The value of information for the management of water resources in agriculture: comparing the economic impact of alternative sources of information to schedule irrigation

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The present study shows a methodology analysing the role plaid by information in conditioning the criteria used to schedule irrigation by farmers. The method is applied to the problem of comparing advanced instruments (advice services) and prevailing current practices (calendar irrigation) in valuing and predicting soil water content to schedule irrigation. Such assessment approach brought to the formulation of two main hypotheses: a) the message service is valuable if those messages with higher failure consequences are enough accurate to drive decisions; b) The use of information services to plan irrigation is favoured by the increasing frequencies of irrigation intervention because of the relatively lower expected consequences of failing to meet predictions. This methodology was applied to few pilot experiments. Observed impacts substantiate model hypothesis, revealing that the introduction of advanced information systems is favoured in sub-arid climate regions and for drip irrigated crops, where it was recorded a 0% to 20% increase in gross margin and a 10% to 30% water saving. The study concludes addressing the condition justifying the use of advanced information systems to schedule irrigation intervention and offering some policy recommendation to drive the development and the early adoption of such technologies .

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Keywords: precision irrigation, uncertainty, value of information

1. Introduction

In Europe, the agricultural sector is facing new challenges driven by climate change and environmental and agricultural policy reforms. Since the early 1990s, both economists and natural scientists have paid more attention to the environmental consequences of land use, with agricultural land use clearly shown to have been one of the major drivers of climate change (Headey, 2016); in turn, climate change causes land use variation (Olesen and Bindi, 2002). In this respect, European agriculture is experiencing the expansion of suitable areas for crop cultivation in Northern regions and the reduction of water availability in Southern regions because of climate change (AEA 2007; Headey 2016; Olesen and Bindi 2002). The effect of climate changes in agriculture significantly impacts on the results of major global and European economic projections (Iglesias, Quiroga, and Diz 2011). According to Carraro (2016), climate change is also seen as a development opportunity, either because new business opportunities and additional financial resources are offered to companies operating in water sectors, or because climate change mitigation and adaptation provide new modern infrastructures and help enhancing economic development.

The new Common Agricultural Policy (CAP) reform dedicates funds for irrigation scheduling services and for supporting investments to adapt farm structures and production methods to incentivise the diffusion of sustainable practices. In this respect, during the last decade, the agricultural sector experienced the introduction of information and communication technologies (ICT) that have the potential to increase farmers' access to public and private information, facilitate agricultural data collection and improve access to financial services (Aker, Ghosh, and Burrell 2016). Lack of access to information is considered as a major problem in the agricultural sector as this contributes in maintaining unsustainable agricultural practices and resource use (Nakasone and

Torero 2016). According to Martin (2016), ICT have generally three main impacts on the agricultural sector: (i) promoting greater inclusion in the broader economy, (ii) raising efficiency by complementing other production factors, and (iii) fostering innovation by dramatically reducing transaction costs.

In the present paper, we will mainly focus on the second point, analysing the factors that might influence the profitability to adopt ICT to plan irrigation intervention in agriculture, as these technologies have the potential to increase economic efficiencies of operations by optimally matching water input to yields, reducing costs.

However, it is still missing a clear understanding of the actual usage of ICT to plan irrigation intervention and of the relevant impacts. This is because of the intangible nature of such kind of innovation. Obviously, prior to a decision of adopting ICT to plan irrigation, farmers must count the value of information against costs, as a sustainable use of the technology is contingent on its economic performances (Plant, 2001). Most farmers will decide to adopt new management practices and to begin to purchase and to learn to use the technology only when they are convinced that the time and money spent are justified by improved yield or reduced costs or risk. Thus, the decision to use new information technologies to plan irrigation starts from (quality of) information evaluation.

The identification of a methodology for evaluating the profitability to adopt ICT to plan irrigation intervention is a challenging issue due to the uncertainty caused by insufficient data availability and due to incomplete knowledge on both its cause and effects. Indeed, information about the linkage between conditions required to get a benefit from the change of sources of information used to schedule irrigation, problems that might constrain the introduction of new information sources and instruments that might be implemented to overcome problems is still missing in the agricultural economics literature.

In this respect, the objective of this study is to develope an analytical method to assess the profitability of adopting precision irrigation. The method is based on Bayesian decision theory (BDT) and assess to which extent an improvement in the available information justifies the change in the criteria used to schedule irrigation. The method is applied to the problem of comparing advanced instruments (advice services) and prevailing current practices (calendar irrigation) in valuing and predicting soil water content to schedule irrigation. Specifically, the method illustrates that better information do not necessarily imply changes in the criteria used to schedule irrigation. The transition to new information sources is rather conditioned by the consequences of using such information and the accuracy of the information itself. The method provides also an analytical foundation about the condition that might favour the introduction of advanced information systems to plan irrigation intervention.

Since the pioneering article of Raiffa (1974), a number of scholars introduced methodologies and empirical analysis similar to the one developed in the present study in different field of research. However, to our best knowledge, the use of BDT was mostly applied to count the value of information. Our methodology is rather applied to analyse the role plaid by information in influencing decision making, disentangling the process of value creation brought by information. A further novelty can be sought in the fact that the assessment approach developed in the present study is applied in the field of agriculture, with special reference to irrigation scheduling, a practice particularly sensitive to the availability of information but not yet studied in a Bayesian decision perspective.

The reminder of the paper is organized in the following sections: the literature review (section 2) is discussing how uncertainty is approached in the agricultural economic literature, motivating the criterion used to assess the viability of new sources of information. The methodology (section 3), is describing the assessment approach that was adopted, an empirical example, in section 4), where we compare different sources of information to schedule irrigation intervention at a site specific level using the assessment approach previously discussed. Finally, the last section, is discussing the main implication of the results obtained; and also is addressing limits and opportunities brought with the latest information technologies to plan irrigation intervention at the farm level.

2. Literature review

Global warming, increasing price volatility, lack of knowledge and information are among the most sources of uncertainty faced by the agricultural sector (Dovers and Handmer 1992; Just 2001).

"Uncertainty is transformed into risk when it becomes an object of management, regardless of the extend of information about probability" (Power 2007). Risk is the uncertainty that 'matters' and may involve the probability of losing money, possible harm to human health, repercussions that affect resources (irrigation, credit), and other types of events that affect a person's welfare.

A considerable number of studies over the last years have been analysing the possible effects of uncertainty in agriculture, with particular reference to the management of water resources (Perry and Narayanamurthy 1998) both at the district level (Anon 2014; Chung, Lansey, and Bayraksan 2009; Das et al. 2015; Qin et al. 2007; Sabouni and Mardani 2013; Wang and Huang 2012) and at the farm level (Carey and Zilberman, (2002). These studies agree in that the natural variability of production and the uncertain outcome associated to the management of irrigation hamper the adoption of advanced irrigation technologies. With these contributions, scholars emphasized the key role played by the decision makers attitudes toward risk in conditioning their adaptation strategies. Such scholars handled decision maker' risk attitudes as intrinsic characteristics that do not varies over time. Among these literature, Koundouri et al. (2006) found that those farmers who faces higher risk of extreme outcomes are also more informed and this increases the probability that the farmer is wishing to adopt new irrigation technologies. However, none of these studies addressed the key role that information might play in conditioning the perception of uncertain outcomes and consequently of the decision maker attitudes toward uncertain events.

But understanding uncertainty helps farmers develop strategies for mitigating the possibility of adverse events (Harwood et al. 1999). When making decisions under uncertainty and risk, there might be the possibility to receive different degrees of information prior to making the decision. More information reduces the uncertainty and facilitates improved decision-making. In BDT, the concept of "value of information" (VOI) is used as a generic term for the increase in value resulting from better informed actions (Raiffa 1974). Generally, the higher the uncertainty of the decision makers is and the higher is the value of information. Additionally, the more it will cost to use the information to make decisions and the higher the price of the next-best substitute for the information, the lower is the value of information (Laxminarayan and Macauley 2012).

The concept of the value of information has been applied in different fields like economics, finance, medicine and engineering (Chiang and Feng 2007; Koerkamp et al. 2006). Furthermore, the value of information has been estimated by different studies dealing with environmental resource management and disaster prevention (Bouma, van der Woerd, and Kuik 2009; Trigg and Roy 2007).

To our best knowledge, the VOI approach has been seldom applied to the agricultural sector. Most of the applications of the Bayesian theory to information in agriculture refers to the adoption of new varieties by farmers(Fischer, Arnold, and Gibbs 1996; Ghadim, Kingwell, and Pannell 1991; Lindner and Gibbs 1990; Marra, Hubbell, and Carlson 2001) and are about the introduction of innovation which is not necessarily linked to the improvement in the quality of information. Indeed, there is a limited discussion and application of information value into issues of agricultural economics (Adams et al. 1995; Liu, Nelson, and Ibrahim 2008). A first attempt in applying the VOI approach in agriculture was made by Adams et al. (1995). Specifically, they applied such approach to estimate the economic effects on agriculture caused by an improvement in the capacity to predict extreeme weather events early in advance to the growing season in the southeastern US. They found that increases in long-term forecasts accuracy have substantial economic value to agriculture, allowing to take precautionary measures on land uses mitigating damages.

More recently, Liu et al. (2008) developed a methodology to assess the VOI in precision farming. Specifically, they developed a methodology to assess any economic improvement in applying nutrients through variable rate application and a methodology to assess economic improvements in rationalizing land uses by applying technologies to discriminate management zones with different production potentialities. However, such methodology was not yet applied and the role played by information in improving farm performances in the field of precision farming is still unclear. Actually, there is not a clear evidence that precision farming increases profit or decreases environmental impacts (Plant et al., (2001).

The value of information approach is particularly relevant when analysing decisions regarding irrigation. An irrigation scheduling service, which provides irrigation information, can increase irrigation efficiency. Better information about crops and their environment has potential to help farmers in improving the economic efficiency of water and energy use. In this respect, the most recent innovation in the field of irrigation is under the item 'precise irrigation' (PI)and concerns the use of information and communication technologies to improve the quality of information to schedule irrigation coupling real-time micro-weather stations, plant-based sensors (e.g., reflectance, infrared temperatures or video) and numerous real-time soil water sensors scattered around the field at critical locations with a set of predictive models into a decision support system. PI practices seems to ensure higher economic returns, mainly thanks to a more rational use of inputs (Delgado and Bausch 2005; Hedley et al. 2009; Meisinger and Delgado 2002; Sadler et al. 2005; Tas et al. 2016), higher yield, and higher production quality (Cambouris et al. 2014; Fallahi et al. 2010, 2011, 2015; Montesano et al. 2015).

With respect to input uses, scholars agree in that PI practices make it possible to save labour, energy for pumping water, water and fertilizers consumption. Moreover, the possibility to differentiate the field in management zones would reduce the risk of having areas in the same field that are either too wet or too dry rationalizing the use of pumping energy and the consumption of water for irrigation (Sadler et al. 2005). Irrigation scheduling is also considered the primary management tool to reduce N leaching (Delgado and Bausch 2005; Meisinger and Delgado 2002) and to minimize the need for continuous and expensive monitoring, reducing labour efforts (Sadler et al. 2005). With respect to the production, recent studies demonstrate that with PI it is possible also to increase product quality.

Recent evidences were reported for tomatoes (Montesano et al. 2015), potatoes (Cambouris et al. 2014) and especially for fruit (Fallahi et al. 2015).

Several studies have found that the magnitude of the benefit brought about by the use of irrigation scheduling services is conditioned by a number of factors, especially: the type of crop (Evett and Schwartz 2011), the type of irrigation systems (Caswell and Zilberman 1985; Genius et al. 2013), field characteristics (Sadler et al. 2005; Sunding and Zilberman 1999), climate condition (Sauer et al. 2010) and the quality of information (Sadler et al. 2005; USAID 2012). However, farmers are hesitant to use information services to schedule irrigation, because of different uncertainties regarding the economic value of better irrigation information, especially if the availability of irrigation water is also uncertain (Botes, Bosch, and Oostuizen 1995) and by the perception of more complicated management procedures and learning needs that can be considered to increase transaction costs for the farm. These conditions substantiate the need to identify an appropriate methodology to evaluate whether an improvement in the quality of information to schedule irrigation brought by the availability of new technologies justifies the use of such technologies.

3. Methodology

The approach presented here values information for a decision maker (farmer) whose aim is to maximize expected income. Let us suppose the existence of an information service to support irrigation scheduling. With such hypothesis, farmers can decide whether to drive / or not to drive irrigation interventions through the messages delivered by the information service. Thus, farmers have two options, identified here as ‘don’t follow the message’ and ‘follow the message’. Assuming that the farmer is aware of the reliability of the message received by the information service, the choice of whether to follow the message is ultimately conditioned by his expectations on consequences (impact on revenues).

In our decision problem, we have Messages, States and Actions. Messages provide expectations about the occurrence of States in the near future. States represent the different environmental conditions under which the farmer operates and that influence crop water requirements. Actions are the possible choices the farmer can make to satisfy crop water requirements. Specifically, we consider two Messages (‘irrigate’ and ‘don’t irrigate’), two States (‘rain’, ‘no rain’), two actions (‘irrigate’ and ‘not irrigate’).

Messages, Actions and States are integrated in a sequential process where: first, the farmer receives a message by the information service; second, the farmer makes a choice among a set of alternative actions; third, the farmer faces a set of alternatives ‘States’ and suffer the consequences of his actions. Thus, following a backward induction process, the farmer takes decisions and faces expected consequences on the basis of his revised beliefs. Consistently with the BDT, we refer to farmer’s revised belief as farmer’s expectation about the occurrence of forthcoming States conditional to the message received. The sequential process so far described is depicted with the decision three reported in figure 1.

Figure 1 – Decision tree to schedule irrigation with alternative messages

To formalize our problem, we use: the term *m* for a generic message supplied by the information service; *s* for the occurrence of the State predicted by the message and $\bar{\boldsymbol{s}}$ for the occurrence of the State not predicted by the message; *a* for the action 'follow the message' and $\bar{\boldsymbol{a}}$ for the action 'not follow the message'. In this framework, *a* is coherent with m and $\bar{a}$ is not coherent with *m*. Likewise, *s* is coherent with m and $\bar{s}$ is not coherent with *m*.

In addition, we use the term $p_{s|m}$ for the probability of occurrence of the State predicted by the message and $p_{\bar{s}|m}$ for the probability of occurrence of the State not predicted by the message. If the information provided by the message is perfect, $p_{s|m} = 1$ and, consequently, $p_{\bar{s}|m} = 0$ for each message provided by the information service. On the other hand, if the information provided by the message is not perfect, $p_{s|m} < 1$ and, consequently, $p_{\bar{s}|m} > 0$ and such that: $p_{s|m} + p_{\bar{s}|m} = 1$.

Finally, we use the term $c_{a,s}$ for the consequences faced by the farmer when taking the right action and $c_{a,\bar{s}}$ for the consequences faced by the farmer when taking the wrong action. Actions causes a loss when these are not consistent with States ($c_{a,\bar{s}} \geq 0$) otherwise the consequence is null ($c_{a,s} = 0$). The expected consequence associated to each action taken by the farmer is, then, conditioned by her revised belief about the likelihood of the upcoming States. In the context of BDT, expected consequences based on farmer's revised beliefs are named conditional risk, *R*. The value of the conditional risk associated with the decision to follow the message is, then, obtained by the following equation:

$$R_{\mathrm{a}|m} = c_{a,s}p_{s|m} + c_{a,\bar{s}}p_{\bar{s}|m} \quad \forall\, m \in M \qquad (1)$$

The calculation of the conditional risk implies that both probability and consequences values are known by the decision maker. When this hypothesis holds, the message offered to the decision maker might drive his choices only if the information provided are enough reliable and the expected losses are enough small. As a consequence, the farmer decides to follow the message when the conditional risk associated to the action 'follow the message' is lower than the conditional risk associated to the action 'don't follow the message', such that:

$$R_{\mathrm{a}|m} < R_{\bar{a}|m} \qquad or \qquad \frac{p_{\bar{s}|m}}{p_{s|m}} < \frac{c_{\bar{a},s}}{c_{a,\bar{s}}} \qquad or \qquad \frac{PR_m}{CR_{\mathrm{m}}} < 1 \qquad \forall\, m \in M \qquad (2)$$

where: PR_m is the ratio between the relative error probability, wrong predictions divided by right predictions; CR_m is the relative loss, possible losses faced when disregarding messages prescriptions divided by possible losses faced when following messages prescriptions. The decision maker will decide to drive his action through the irrigation service on the basis of the ratio between the relative error probability and the relative loss. When this ratio is below 1, the conditional risk faced by following message prescriptions is lower than the conditional risk faced by disregarding messages and messages can be considered enough accurate to drive decisions. From the former equation (2) it is possible to calculate a Reference accuracy threshold, the minimum probability to correctly predict events needed to justify the decision to follow the message ($p^*_{s|m}$):

$$\frac{p^*_{\bar{s}|m}}{p^*_{s|m}} = \frac{1 - p^*_{s|m}}{p^*_{s|m}} = CR_m \qquad and \qquad p^*_{s|m} = \frac{1}{1 + CR_{\mathrm{m}}} \qquad \forall\, m \in M \qquad (3)$$

The reference accuracy threshold is an inverse function of the relative loss. This is high when the relative loss is small and low when the relative loss is high. When the probability to correctly predict States is greater than the reference accuracy threshold, $p_{s|m} > p^*_{s|m}$, then the message is considered enough accurate to drive decisions (figure 2).

Figure 2 – Relation between the accuracy of the information provided by message, m and the reference accuracy threshold for message m

The relative loss is zero if there are no consequences when disregarding messages. That implicitly means there are no rational reasons to join the suggestion provided by the message, even though the message delivered by the information service is extremely accurate ($p_{s|m} \approx 1$). In these extreme circumstances the reference accuracy threshold equals 1.

The magnitude of the relative loss is conditioned by the type of message delivered by the information service. When the message is 'don't irrigate' and the farmer choses to follow the message, then the losses suffered when failing to meet prediction are that the farmer is missing an irrigation intervention when irrigation is actually required with direct consequences on crop yield. On the contrary, when the message is 'irrigate' and the farmer choses to follow the message, then the losses suffered when failing to meet prediction are that the farmer is misusing water when irrigation is actually not required with direct consequences on water uses and irrigation costs. The reference accuracy threshold is higher for the message 'don't irrigate' and lower for the message 'irrigate'. This is depending on differences in failure consequences. That is, higher accuracy is required to drive decisions for the messages with higher failure consequences. This is the message 'don't irrigate in our problem. If the probability to correctly predict States for the message 'don't irrigate' is higher than the reference accuracy threshold, then it would be worth for the decision maker to schedule irrigation through the message service, otherwise it would be better to disregard the message. In general, the message service is valuable if those messages with higher failure consequences are enough accurate to drive decisions. These considerations allow to formulate the following hypothesis:

Hypothesis 1*: the reference accuracy threshold is likely to be lower than the probability to correctly predict events through an information service for the messages characterized by lower failure consequences and it is likely to be higher than the probability to correctly predict events for the messages characterized by higher failure consequences.*

The analysis made so far allowed to rank the messages delivered by a hypothetic information service compared to the relevant expected consequences caused by following the messages themselves and to verify if messages are enough accurate to be used to schedule irrigation, keeping constant other factors as crop type, climate condition and irrigation technologies. These factors contribute in influencing the expected consequences faced by the decision maker when using the information service.

A further improvement of the former analysis is to include a sequence of independent decision events distributed along the whole irrigating season. To simplify calculation and without loss of generality we assume same consequences for each decision event within a specific phenological stage of the growing. Such variant to equation (4) takes the following form:

$$\frac{1}{CR_{\mathrm{m}}} < 1 \qquad \forall\, m \in M \tag{6}$$

Equation (6) reveals that, when dealing with a sequence of independent events, the error probability loss ratio (lhs of equation 4) is also function of the number of decision events. For increasing number of decision events increase the discrepancy between the numerator and the denominator of the second term on the left hands side (lhs) of equation (6). This is because the probability to wrongly predict states is assumed to be lower than the probability to correctly predict states, $p_{\bar{s}|m} < p_{s|m}$ (figure 3). These considerations allow to formulate this additional hypothesis:

Hypothesis 2*: The use of information services to plan irrigation is favoured by the increasing frequencies of irrigation intervention because of the relatively lower expected consequences of failing to meet predictions.*

In the following we introduce a case study where we applied the methodology so far developed providing some evidences about the consistency of the stated hypothesis.

Figure 3 – Relation between consequences of using an information service and the quality of information for increasing number of decision events.

4. An empirical application

4.1 Data sources

The above assessment methodology was applied using the data collected in the context of the FP7 FIGARO project. The collected information allowed to estimate the consequences of using two alternative sources of information to schedule irrigation. Specifically, we compared two treatments: a first treatment that followed a 'calendar irrigation' and a second treatment where irrigation was scheduled by the means of the information service developed in the project. The first is considered the benchmark strategy where the farmer irrigate on the basis of fixed irrigation intervals with respect to a planting date. Here, any variation on irrigation intervention during the season is determined by the uses of observed rainfall amounts but no additional soil water or weather information. The latter incorporates advanced instruments (such as local weather station, soil moisture sensors and agronomic models) to estimate and predict crop water requirements in the near future during the irrigation season.

The comparison was performed for five different pedo-climatic areas (Denmark, South Portugal, South Spain, North Greece, North Italy) and five major water demanding crops (maize, processing tomato, cotton, potato and citrus) from 2013 to 2015 in the context of the FP7 FIGARO project (Table 1). Considering the whole period of field experiments, 32 comparison where made between the alternative irrigation scheduling practices.

Experimental sites where selected following three key criteria: 1) the existence of significant temporal variability in factors influencing irrigation intervention (by cultivating summer crops). 2) the presence of adequate equipment to monitor the status of the water content in the soil (soil moisture and plant sensors); 3) that information from these measurements can be used to modify crop management practices to increase profits and/or decrease environmental impacts (field scientist capacity to convert monitoring signals in messages).

Table 1 – Information on field experiments.

To carry out the assessment we collected information on yield, water uses, technical information, management practices (specifically, frequencies and duration of each irrigation intervention) and on prices. In addition, we estimated the number of decision events by fixing a time window between consecutive events defined according to technical parameters (i.e. soil characteristics, volume of water applied per irrigation intervention). We, then, estimated consequences by calculating the economic impact of taking the wrong action, that is: a) missing irrigation intervention when irrigation is actually needed; b) irrigating when irrigation is not needed. Missing irrigation causes water stresses with direct consequences on the production, hence, on revenues. Misusing water causes unnecessary expenses with direct consequences on irrigation costs (specifically, labour and energy costs). Consequences on production where estimated by calculating the differences in revenues between irrigated and rainfed crops.

Besides the information so far described, we made the following assumption to implement the above methodology:

- The consequences suffered when missing an irrigation intervention are constant. These are obtained by the ratio of the differences in revenue between irrigate and rainfed crops and the target number of effective irrigation events.
- The target number of effective irrigation events is driven by the most performing comparing experiment.
- The quality of information is constant over time (does not varies during the season).

The information collected and the assumption made so far enabled to roughly estimate variation of the comparing information sources on the quality of information and on the relevant consequences, both in term of production, water uses and income.

The term 'quality of information' in the present empirical framework is used as a synonymous of the accuracy of the messages provided by the comparing information services (probability to correctly predict States). The number of missing irrigation intervention for each treatment was computed by calculating the differences between the target number of effective irrigation intervention and the actual number of effective irrigation (then, obtained by the ratio between the total revenue and the consequences caused by missing an irrigation intervention). Further, the number of irrigation intervention where water was misused was calculated by the difference between the actual number of irrigation intervention and the actual number of effective irrigation. Finally, the probability to wrongly predict 'no need to irrigate' was computed by the ratio of the number of missing irrigation intervention and the target number of effective irrigation intervention. Seemingly, the probability to wrongly predict 'need to irrigate' was obtained by the ratio of the number of irrigation intervention where water was misused and the difference between the total number of decision events and the target number of effective irrigation intervention.

4.2 Results

Table 2 is about the information service capacity to meet predictions. The results reveal that the information service developed in the project seems to be relatively accurate for the experiments carried out in Spain, Italy and Greece, less accurate for the others. However, the experiments conducted in Italy and in Spain revealed a great variability between the different years of investigation (higher coefficient of variation). That is, the response of the service, in term of capacity to meet the predicted States, was very different among the 2013-2015 irrigating seasons. Specifically, the table include information about the number of effective irrigation intervention, when the irrigation intervention satisfies crop water requirement, the number of un-effective irrigation intervention, when the irrigation intervention is unnecessary, and the number of missing irrigation intervention, when not irrigating and failing to satisfy crop water requirements.

Such results offer a first rough approximation of the service reliability. However, this information alone is far to offer an evaluation about the service capacity to generate utility. Indeed, the service capacity to generate utility is also conditioned by the consequences suffered when taking wrong decisions. The assessment of such consequences is reported in table 3. By comparing revenues and costs per irrigation intervention of the different experiments it appears that for some experiments revenues are higher than costs (as Tomato drip irrigated in Italy, Cotton drip irrigated in Greece and Maize sprinkler irrigated (mini sprinkler) in Portugal) and for some others they are not. Moreover, costs are generally less variable than revenues. That is, it is approximately known how much the decision maker would pay if he irrigates when irrigation is not required while losses are extremely variable if the decision maker does not irrigate when irrigation is needed.

Table 2 – Information service capacity to meet predictions (the coefficient of variation is reported on parenthesis).

Table 3 – Revenues and Costs per irrigation intervention (the coefficient of variation is reported on parenthesis).

Figure 4 compares the differences in water uses (A), yield (B) and economic performances (C) between scheduling irrigation using the information service developed for the project and scheduling irrigation on a calendar basis, during three consecutive irrigation seasons (from 2013 to 2015) for different crops (Maize, Potato, Tomato, Cotton and Citrus fruits), irrigation technologies (drip and sprinkler irrigation) and pedo-climatic regions. The box-plot representation of results does not offer a clear evidence that the irrigation driven by the information service (IS) perform unambiguously better than the irrigation scheduled on a calendar basis (CI). Notably, the use of IS seems to perform better than CI for drip irrigated crops, while performances reverse when comparing IS with CI for sprinkler irrigation. The improvement of economic performances using IS (figure 4 C) is mainly attributable to water saving (figure 4 A). Less evident is the impact on yield (figure 4 B).

Figure 5 shows the relation between the Reference accuracy threshold and the probability to correctly predict events for the messages provided by the information service. Results weakly corroborate our first hypothesis showing that the probability to correctly predict events is likely to be higher than the reference accuracy threshold for the message with lower failure consequences, ‘irrigate’, and lower for the message with higher failure consequences, ‘don’t irrigate’. In any case, most of the comparison results reveal that the information service was not enough accurate to drive decisions instead of the common practice, calendar irrigation. This is particular evident when comparing crop irrigated with sprinkler irrigation systems.

Figure 6 shows the trend of the error probability loss ratio of each message provided by the information service for increasing number of decision events. Variation in the number of decisional event is attributable to the different climatic condition where the information service was tested and to the use of different irrigation technologies. The error probability loss ratio, $\frac{Pr_m}{Cr_{\mathrm{m}}}$, draws from equation (6) and it can be used to compare the results obtained from different experiments. When this ratio goes down the threshold line, whose value equal 1, then, it is worth to drive decision trough the information service instead of keeping irrigating on a calendar basis. The figure shows that irrigation scheduled through the information service tend to perform better than calendar irrigation for increasing number of decision events. This is because, keeping constant the quality of information, expected consequences of failing to meet predictions decreases with increasing number of decision events. Thus, results weakly corroborates our second hypothesis. Specifically, the error probability loss ratio curve crosses the threshold line approximately on a number of 20 decision events and 0 decision events respectively for the message ‘don’t irrigate’ and the message ‘irrigate’. We recall that higher relative failure consequences are associated to the message ‘don’t irrigate’ and lower to the message ‘irrigate’. Indeed, the message irrigate does not change actual water use attitudes for any improvement in the quality of information and for any reduction of expected failure consequences, as the farmers is assumed to irrigate on a calendar basis. This is not the case for the message ‘don’t irrigate’. Here the reduction of expected failure consequences for increasing number of decision events justify the use of the service. These results are consistent with the theoretical consideration made so far, according to which the number of decision events is a key factor motivating to schedule irrigation by the support of information services, whatever is the climate condition of a region, the cultivated crop and the irrigation technology used.

Figure 4 – Relative performances of the alternative information sources to schedule irrigation during the period 2013-2015

Figure 5 – Relation between the Reference accuracy threshold and the Probability to correctly predict events for the messages provided by the information service

Figure 6 – Trend of the Relative Error Probability Loss ratio of the messages provided by the information service for increasing number of decision events.

5. Discussion and conclusions

The interpretative model developed in the present study compares the quality of information available to the farmer against costs, namely, whether or not an improvement in the quality of information to schedule irrigation justifies the use of new sources of information. We introduced a theoretical approach, drawing from the BDT, describing the way the information source available to the farmer can improve irrigation scheduling. Such arrangement offers an explanation of the reason why farmer might behave differently in selecting information sources. Actually, there is a limited discussion on applying information value into issues of agricultural economics (Abadi Ghadim and Pannell 1999; Bosch and Eidman 1987; Koundouri et al. 2006; Lindner and Gibbs 1990; Liu et al. 2008). The interpretative model proposed in the present study differs from these approaches both in the method and in the application of the method. With the exception of Liu et al. (2008), to our knowledge, the presented empirical example is a first attempt of modelling how information might cause changes in the perception of uncertain parameters conditioning farmers irrigation practices in the evaluation stage (that is, preceding first use of the technology). Other studies focused on the adoption stage, analysing whether changes in irrigation strategies can be explained by differing knowledge on soil characteristics and weather condition and the information environment in general (Bosch and Eidman, 1987, Kondouri et al., 2006) and by analysing if changes in agricultural land uses can be explained because of differing knowledge on crop varieties performances (Ghadim and Pannell, 1999; Lindner and Gibbs, 1990). Most of the above studies show that (risk averse) farmers facing risky (uncertain) prospects are also those more 'informed' and that differences in information are positively correlated to differences in performances. Indeed, on the basis of the Bayesian decision hypothesis, learning encompass improvement in skills as well as reduction in uncertainty. Such consideration might imply that risk averse farmers make use of Bayesian rule to revise their belief. However, none of the above studies was really capable to capture changes in the information structure and the relevant impact on performances.

Besides the aspects discussed above, the present study faced different limitations and challenges, both regarding the method and especially the application of the method. On a methodological perspective, the theoretical model assumes that the accuracy of the information system is known. This is a simplification compared with real-life situations. However, this approach enabled to find more evidences around the opportunity offered with the introduction of new information sources to schedule irrigation. In addition, making explicit this issue also highlights the relevance of building realistic expectations about the quality of the tools used, that is sometimes (often?) overstated by the tools developers.

From the point of view of the empirical application, the evidences reported on a case study basis lacks a sufficient number of observations in time and space to yield very robust results. Three years of investigation and analysis were not enough to achieve very strong results and a longer testing with more replication should be sought in the future. However, the study made it possible to collect additional evidence around the opportunity offered with the introduction of new information sources to schedule irrigation. Indeed, the sources of information used by the farmer to schedule irrigation intervention are not perfect and condition his expectation on both production and water requirements.

Results reveal that new information sources perform better when comparing them with the farm practice, 'calendar irrigation', especially for drip-irrigated crops. Performances reverse when comparing the new information technology in sub-humid regions and for sprinkler irrigation. Performance improvement are mainly attributable to water saving. Less evident is the impact on yield. Results (weekly) corroborate the theoretical hypothesis made so far, bringing some evidences about the fact that for specific crops the frequencies of decisional events motivate the introduction of new information technologies to schedule irrigation, improving farmer's competitiveness and, at the same time, reducing pressures on water resources.

These opportunities brought by the introduction of advanced information technologies might also entail some drawbacks. Indeed, with the introduction of such technologies there is an increase in water productivity with a reduction of the elasticity of the demand for water. This fact might favour the expansion of the irrigated agricultural land increasing the overall consumption of water resources (rebound effect) reducing at the same time the effectiveness of some economic instruments usually adopted to control water uses, such as water pricing. Because of this drawback, policy makers should drive the adoption of information technologies coherently with the priority of intervention established in the region where they operate (competitiveness, sustainability) also discriminating the instruments to be implemented in the evaluation stage of the technology (i.e. subsidizing research) and in the early stage of adoption (i.e. subsidizing the creation of advisory services, implementing water pricing policies, providing subsidies for investments).

A further investigation on the issue of information for the management of water resources in agriculture is needed as it is still missing the linkage between possible conditions that might be required to induce farmers to change the sources of information used to schedule irrigation, problems that might constraint the introduction of new information sources, instruments that might be implemented to overcome potential problems. Therefore, there is no yet a clear understanding of whether an improvement in the quality of information available to the farmers to plan irrigation intervention is effective (capable to improve management practices) and what would be the relevant impact on the use of water resources.

On a methodological perspective, it would be worth to extend the method from the evaluation stage of the information technology to the early adoption stage and analyse the linkages between farm risk attitudes and the quality of information. To our knowledge, other studies in the field of BDT applied 'informed' and 'uninformed' probabilities in conditioning decisions as being independent from utility functions, while Bayesian learning hypothesis suggests that information might have a direct influence in the perception of uncertain events with direct consequences on the decision maker behaviour, that might vary with the availability of information assets.

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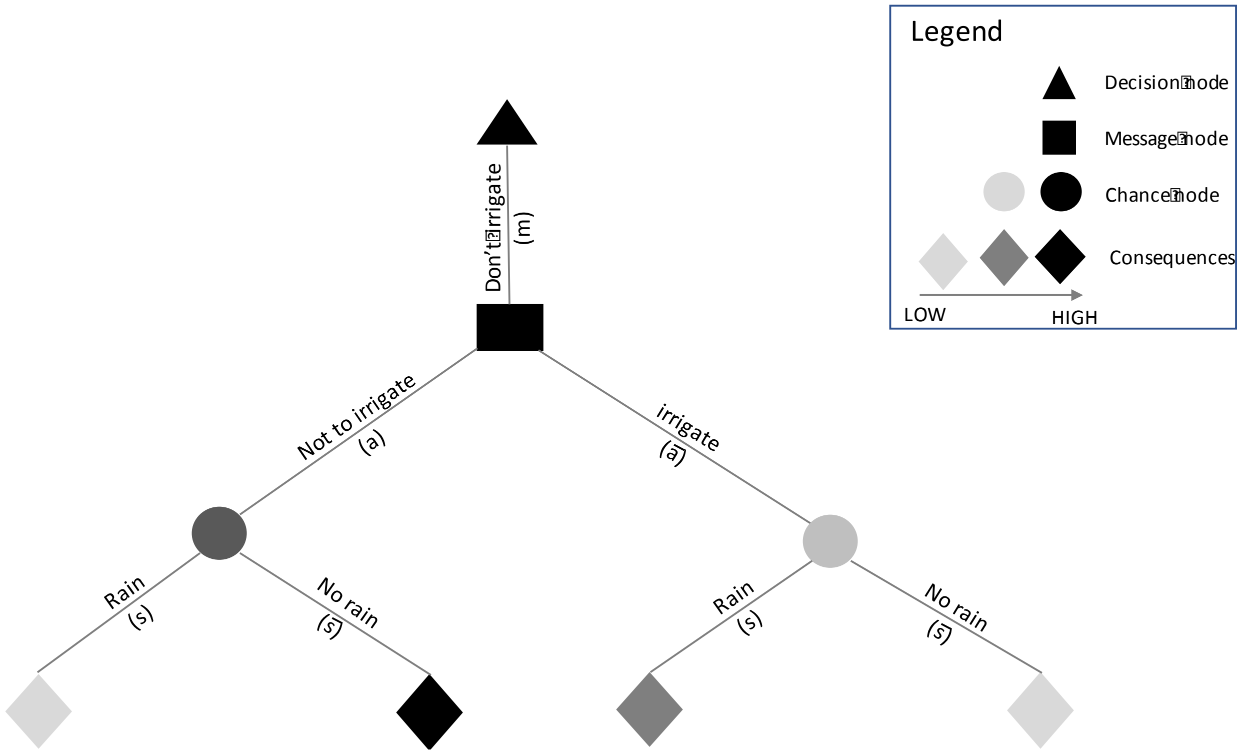

Figure 1 – Decision tree to schedule irrigation with alternative messages

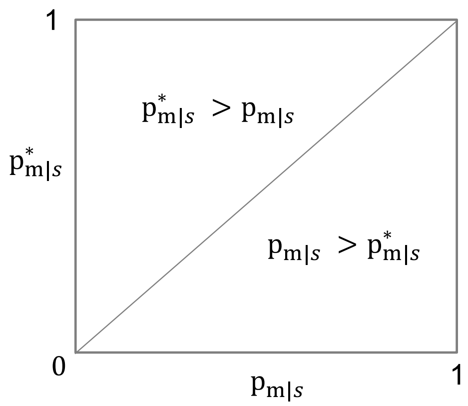

Figure 2 – Relation between the accuracy of the information provided by message, m and the reference accuracy threshold for message m.

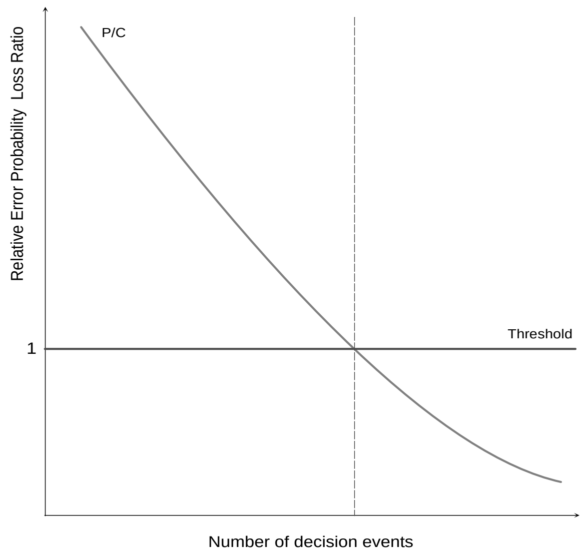

Figure 3 – Relation between consequences of using an information service and the quality of information for increasing number of decision events.

Table 1 – Information on field experiments.

Region	Crop Typology	Irrigation technology	Seasons (s.)*	Treatments (t./s.)**	Replication (r./t.)
Greece	Cotton	Drip	2	2	1
Greece	Cotton	Sprinkler	2	2	1
Denmark	Potato	Drip	2	2	4
Italy	Tomato	Drip	2	2	2
Spain	Citrus	Drip	3	2	3
Italy	Maize	Drip	2	2	2
Portugal	Maize	Sprinkler	3	2	1

* from 2013 to 2015; ** irrigation scheduled on a calendar basis VS irrigation scheduled through the information service.

Table 2 – Information service capacity to meet predictions (the coefficient of variation is reported on parenthesis).

Region	Crop Typology	Irrigation technology	Effective irrigation interventions (n)	Uneffective irrigation interventions (n)	Missing irrigation interventions (n)
Greece	Cotton	Drip	11.09	3.07	1.81
			0.55	*0.75*	*1.23*
Greece	Cotton	Sprinkler	8.24	1.36	1.96
			0.70	*1.10*	*0.97*
Denmark	Potato	Drip	8.53	5.40	4.97
			0.24	*0.45*	*0.41*
Italy	Tomato	Drip	16.36	2.41	1.78
			1.00	*1.98*	*1.78*
Spain	Citrus	Drip	123.14	2.78	1.43
			0.32	*1.91*	*2.07*
Italy	Maize	Drip	29.77	0.53	5.96
			0.11	*4.66*	*2.06*
Portugal	Maize	Sprinkler	25.15	5.35	3.05
			0.26	*0.45*	*0.99*

Table 3 – Revenues and Costs per irrigation intervention (the coefficient of variation is reported on parenthesis).

Region	Crop Typology	Irrigation technology	Average Revenues (€/irrigation)	Average Costs (€/irrigation)
Greece	Cotton	Drip	107.38	24.96
			0.62	*0.16*
Greece	Cotton	Sprinkler	99.53	55.02
			0.49	*0.09*
Denmark	Potato	Drip	50.68	33.23
			0.05	*0.48*
Italy	Tomato	Drip	372.63	67.70
			0.84	*0.77*
Spain	Citrus	Drip	19.93	6.88
			0.48	*0.57*
Italy	Maize	Drip	74.41	42.02
			0.51	*0.01*
Portugal	Maize	Sprinkler	98.23	27.31

	0.83	*0.18*

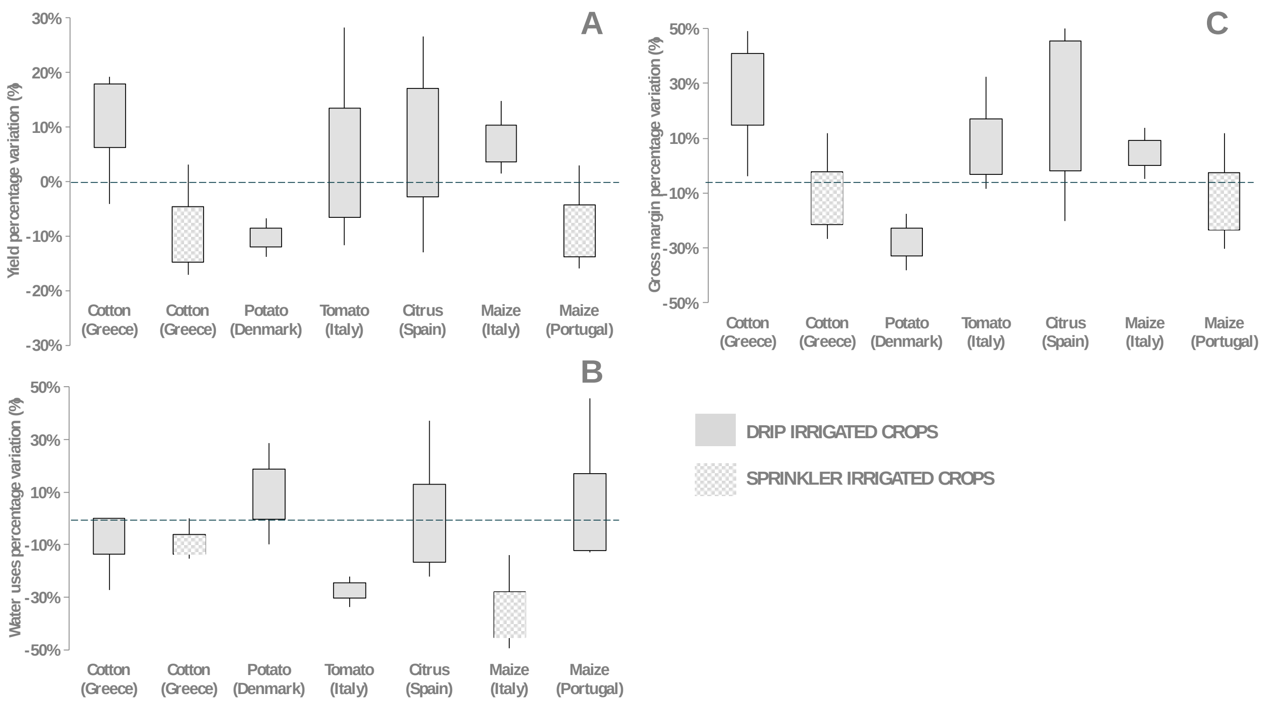

Figure 4 – Relative performances of the alternative information sources to schedule irrigation during the period 2013-2015.

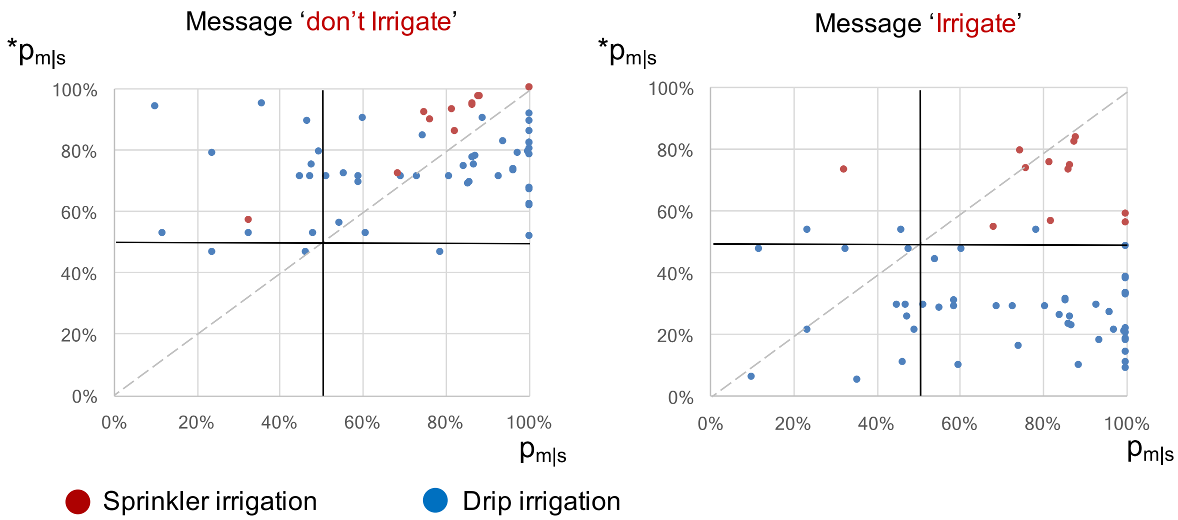

Figure 5 – Relation between the Reference accuracy threshold and the Probability to correctly predict events for the messages provided by the information service.

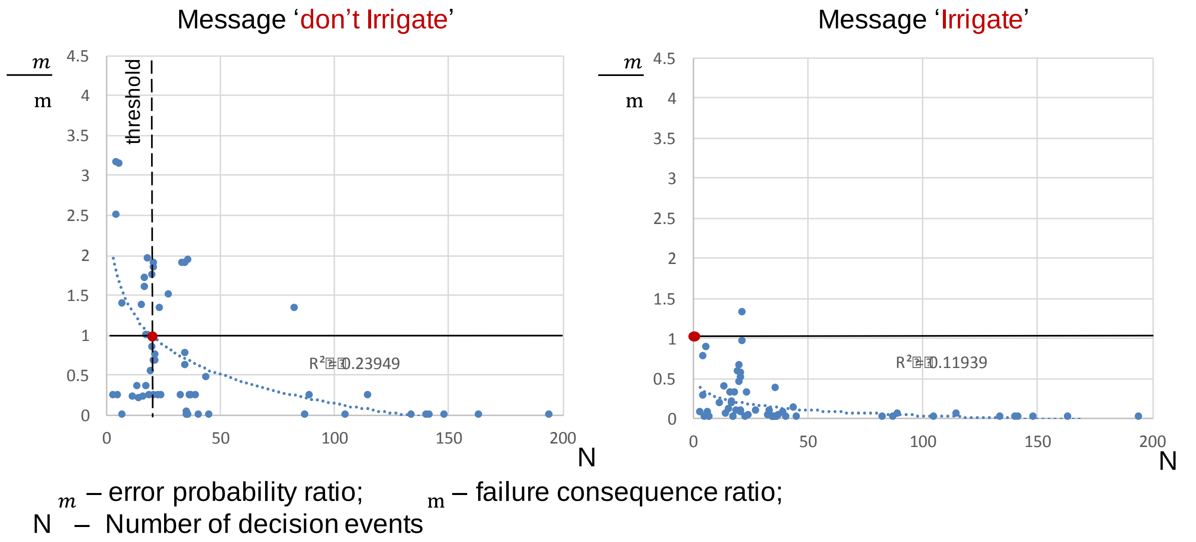

Figure 6 – Trend of the Relative Error Probability Loss ratio of the messages provided by the information service for increasing number of decision events.