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Short Communication

The economic value of a climate service for water irrigation. A case study for Castiglione District, Emilia-Romagna, Italy

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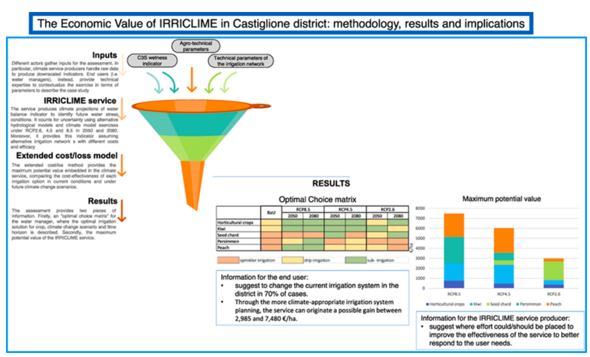
HIGHLIGHTS

- The methodology proposed can be a useful starting point to evaluate the service and contribute to bridge the knowledge gap on the possible returns originated by climate services.
- This case study shows a practical example of co-evaluation, where service developers, end users and evaluators participate.
- The IRRICLIME service can originate a possible gain between 2,985 and 7,480 €/ha in 2050 and 2080 respectively, adopting the most climate-appropriate irrigation system planning.
- IRRICLIME maximum potential value information would be valuable to the end user to implement a better-informed, profit maximizing investment plan in irrigation, accounting for climate change while getting also important insights on the value of preparedness.
- IRRICLIME maximum potential value information can be a starting verification phase that can suggest developer where improve the effectiveness of the service to better respond to the user needs.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of climate services to support decision makers in incorporating climate change adaptation in their practices is well established and widely recognized. Their role is particularly relevant in a climate sensitive sector like agriculture where they can provide evidence for the adoption of transformative solutions from seasonal to multi-decadal time scales. Adaptation solutions are often expensive and irreversible in the short/medium run. Accordingly, end users should have a reliable reference to make decisions. Here, we propose and apply a methodology, co-developed with service developers and a representative potential user, to assess the value of the IRRICLIME climate service, whose information is used to support decisions on climate smart irrigation investment by water planners in a sub-irrigation district in Italy. We quantify the value of the information provided by the climate service, that we consider the intrinsic value of the service, or the value of adaptation. We demonstrate that under three different climate change scenarios, the maximum potential value of IRRICLIME could range between 2,985 €/ha and 7,480 €/ha.

Practical implications

In this study an interdisciplinary collaborative co-evaluation approach has been used to assess the economic value of a climate service, IRRICLIME, aimed at supporting decisions of water managers in irrigation practices. While several climate services supporting agricultural activity are tailored to the "short term" featuring weather or seasonal forecasts, the service hereby considered addresses changing climatic conditions in 2050 and 2080. It is aimed to support long-term investment decisions on irrigation technologies/infrastructures, many of which, once implemented, involve sunk costs and are not rapidly reversible.

The co-evaluation engaged the evaluators, the climate service producer, and the user that share their knowledge on the methodology to apply, the service features and the characteristic of the case study location, the Italian Castiglione irrigation district, to deliver a product of practical use and utility. In the process, the end user's participation proved to be fundamental in framing "realistically" the exercise, providing information on the agrological features of the location, on current and future alternative irrigation practices and on the potential returns associated. The climate service producer re-elaborated this information "through" the service delivering an output that is usable for the evaluators. The specific evaluation method applied is the cost/loss approach extended to examine multiple time scales and scenarios.

Two main outputs emerge from the assessment. The first is an "optimal choice matrix" that schematically depicts the best (yield loss minimizing) technological irrigation option in the Castiglione district per crop and climate change scenario, compared with today's practice (sprinkler irrigation). For almost all crops, today irrigation system appears inappropriate in the future and should be changed. Furthermore, irrigation technologies should be changed over time and across crops.

The practical feasibility of this strategy is constrained by real time complexities. Firstly, as said, considering economic inertias and irreversibility is unlikely that a decision maker can change the irrigation network as often as suggested by the service. Furthermore, realistically, just one irrigation network can be implemented in the whole district, rather than one specific for each crop. Nonetheless, the service indications remain useful to orientate the decision toward what is "on average" more efficient.

The second is the monetary quantification of the "maximum potential value" originated by the service in each scenario and for each crop. This information is valuable both to the end user and to the service developer. The former can implement a better-informed investment plan in irrigation considering climate change and getting important insights on the value of preparedness. The latter can get a practical and quantitative information on the maximum gains the service can generate once applied in the customers' decision process. This can be also a starting verification phase that can suggest to the developer where additional effort may be required to better respond to the user needs.

Finally, some caveats apply to the interpretation of our results. Firstly, the value of the service is determined considering only the value of the information it provides. Service production costs or the user's willingness to pay to buy the service are not analyzed as they are part of the business model development. Secondly, the evaluation is user driven and context specific. This means that changing the location of the case study, IRRICLIME value will probably change as the user characteristics will differ. Directly linked to the previous point, our evaluation considers only the value originated for a single specific user and not a whole group or category. Finally, we do not consider feedbacks or imitation processes triggered by the decisions the informed user takes.

Data availability

Data will be made available on request.

Introduction

Developing climate services for agricultural users is an interdisciplinary process that involves many steps and actors (Haigh et al., 2018). The process should be tailored to the local context and to the needs and preferences of the intended users (FAO, 2019; FAO, 2021). One major challenge is the communication and uptake of climate-informed advisories and early warnings requiring feedback mechanisms that systematically connect the producers and users of information in co-design and co-production (Born et al., 2021). Defining the socio-economic value of climate services is a fundamental step that provides a tangible indication of possible gains from their use. However, efforts in monitoring and evaluating socio-economic benefits of the use of climate services remain weak (WMO, 2019). In fact, the WMO recognizes the urgency for a systematic documentation of adaptation outcome as well as the returns for investments in climate services. This could consolidate their use and ensure that investments in their production continue to grow (WMO, 2019). As all other phases, also assessing their socio-economic value should be a co-evaluation process.

According to the Global Framework for Climate Services (GFCS), agriculture is one of the priority areas to mainstream climate services in a robust decision-making environment (WMO, 2014). However, the studies attempting evaluations (for a review Meza et al., 2008) show that these remain challenging (Tall et al., 2018). An important difficulty is posed by the heterogeneity of services' end users and the many different decisions they can take using the climate services' information (Born et al., 2021; Hansen, 2002). In a broad sense, these services focus on the optimization of management practices to reduce adverse impacts during "bad" years and enhance the opportunities during "better-than-average and average" years (Ramasamy, 2012). In practice, this can translate in many different actions concerning, for instance at the farmer level, tillage or pesticide usage, crop rotation, and land allocation. At a more aggregated level - for example of consortia and irrigation authorities - decisions can aim to determine whether transformative changes, such as new production systems or new investments for irrigation infrastructure, are required. Temporally, actions can range from the sub-seasonal to the multidecadal scale (Fig. 1).

In this paper, we propose a methodology to assess the potential value of the IRRICLIME climate service, developed by GECOSistema Srl (https://gecosistema.com/climate-tools/irriclime/) in the context of the H2020 project CLARA (www.clara-project.eu). The service has two components, one based on seasonal forecasts and targeted on farmers, and another based on long-term projections targeted to managers of the Land Reclamation and Irrigation Authorities. The case study area is the Castiglione irrigation district depending on the Romagna Land Reclamation and Irrigation Authority for water supply. This study focuses on the second service component. The need for a long-term perspective in water management is clearly stated in the Emilia Romagna Region Mitigation and Adaptation Strategy (Emilia-Romagna Region, 2019).

Indeed, evidence of a changing climate is already detectable in the region (Emilia-Romagna Region, 2019). During the 1961–2016 period, a significant increase in both minimum and maximum annual and seasonal temperatures have been detected. Compared to the 1961–1990 period, frequency of extreme temperature increased with an average increase in temperature of 1.5 °C in 1991–2016. After the 1980s there were also significant anomalies in cumulative precipitation with an increase in the maximum consecutive number of days without precipitation, especially during summers. Under the Representative Concentration Pathway (RCP) 4.5 emission scenario regional average temperature is expected to increase by 2.5 °C in the summer and by 1.5 °C in the other seasons by mid-century. Heatwave duration and tropical nights are estimated to intensify as well. Precipitation is projected to decline in all seasons (with a 10% decline in spring) except autumn when total precipitation and extreme events are expected to increase by 20%. Similar trends are projected in RCP8.5.

This will exert direct (i.e. increased concentrations of pollutants in groundwater and surface water, increase in the level of CO_2 emissions due to the increase in temperature, and soil degradation) and indirect effects (salinity intrusion due to sea level rise) on regional agriculture. The situation is even more concerning considering that the availability of water resources in Emilia-Romagna is low compared to the other Po Valley-Veneto regions and in the light of the high leaks in the irrigation system. This will expose crops with a spring-summer production cycle to significant decreases in yields, as experienced during the 2003 and 2012 drought events. This will also translate into increased business risk due to higher costs of irrigation.

The role of IRRICLIME is to support the adoption of climate smart behavior by farmers and planners guiding a better-informed decision process on the adoption of practices such as irrigation systems and precision agriculture. In particular, the improvement of irrigation infrastructures and optimization of irrigation planning at the consortium level are key elements of future investment plans. Demonstrating the economic benefits of climate service thus represents an important means to support the use of climate-based information in decision making for investors/planners.

This said, there is a clear difficulty in evaluating long-term projection-based climate services. While for seasonal forecasts it is possible to compute the skill e.g., comparing them with a historical benchmark, this is not (or less) feasible for climate projections. It is difficult to know the accuracy of projections in advance, as such evaluation cannot include a robust measure of quality. However, this is also a key information a potential user of the service would need to accept suggestions on strategic decisions that would commit scarce resources today for the future. It is, however, feasible to develop an evaluation that assumes that the service can correctly predict future states of the world. Under this assumption, the value of the service emerging from the evaluation procedure corresponds to its "maximum potential value". This can be considered an "upper bound" for the value of the information conveyed and can still give to the user a useful reference about the maximum economic benefits extracted from using the service. This can be also the starting point to then expand the assessment further, including other elements or different assumptions in the evaluation.

In this study we assess the value of the IRRICLIME service considering (i) a perfect ability of the climate projections to predict climate change and (ii) analyzing different climate scenarios assuming they have an equal probability to happen. We acknowledge that there is a limitation in the analysis when we come to a quantification of the uncertainty associated to the results. There are multiple sources of uncertainty about the probabilities of the adverse event (i.e. water deficit), that is key element of the methodology as discussed in section 3. Firstly, an uncertainty is associated with the climate data underlying Copernicus Climate Change Service (C3S) product, *Wetness1*, that is used to produce the IRRICLIME indicator. Secondly, the intrinsic uncertainty for each climate modelling exercise considered. Indeed, the service producers consider the mean value of *Wetness1* for each climate modelling exercise and not a minimum and maximum for each exercise. Thirdly, another layer of uncertainty is associated to the use of different climate model exercises in each RCP[1] obtaining an ensemble of models capturing the spread within each RCP. Finally, similarly to the previous uncertainty source another layer is added by the use of alternative hydrological models coupled with the same climate model exercises. Only these two uncertainty sources are directly considered in this assessment since they are openly represented in IRRICLIME (see section 4). The inherent uncertainty related to the inputs to compute Wetness1 is not considered as IRRICLIME itself does not represent it.

The paper is structured as follows: Section 3 illustrates the methodology and the information exchanges among the actors involved in the co-evaluation exercise. Section 4 introduces the case study, explaining IRRICLIME key characteristics and then the data used. Section 5 shows and discusses the results of the evaluation. Section 6 concludes.

Materials and methods

In the assessment process, we apply a theoretical framework derived from the decision theory analysis. Following the definition of Murphy (1994), a climate service generates economic value not *per se* but only if it impacts the final user decision. Here, we extend the framework of the cost-loss ratio as presented in Katz and Murphy (1997).

Stating the framework formally: a potential user of the service has a decision/action space A, where at least two choices are available (a_1, a_2). Under uncertainty, the user faces a state space X which summarizes all the likely future states of the world $(x_1, x_2, \cdots x_n)$ each of them is characterized by a probability $(p_1, p_2, \cdots p_n)$. For each combination of action and future state of the world, the user gets a payoff, whose function is $\pi(x, a)$. This means that both the state of the world and the action affect the final gains/losses from each choice. Payoff π could be either costs or revenues. Here we consider costs. The user has some priors on the probabilities of future states of the world determined by what is known, i.e. a stock of knowledge (y). This can come from information produced by a climate service or from any other source say, for instance, historical climatological records or "previous experience". The aim of the decision maker is to choose the action which minimizes costs (or conversely, maximizes revenues) given the available stock of knowledge.

Given the knowledge available without the climate service $(\overline{y})$, the

[1] RCPs represent pathway results in a different range of global mean temperature increases over the 21st century due to different concentrations of greenhouse gases that will result in total radiative forcing increasing by a target amount by 2100, relative to pre-industrial levels. Radiative forcing targets for 2100 have been set at 2.6, 4.5, 6.0, and 8.5 W m^{-2} to span a wide range of plausible future emissions scenarios and these targets are incorporated into the names of the RCPs: RCP2.6, RCP4.5, RCP6.0 (here not considered), and RCP8.5.

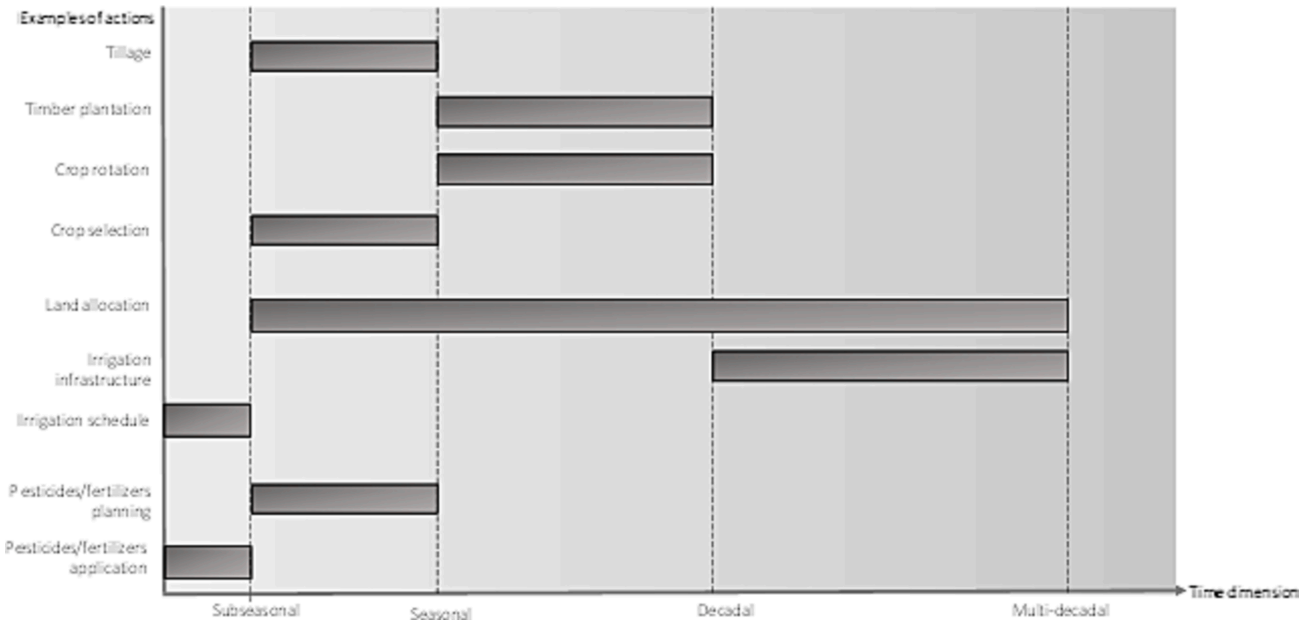

Fig. 1. Time scale and decisions supported by climate services for agriculture.

optimal action a_o is taken according to:

$$EV(a_0|\overline{y}) = min\{E([\pi(a,y)|\overline{y}, a = a_1, a_2\cdots a_n])\} \tag{1}$$

Here, the aim of the user is to minimize payoff π (expressed in terms of costs), which depends on the decision and the stock of knowledge about the future states of the world.

Give the knowledge available with the climate service ($\widehat{y}$), the user follows the same minimization rule, and another optimal decision (a^*) is taken following:

$$EV(a^*|\widehat{y}) = min\{E([\pi(a,y)|\widehat{y}, a = a_1, a_2\cdots a_n])\} \tag{2}$$

In this framework, the value of the climate service is the difference between the final payoff produced by climate service knowledge and that of the "other" knowledge source.

Formally:

$$CSvalue = EV(a^*|\widehat{y}) - EV(a_0|\overline{y}) \tag{3}$$

Let us consider a simple case of an action space A, with two options: a_0, "don't take any action" and a_1, "take a specific action". In the former option, the associated costs are zero while in the latter they equal C. Then, the state space X is composed of two states of the world: $x_0 =$ a positive state of the world and $x_1 =$ a bad state of the world. Given a_0, if the *positive* state of the world occurs, there is no loss, while in the *bad* state of the world the loss equals L. Given a_1, the outcome is C irrespectively of the state of the world. Then, we have two sets of information Y, $\overline{y}$ is the information taken from experience (i.e., the Business as Usual) and $\widehat{y}$ is the information from the climate service. Each information set conveys a different probability set. Thus, probabilities of being in the bad state of the world are $\overline{p}$ and $\widehat{p}$ respectively. Table 1 summarizes the payoff matrix and the associated probabilities under the two information sets.

The expected monetary values (costs) of the decisions according to "BaU" information are:

$$EV(a_0) = \overline{p}L \tag{4}$$

$$EV(a_1) = (1-\overline{p})C + \overline{p}(C) = C \tag{5}$$

The choice between a_0 and a_1 depends on which of the expected values is the lowest. Say for the sake of our example $C < \overline{p}L$, so a_1 is chosen.

The same holds for the climate service information set (CS):

$$EV(a_0) = \widehat{p}L \tag{6}$$

$$EV(a_1) = (1-\widehat{p})C + \widehat{p}(C) = C \tag{7}$$

Following our approach, if CS confirms the choice that would have been made under BaU information set, then the climate service has "0" value, if it suggests a different action then it has a positive value represented by the difference in the expected loss in the two cases. Formally:

$$\begin{cases} if \quad \widehat{p}L \geq C \ then \ value \ CS = 0 \\ if \quad \widehat{p}L < C \ then \ value \ CS = \widehat{p}L - C \end{cases} \tag{8}$$

This methodology is *user oriented* and *context specific*. The set of actions, the decision space, and individual characteristics change across the different users This ultimately means different values of the service. Thus, this evaluation does not capture the "societal" value of the climate service. At the same time, it measures the maximum value of the information embedded in the climate service neither considering the service production costs nor the price the final user is willing to pay. All these aspects are part of the business plan phase in the development of a climate service. This methodology analyses the individual benefit; sectoral or economy wide impacts of climate service adoption are better explored using partial or general equilibrium models. In this framework there are neither imitation processes among final users nor indirect feedbacks.

The methodology discussed above has been applied in a co-evaluation framework. The assessment involved different actors and collected the required inputs from many sources. Specifically:

Table 1
Payoff matrix and probabilities under different stocks of knowledge.

$Y = \overline{y}$	a_0	a_1	Probabilities
x_0	0	C	$(1-\overline{p})$
x_1	L	C	$\overline{p}$
$Y = \widehat{y}$	a_0	a_1	**Probabilities**
x_0	0	C	$(1-\widehat{p})$
x_1	L	C	$\widehat{p}$

(i) Probabilities of the “states of the world” according to different models and under alternative climate scenarios (specifically: RCP2.6, RCP4.5, and RCP8.5) have been delivered by the IRRICLIME service producer: GECOSistema.
(ii) Information about costs, benefits, and technical parameters to set up and evaluate the service have been delivered by the end user, that is a representative from the Romagna Land Reclamation and Irrigation Authority, whose on-site knowledge is more accurate. These parameters are determined by both physical characteristics, such as soil composition and humidity, and technical characteristics, such as the efficiency of the irrigation systems.

Fig. 2 shows how the information flows among the agents involved and the different actions to produce the assessment.

The analysis developed along different phases. The first collected raw climate data from the data purveyor (here C3S) and technical parameters from the end user. The second fed these data to the IRRICLIME service that produced an output tailored on the case study. Thirdly, the end user provided the information on the payoffs both in terms of costs of actions and benefits (avoided loss of crop production). Finally, the evaluator applied the cost/loss extended model to get the value of the service. Interactions among the actors have been multiple and multidirectional.

The case study

The IRRICLIME tool

The IRRICLIME service combines a simplified soil water balance indicator (*BIC*), that counts for water supply and water demand. The supply of water is modelled as the difference between precipitation (*prec*) and potential evapotranspiration (*ETP*) plus the irrigation availability (*I*); water demand is crop specific and changes through the growing season. Therefore, this indicator is produced for each specific crop and counts for on-farm meteorological drought (through the elements *prec* and *ETP*). The irrigation availability, *I*, is an exogenous component that considers a series of elements that are beyond the scope of IRRICLIME, such as changes in water uses along the Po River. Since the river serves multiple uses (agriculture, industry, urban environments), a change in distribution among the uses also means a change in water availability for the agricultural sector. Ultimately, this affects the water supply in the Castiglione irrigation district as well.

BIC is based on *Wetness1* data, provided by Copernicus Data Store (SMHI, 2016) at decadal values and at spatial resolution of 5 km, are validated, bias-corrected and downscaled to 2 km to predict the water irrigation needs under climate change scenarios. Depending on the type of climate data, two different downscaling procedures can be used: relative variation and absolute variation. The former applies a rescaling factor to decadal *Wetness1* values as registered by the meteorological stations located in the study area. The rescaling factor consists in the percent variation of the *Wetness1* indicator available in C3S. The latter, adds the predicted variation to the values registered by the meteorological stations located in the study area.

IRRICLIME uses a user-friendly web mapping interface to generate high-resolution (2 km) maps of the indicator through the selection of a Hydrological Model (E-HYPE, LISFLOOD or VIC421), a climate modelling exercise (CSC_REMO2009_MPI-ESM-LR, IPSL_WRF33_CM5A, KNMI_RACMO22E_EC-EARTH, SMHI_RCA4_EC-EARTH, and SMHI_RCA4_HadGEM2-ES), the time frame (2020s, 2050s, 2080s) and the climate change scenario (RCP2.6, RCP4.5, and RCP8.5). The indicator produced is connected to a series of uncertainties, from the raw data producing the *Wetness1* indicator to the uncertainty within each climate modelling exercise. IRRICLIME is able to capture only one layer of uncertainty through the presentation of an ensemble of climate modelling exercises and hydrological models in each RCP.

Moreover, the user can produce context specific output through the specification of decadal values of irrigation (mm/decadal) and of the crop’s specific coefficient of potential evapotranspiration. Finally, the output generates maps for (i) absolute value for a specific decadal (or their cumulative sum) using either a single scenario or the ensemble, (ii) relative changes for a specific decadal, (iii) number of decadal with negative cumulative sum of absolute values.

Set up of the economic co-evaluation assessment

This exercise aims to assess the value of the IRRICLIME service in the context of the Castiglione irrigation district. The climate service is devoted to advising the Romagna Land Reclamation and Irrigation Authority that is responsible for meeting irrigation demand. This district is 2,062 ha wide, and its main cultivated crops are horticultural crops, kiwi, seed chard, persimmon, and peach. Fig. 3 shows a comparison of each crop production (€/ha) and cultivated area (ha). In 2016 Persimmon and kiwi counted for roughly 3% of cultivated area but 40% in terms of value of production. Combined seed chard and horticultural crops’ area is around 90% of total and they build nearly 25% of the value of production. The exercise assumes that the same crops are available also in the future. Indeed, the end user is interested in understanding if today irrigation infrastructure can cope with climate change, thus any crop switching is not considered.

As discussed in Section 2, the evaluation depends upon the action space, the state space, the payoff function, and the information (prior and updated) of the decision maker. In our case, the user of the service is

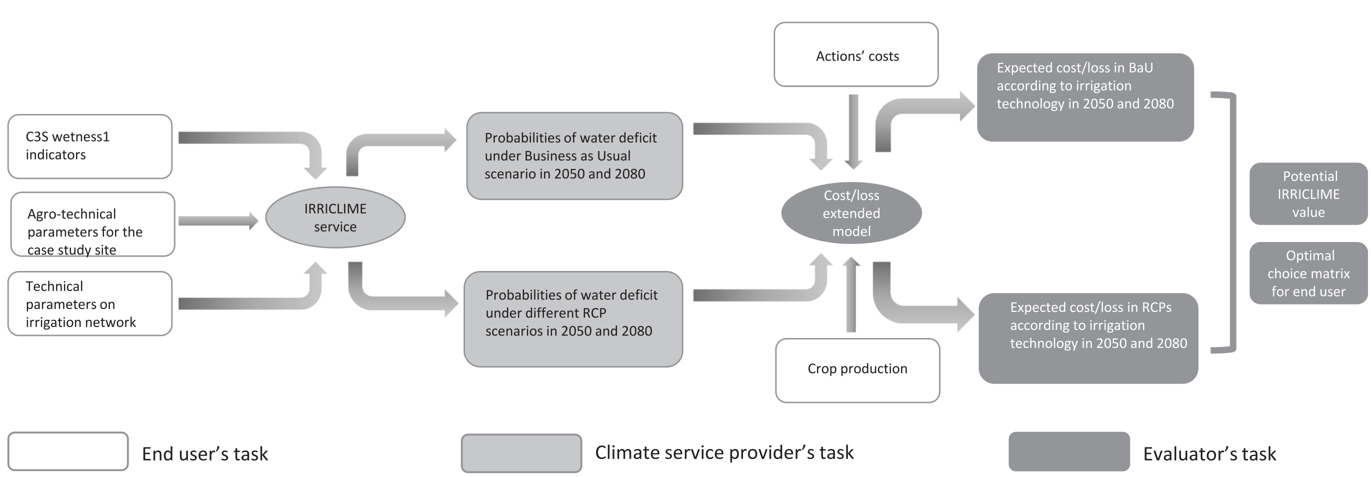

Fig. 2. Workflow of the methodology and role of involved key actors.

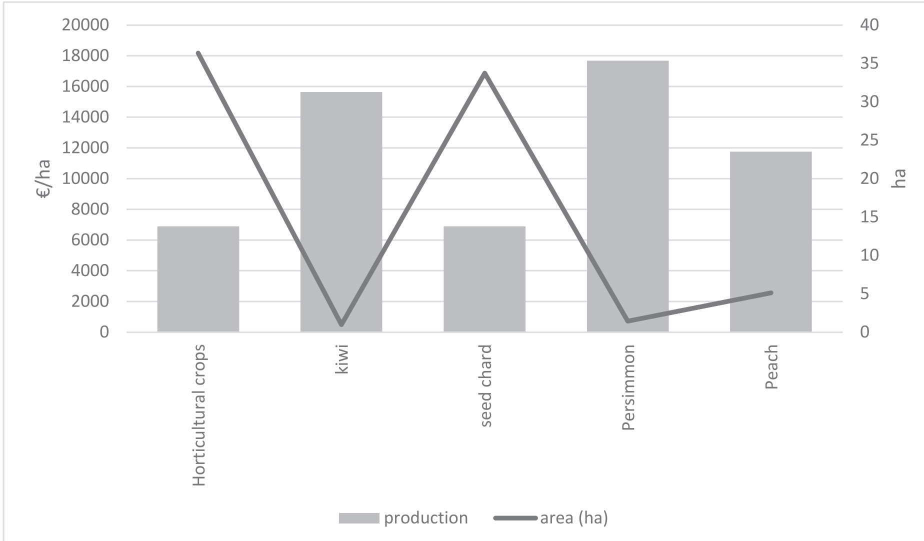

Fig. 3. Unit value of production (€/ha) and cultivated area (ha) by crop in Castiglione district (2016).

a representative irrigation manager that must decide among three alternatives irrigation systems (decision space) to meet water demand under climate change: (i) keep on using the current irrigation system (i.e. sprinkling irrigation) or investing in new, more efficient, irrigation systems such as (ii) drip irrigation, or (iii) sub irrigation. The latter is the most efficient irrigation technique available, but it has also the highest costs (DEISTAF, 2012, Table 2).

The state space consists of two alternative conditions stemming from the interaction across water supply and demand: "water deficit" and "no water deficit". The definition of "water deficit" can vary with the geomorphological characteristics of the case study. In the current case, water managers suggested that a cumulative reduction in water equal to 40 mm/decadal is the threshold beyond which reduction in crop production can be experienced. Then, on average, experiencing drought leads to a 30% loss in crop production compared to a "normal" year which is represented by 2016. In other words, our damage function is binary: either you experience "no water deficit", or you experience "water deficit" associated to the same loss independently of the severity of the water stress. This simplifying assumption is due to lack of data for the end user in defining different "severity" levels and associate losses per crop.

Both the threshold to define "water deficit" and the loss in crop yields are set according to some characteristics of the study area, such as medium soil texture, soil moisture residual conditions and medium root length for cultivated crops. Table 3 monetizes the losses per hectare and crop in the district.

These two states can be originated by a combination of climate conditions (i.e. meteorological drought, through the coefficient *prec*), crops' characteristics (ETP) and the availability of water (I). While *prec* and *ETP* are endogenous in IRRICLIME, the coefficient *I* is exogenous. This assessment assumes a 25% reduction in water availability in both 2050 and 2080, deemed realistic by the end user also in the absence of climate change.

Table 4 is the "payoff matrix". It reports the "net" costs per hectare combining crop-specific production losses and irrigation costs in the alternative states of the world. When water deficit occurs, the costs include both components. When there is no water deficit, the cost originates only from the irrigation system.

Table 5 reports the probabilities of water deficit for each crop under current climate conditions and the different irrigation systems. We assume that this is the "knowledge" initially available to the water

Table 2
The action space and the alternatives.

Action	Efficiency rate	Costs (2016 €/ha)
Sprinkling irrigation	70 %	600
Drip irrigation	90 %	900
Sub irrigation	100 %	1,200

Table 3
Crop production loss (€/ha) in Castiglione district (2016).

	Total production (€/ha)	Production loss (€/ha)
Horticultural crops	6,900	2,070
Kiwi	15,640	4,692
Seed chard	6,900	2,070
Persimmon	17,680	5,304
Peach	11,750	3,525

Table 4
Payoff matrix (€/ha).

	Water deficit	No Water deficit
Horticultural crops		
Sprinkling irrigation	5,430	600
Drip irrigation	5,730	900
Sub irrigation	6,030	1,200
Kiwi		
Sprinkling irrigation	11,548	600
Drip irrigation	11,848	900
Sub irrigation	12,148	1,200
Seed chard		
Sprinkling irrigation	5,430	600
Drip irrigation	5,730	900
Sub irrigation	6,030	1,200
Persimmon		
Sprinkling irrigation	12,976	600
Drip irrigation	13,276	900
Sub irrigation	13,576	1,200
Peach		
Sprinkling irrigation	8,825	600
Drip irrigation	9,125	900
Sub irrigation	9,425	1,200

Table 5
Probabilities of water deficit under current climate conditions (BaU), different actions and crop.

	Probabilities of water deficit		
	Sprinkling irrigation	Drip irrigation	Sub irrigation
Horticultural crops	1.00	0.00	0.00
Kiwi	1.00	0.00	0.00
Seed chard	1.00	1.00	1.00
Persimmon	0.00	0.00	0.00
Peach	0.00	0.00	0.00

manager. According to it and under the current irrigation system, namely sprinkling irrigation, it emerges that water-intensive crops, such as kiwi, and horticultural crops, are already under water stress. This could be avoided if the system was changed. Seed chard results always affected by water stress irrespectively of the system. In the Business-as-Usual situation, these probabilities stay constant in the future and in each climate scenario.

Table 6 reports the same information as in Table 5 but according to the climate service. The information is now richer as it can be differentiated across different climate scenarios and future years.

The service analyzes three Representative Concentration Pathways, namely RCP8.5, RCP4.5, and RCP2.6. Water stress is evaluated combining three different hydrological models (LISFLOOD, E-Hype21, and VIC421), and realizations from five different climate model exercises. The probabilities of water deficit in Table 6, are reconstructed as "*the number of combinations hydrological models-climate model exercise predicting a water deficit situation over their total number of combinations in each RCP*". For instance, looking at the values associated to horticultural crops in the first column of Table 6 it emerges that all the combinations hydrological models-climate models in RCP8.5 predict a "water deficit" under sprinkler irrigation. In RCP4.5 this occurs also in 2050, while in 2080 it happens only in 12 out of 15 simulations (i.e. 80 % probability). Probabilities reported in Table 6 are already a measurement of the uncertainty that the IRRICLIME tool is able to consider.

According to the knowledge initailly available to the water manager (i.e. from current climate reported in Table 5), sprinkling irrigation had to be changed in the case, for instance, of horticultural crops and kiwi. In these cases the best choice is drip irrigation that would reduce to zero the probability of water scarcity at a cheaper cost than sub irrigation. Conversely, sprinkling irrigation would be the right choice for persimmon and peach. Table 6, reporting IRRICLIME data, shows a different picture suggesting many more cases in which drip irrigation and sub irrigation are superior to sprinkling irrigation.

Table 6
Probabilities of water deficit under different RCPs, time scale and crops.

		Sprinkling irrigation	Drip irrigation	Sub irrigation
Horticultural crops				
RCP8.5	2050	1.00	0.73	0.36
	2080	1.00	1.00	1.00
RCP4.5	2050	1.00	0.73	0.40
	2080	0.80	0.66	0.47
RCP2.6	2050	1.00	0.50	0.17
	2080	1.00	0.00	0.00
Kiwi				
RCP8.5	2050	0.91	0.64	0.27
	2080	1.00	1.00	0.91
RCP4.5	2050	0.80	0.53	0.07
	2080	0.80	0.47	0.40
RCP2.6	2050	0.50	0.33	0.17
	2080	0.50	0.00	0.00
Seed chard				
RCP8.5	2050	1.00	0.91	0.73
	2080	1.00	1.00	1.00
RCP4.5	2050	1.00	0.87	0.50
	2080	0.80	0.80	0.67
RCP2.6	2050	1.00	0.50	0.5
	2080	1.00	0.67	0.17
Persimmon				
RCP8.5	2050	0.13	0.00	0.00
	2080	0.81	0.36	0.27
RCP4.5	2050	0.00	0.00	0.00
	2080	0.20	0.00	0.00
RCP2.6	2050	0.00	0.00	0.00
	2080	0.00	0.00	0.00
Peach				
RCP8.5	2050	0.45	0.09	0.00
	2080	1.00	0.73	0.45
RCP4.5	2050	0.40	0.00	0.00
	2080	0.47	0.00	0.00
RCP2.6	2050	0.17	0.00	0.00
	2080	0.00	0.00	0.00

Results and discussion

From a practical point of view IRRICLIME will deliver to the water manager, an "optimal choice matrix" such that depicted in Fig. 4. It summarizes the best irrigation solution per crop, climate change scenarios, and time horizon including "today" where instead only sprinkler irrigation is adopted.

Recalling that we are assuming a perfect ability of IRRICLIME to predict future climatic conditions and only one layer of uncertainty and comparing with what the manager would have chosen assuming persistent climatic conditions it can be noticed that, for almost all crops, today irrigation system is not appropriate. The only exceptions are seed chard and persimmon where sprinkler irrigation could avoid water deficit in RCP8.5 and RCP2.6, respectively. According to our set up, since water managers would not change their actions, in these cases the maximum potential value of the service is also zero.

In the other cases, BaU technology cannot meet the water demand and managers should change the infrastructure. Switching from drip irrigation to sub-irrigation is sufficient to avoid water stress under both RP8.5 and RCP4.5 for horticultural crops and kiwi. In RCP2.6 the choice is not univocal. For seed chard, BaU irrigation system can cope with climate change in RCP8.5 only, while for persimmon it is the best choice in RCP2.6. Eventually, the irrigation system under current climate can cope with changing climate conditions in only 30% of the cases.

The optimal choice matrix overlooks many real-life complexities. For instance, in the case of persimmon, the service would suggest changing the irrigation infrastructure in all the two reference years. The practical feasibility of this strategy may be limited due to sunk costs or technological lock ins. The exercise, in fact, assumes that each irrigation technology is completely reversible, without additional costs or constraints, assuming a lifetime for these infrastructures of nearly 30 years. Another constraint to the water manager action could derive from the fact that, realistically, just one irrigation network, and not a mix, can be implemented in the whole district which could greatly reduce the decision space of the manager.

With that said, Fig. 5 depicts the potential value of the climate service per hectare and crop under the different climate futures in 2050 and 2080.

Positive values are experienced in all the representative years across the different scenarios, but they vary by crops and periods. In RCP8.5 and RCP4.5 in 2050 the major contributor is kiwi (1,436 €/ha and 1,858 €/ha, respectively) while in 2080 the major contributors are persimmon in RCP8.5 (2,264 €/ha) and peach in RCP4.5 (1,357 €/ha). In RCP2.6, the major contributor, seed chard, is the same in both 2050 and 2080 (735 €/ha and 1,118 €/ha, respectively).

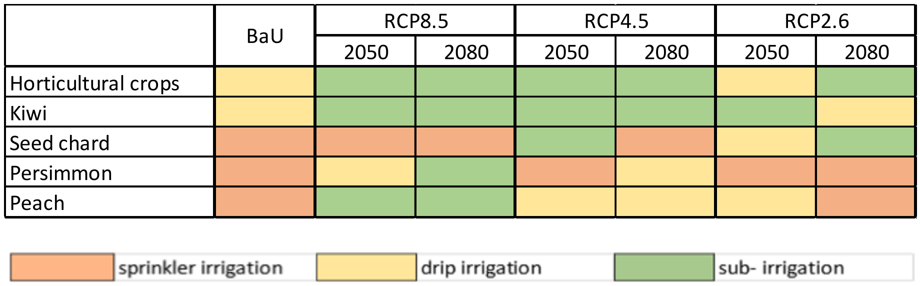

Fig. 4. The "optimal choice matrix".

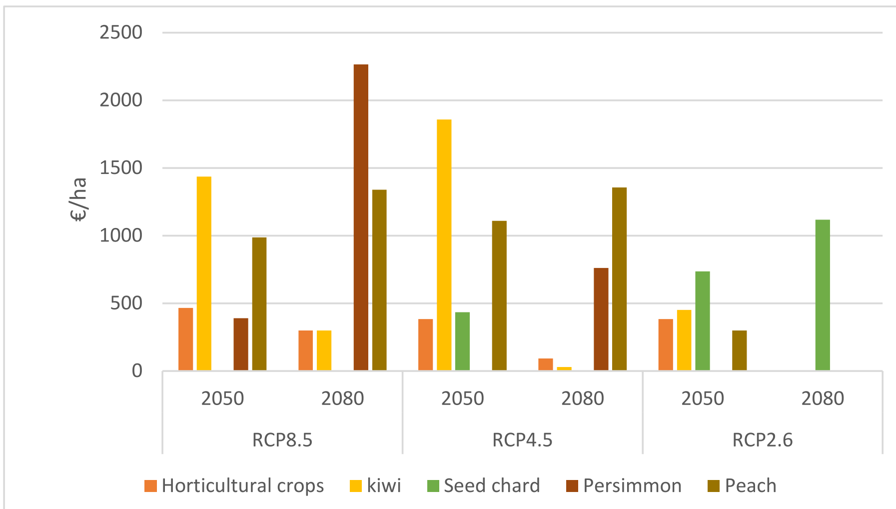

Fig. 5. IRRICLIME maximum potential value break down (€/ha).

Fig. 6 aggregates the potential value of the climate service over time summing the values originated in the two representative years of 2050 and 2080 (no discounting). The highest service value is obtained in RCP8.5 reaching nearly 7,480 €/ha. In RCP4.5 and RCP2.6 it amounts to 6,025 and 2,985 €/ha respectively. In RCP8.5 the value of the service is driven mainly by lower yield, and accordingly production, losses in kiwi, persimmon, and peach (that count for 90% of the total value), in RCP4.5 by those in kiwi and peach (70% of the total value) and in RCP2.6 by those in peach and seed chards (70% of the total value).

As one can expect the service produces higher benefits the more the future situation differs from the current one. This indeed occurs in RCP8.5.

Conclusions

This paper presents one practical case-study methodology to

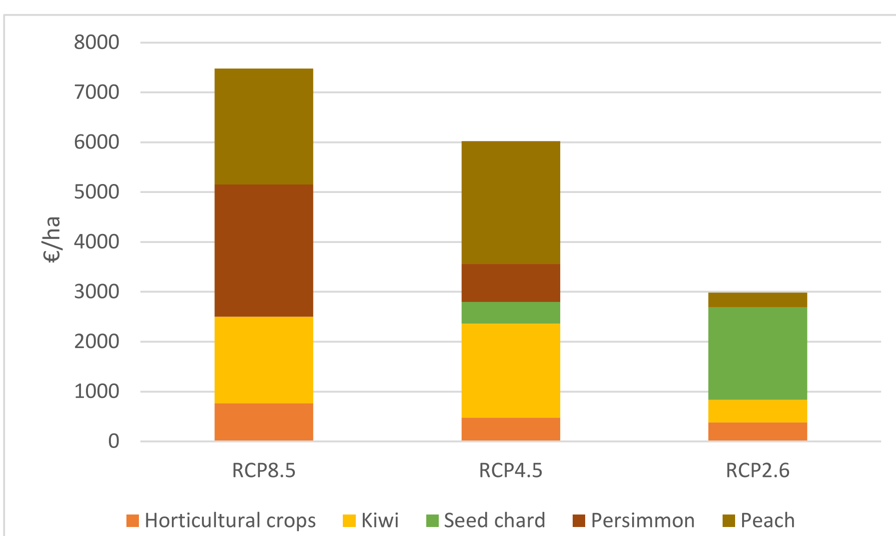

Fig. 6. IRRICLIME value according to RCPs (€/ha) aggregated by crops and over the representative years 2050 and 2080.

estimate the value of a specific climate service for agriculture. The IRRICLIME service is designed to support long-term projections of future climate conditions for water management at the Land and Reclamation Board level. The value of the service is tested in collaboration with service developers, GECOSISTEMA Srl and the potential user, the Romagna Land Reclamation and Irrigation Authority in the Italian Castiglione irrigation district, in two representative future years, i.e. 2050 and 2080, for different climate-change scenarios: RCP2.6, RCP4.5, and RCP8.5.

First, the exercise demonstrates that, based on climate service information, to optimally cope with climate change, water managers would be suggested to change the current irrigation system in the district in 70% of cases. This finding shows that the service information set is quite different from the information set assumed to be available to the decision maker.

Second, we show that the service, through the more climate-appropriate irrigation system planning, can originate a possible gain, ranging between 2,985 and 7,480 €/ha, to the user. This is also the "maximum" value attributed to the service.

The information provided in this paper would be valuable not only to the end user but also to the service developers. The former can implement a better-informed, profit maximizing investment plan in irrigation, accounting for climate change while getting also important insights on the value of preparedness. The latter can get a practical and quantitative information on the maximum gains their service can generate once embedded in the real-life decision process of their customers. This can be also a starting verification phase that can suggest developer where effort could/should be placed to improve the effectiveness of the service to better respond to the user needs.

This case study also shows a practical example of how a co-evaluation exercise for climate service could be conducted, engaging the main actors of the process: service developers, service users and evaluators.

Another issue worth highlighting is the complexity of the exercise. Notwithstanding the effort to use "real data" and engage directly all the relevant actors, many simplifying assumptions are needed to complete the assessment. Eventually, only the "maximum potential value" of the service can be quantified, that is under the assumption that the service perfectly predicts future climate, and that the user can have a perfect flexibility (no inertias or lock ins) to put in practice service suggestions. Furthermore, the value extracted, is case and user orientated. The value would be quite different in a different geographical context or if the users were different. Therefore, the current values cannot be easily generalized. Moreover, this evaluation does not consider several sources of uncertainties connected with the probabilities of the adverse event (water deficit). This means that the final "maximum potential value" obtained should be not considered as deterministic but a probability should be attached when all the uncertainties are considered. Finally, the evaluation does not consider real-life "rebounds" from the social economic context. For instance, if the service were effective in reducing yield losses, crop production would increase. This could on its turn influence crop prices and change the value of production per hectare which is the basis to evaluate possible gains from the service.

Despite the limitations, the methodology proposed in this paper can still be a useful starting point to evaluate the service and contribute to bridge the knowledge gap on the possible returns originated by climate services.

CRediT authorship contribution statement

E. Delpiazzo: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **F. Bosello:** Conceptualization, Methodology, Writing – review & editing. **S. Dasgupta:** Conceptualization, Methodology, Writing – review & editing. **S. Bagli:** Conceptualization, Data curation, Software, Writing – review & editing. **D. Broccoli:** Conceptualization, Data curation, Software, Writing – review & editing. **P. Mazzoli:** Conceptualization, Data curation, Software. **V. Luzzi:** Conceptualization, Data curation, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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