk). This threshold is defined for each crop and geographic areas and it is re-evaluated each season. Risk or Insurance premium can be estimated by using statistical and risk evaluation models and the following section shows the analysis for some of the selected sites.

Forecasts about expected future yields are very important for planning inputs production or scheduling the agrarian credits. Additional information about risk premium helps in which insurance decisions or protection levels concerns. If producers have constant absolute risk aversion (CARA), we can use the CARA utility function to calculate the risk premium from the estimated production functions and the probability of drought:

$$U(y) = -\exp\{- \rho\, y\}$$

where: "y" is the yield, and $\rho > 0$ is the Arrow-Pratt risk measure of the absolute risk behaviour (Mas-Collel *et al.*, 1995):

$$\rho = \frac{-U''(y)}{U'(y)} \ ,$$

If we denote y_{dry} as the normal yield in a dry period, which implies a reduction (η) of average yields: $y_{dry} = (1-\eta)\, y$, we can obtain the certain equivalent (as it is shown in Figure 5), as the certain value (without uncertainty) that provide the same expected utility that the expected situation, so we have:

$U[CE] = P_\theta\, U[y_{dry}] + (1- P_\theta)U[y]$, where P_θ represents the probability of drought.

Considering the CARA utility function:

$$P_\theta \exp\{-\rho\, y_{dry}\} + (1- P_\theta) \exp\{-\rho\, y\} = \exp\{-\rho[CE]\},$$

we obtain:

$$\exp\{-\rho\, y\}[P_\theta \exp\{-\rho\, \eta\, y\} + (1- P_\theta)] = \exp\{-\rho[CE]\},$$

so the expression for the certainty equivalent is:

$$CE = y - \frac{\ln[P_\theta .\exp\{-\rho\eta y\} + (1 - P_\theta)]}{\rho}$$

Of course, this certain value is lower than the expected (but uncertain) value for the farmer, and risk premium can be calculated as:

Risk Premium = EV-CE where EV denotes the expected value. So:

$$\text{Risk Premium} = \frac{\ln[P_\theta .\exp\{-\rho\eta y\} + (1 - P_\theta)]}{\rho} - P_\theta \eta y$$

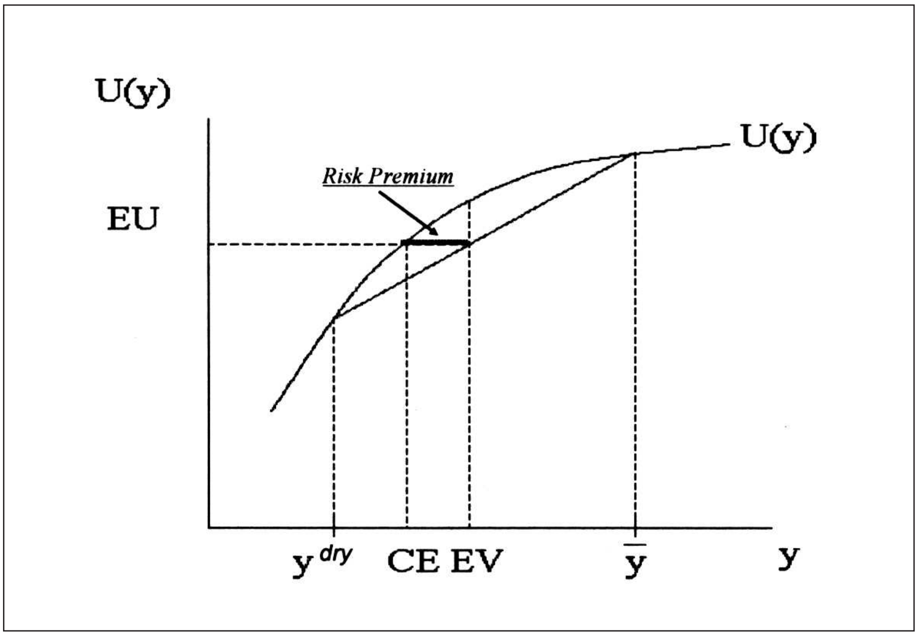

Fig. 5. Certainty equivalent (CE), expected value (EV) and risk premium given the utility function (U(y)).

Individuals' tolerance for risk varies, but, as it is mentioned on Palacios-Huerta *et al.* (2003), Goeree, Holt, and Palfrey (2002, 2003) examine several asymmetric matching pennies games and private-values auction experiments, respectively. These experiments also involve very small gambles, and total pay offs after all rounds have been completed typically range from 5 to 20 dollars per individual subject. Their estimates of ρ are virtually in all cases below 1, and highly significant across treatments and games: estimates typically range from 0.3 to 0.7, centred around 0.5. The value of 0.5 is also almost identical to that obtained in many experimental studies of similar nature that these authors cite, so we have suppose this value representing the producer's utility.

Taking into account normal yields and using the production functions and the probability of drought, we can calculate the premium risk for the cereals production as detailed above.

Example of estimation of risk premium in Spain

Table 3 summarizes the results of the calculation of risk premia for three of the Spanish sites mentioned in the previous sections.

Table 3. Risk premium (t/ha) for the wheat crop in Cordoba, Valladolid and Murcia. $P\theta$ is the probability of drough, η is the yield reduction derived from the production functions and CE denotes the certainty equivalent (t/ha)

Site	$P\theta$	η	CE	Risk Premium
Cordoba	0.230	0.176	2.609	0.014
Valladolid	0.213	0.141	3.415	0.005
Murcia	0.164	0.459	1.048	0.002

We can see that in the "normal" or average yields, the most risk site is Cordoba, followed by Valladolid and Murcia, the same conclusion that we observed in the risk functions results. However, the same analysis could be conducted in the case of "bellow normal" and "above normal" yields.

Conclusions

The chapter shows a metodology to evaluate the influence of climatic and non climatic variables on final crop yield aiming to increase the capacity of the farmers to reduce climate risks, especially those associated to drought. The estimated models at the district scale detect the effect of climate, technological and management variables over different crop yields and districts, and the simulations of synthetic series of precipitation permit the generation of distribution functions adequate for the risk analysis. Inter-annual distribution of precipitations is a key issue in the levels of risk associated to the agricultural systems analysed.

Crop production functions can be used to optimise the technological inputs as an adaptation response to climate variations. Climate risk can be managed by altering decisions before and during the growing season, such as the level of inputs (low levels of fertilizers in dry seasons versus high levels to take advance of good seasons), irrigation regimens, or insurance planning. The results highlight the need for alternative strategies to manage agricultural production in areas with water stress. Northern areas may benefit from climate change conditions while most southern and eastern locations may be very negatively affected, especially when water for irrigation competes with other uses of water.

In all cases the operational risk management cannot guarantee full prevention of drought damage, and a risk level has to be adopted in the drought management plan. Estimations for risk or insurance premium can be useful as a decision tool in this context. In the chapter we also present risk premium estimation for wheat drought risk in some selected sites.

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