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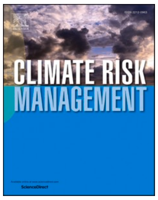

How do irrigation district managers deal with climate change risks? Considering experiences, tipping points, and risk normalization in northern Italy

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ABSTRACT

Agriculture is one of the most sensitive and vulnerable activities to climate variations; climate change impacts crop yield, soil processes, water availability, and pest dynamic. Farmers are on the front lines of climate change-induced stressors, shifts, and shocks, having to provide solutions as planners, performers, and innovators working under challenging and uncertain risk conditions. Extensive research has been carried out to deepen farmers' behavior on risks posed by climate change. However, less attention was paid to irrigation district managers, even though their essential role in guaranteeing hydraulic safety, ensuring water supply, even as on-site observers of farmers' behavior. This paper seeks to uncover the attitudes and actions of irrigation districts managers towards climate change, and their ability to gather significant information on the climate experiences of farmers in the Lombardy region, Italy. Employing a mix of semi-structured interviews and questionnaires, the exploratory approach gathered insights from the managers of the 12 public irrigation districts tasked with governing irrigation development and water management in the region. The study reveals that managers are cognizant of the shifting climate caused by warmer temperatures and extreme weather events, implementing both hard (e.g. water infrastructure maintenance, water storage) and soft (climate and weather services) adaptation countermeasures. Through their own experiences, managers brought to light the driving factors behind farmers' willingness to adopt water-saving techniques or adapt their crops, despite facing obstacles (e.g. financial investment, institutional support). In addition, the identification of tipping points related to water scarcity and security is coupled with managers and farmers' trust in technological solutions to partially counteract risk normalization. In line with the findings, suggestions were put forth to enhance managers' adaptive capacity.

1. Introduction

Climate change encompass a progressive temperature increase, irregular precipitation patterns, and a tendency to amplify the frequency and severity of extreme weather events (Raimond et al., 2020; Twecan et al., 2022). Their manifestations have been scientifically substantiated (IPCC, 2022) and are also culturally ingrained through individual and collective perceptions (Antronico

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et al., 2020; Azeem and Alhafi-Alotaibi, 2023). As farmers operate in a climate-sensitive industry, they are cognizant of the detrimental effects of climate variability on crop production (Lesk et al., 2016; Malhi et al., 2021). These include crop failure and yield reduction (Olabanji et al., 2021), pests and diseases (Pathak et al., 2021), changes in flowering and fruiting times (Dorji et al., 2020), or soil erosion and degradation (Raimondo et al., 2021). Although impacts vary in frequency and intensity across geographic zones (Ricart et al., 2022), studies cite changing crop varieties, adjusting planting dates, adopting agroforestry practices, promoting soil conservation practices, switching fertilizers, and applying supplemental irrigation as the most common adaptation strategies (Asrat and Simane, 2018; Barik et al., 2023; Kamruzzaman et al., 2023). While strides have been made, certain obstacles still hinder adaptation, such as a lack of information on the potential consequences of climate change, limited familiarity with available adaptation techniques, the financial burden of adaptation at the local scale, and insufficient access to weather forecasting services (Lamichhane et al., 2021; Song et al., 2021).

Adaptation to climate change is of paramount importance due to its place-specific nature and considering the significant role played by socio-economic, environmental, and institutional factors (Asante et al., 2021). It is widely agreed upon in the literature that comprehending farmers' perspectives is crucial in making well-informed choices and serves as the initial stage in reducing misguided or maladaptation practices (Asare-Nuamah et al., 2021; Farhan et al., 2022; Dick-Sagoe et al., 2023). However, perception is an intricate phenomenon that involves multiple psychological constructs, including prior knowledge, beliefs, attitudes, and concerns about the changes in climate (Whitmarsh and Capstick, 2018; Savari et al., 2023). Farmers face a difficult task in differentiating between normal short-term weather fluctuations and signs of climate change, as the local climate can vary greatly from day to day, season to season, and year to year (Hansen et al., 2012). Indeed, local short-term fluctuations often overshadow long-term patterns, potentially distorting our perceptions of climate change (Lehner and Stocker, 2015). Moreover, regular exposure to hazards and extreme weather events could paradoxically lead farmers to normalize or minimize risks, especially if the consequences are minimal or perceived to occur in distant locations or time periods (Schultz et al., 2014; Luis et al., 2018). Despite having positive environmental attitudes, farmers may refrain from participating in eco-friendly actions if they lack the necessary skills, opportunities, or resources, or if societal or cultural norms, values, and policies hinder their ability to do so (Miller et al., 2022).

As a result, gaining a deeper comprehension of climate change, implementing alternative adaptation strategies, and identifying factors that affect farmers' ability to adapt are key in preventing risk normalization, that is, a reduced concern about climate change risks (Addis and Abirdew, 2021). Since the early 2000s, there has been a growing interest in understanding the drivers and factors influencing farmer behavior (Hanger-Kopp and Palka, 2022; Ricart et al., 2023), considering both internal (e.g., cognitive) and external (e.g., institutional) dimensions (Mase et al., 2017; Talanow et al., 2021; Etumnu et al., 2023). The cognitive dimension addresses farmers' characteristics, experiences, background, and cultural and geographic context (Fierros-González and López-Feldman, 2021), while the institutional dimension assesses the role and confidence of leaders, policy makers, and decision-makers in mitigating climate change threats and lessening the vulnerability of farmers (Kulin and Seva, 2021). Extensive analysis has been conducted on the cognitive dimension, as irrigation district managers play an indispensable role in guaranteeing hydraulic security, advocating for water supply, and monitoring the actions and attitudes of individual farmers. However, there is a lack of research on managers capabilities and experience in addressing shifting climate conditions. It has been suggested by several studies that the successful implementation of adaptation actions, plans, or strategies using a top-down approach relies on a strong understanding and collaboration among intended beneficiaries, including water managers and policy makers (Paul et al., 2016; Fritsch and Benson, 2019; Tiet et al., 2022). In a similar vein, recent studies have highlighted the importance of considering the viewpoints of managers and policy makers when addressing the impacts of climate change. Failure to do so may lead to a disconnect with farmers' perceptions and reduce the effectiveness of climate change responses (Rust et al., 2022).

Scientists have argued that effective climate change adaptation combines simultaneous, reactive, and planned strategies implemented by farmers and related public and private entities (e.g., government agencies, river basin authorities, risk agencies, and irrigation districts) (Woods et al., 2017; Gholamrezai et al. 2021). The ultimate goal is to mitigate the consequences of climate change and associated stressors by adopting a comprehensive, all-encompassing, and collaborative policy framework for adaptation (Azhoni et al., 2018), leveraging institutional support (e.g., credit extension, training, and expertise) for farmers to obtain up-to-date information and cost-effective solutions to manage climate-related uncertainties (Khan et al., 2020). However, the scientific community has not fully explored the experiences and perceptions of some public entities, such as irrigation districts (with some exceptions addressing water scarcity risks, e.g., Ronco et al., 2017).

Irrigation districts are public economic entities of an association nature that are responsible for planning and managing water distribution, ensuring hydraulic safety, promoting multiple uses of water, preventing and protecting against natural disasters, and developing and implementing action plans to reduce farmers' vulnerability to climate change (Zagaria et al., 2021). Moreover, managers and technicians are able to accumulate farmers' experiences, exchange insights on the effects of extreme weather events, and evaluate their resilience to climate change (Guo et al., 2021) to promote effective risk management at the irrigation area level (Duong et al., 2019). This paper aims to enhance risk management by assessing irrigation districts managers' perspectives on key climate-related impacts, adaptation measures and barriers, considering social learning processes and site-specific narratives derived from their interactions with farmers. Therefore, this study distills a threefold objective: (i) to identify irrigation districts managers' awareness of climate change, perceived impacts, and main adaptation actions and barriers, (ii) to explore the cognitive and external factors influencing farmers' perceptions arising from their feedback with managers, and (iii) to highlight tipping points and discuss whether a process of risk normalization is occurring. The study is organized as follows. Section 2 describes the case study in the Lombardy region, while Section 3 outlines the research methodology, which involves gathering data from semi-structured interviews and complementary questionnaires, and analyzing the data through text coding, descriptive statistics, and causal loop diagram. The outcomes of the study are reported in Section 4 and discussed in Section 5, which covers concluding statements, research limitations, and potential avenues for further investigation.

2. Case study

In northern Italy, the Po valley encompasses a complex water system managed under a multi-objective perspective to accommodate different water interests, namely agriculture, hydropower, flood control, tourism, recreation, and environmental protection. The area is one of the most densely populated and hosts almost half of the Italy's industry (Zullo et al., 2019), while it is recognized as one of Europe's most productive agricultural areas, providing one-third of the country's agricultural output (Casale et al., 2021) and accounting for more than 10 % of this value (CREA, 2021). Approximately 40 % of the total area in Lombardy is dedicated to arable land, with the primary crops being maize, rice, wheat, meadows, and soybean. Water management depends on a complex system of rivers, lakes, regulated reservoirs and canals located mainly in Lombardy. Nearly 52,000 farms are scattered across an area of less than 600,000 ha, which means a quarter of the total irrigated area and about a third of irrigation water usage nationwide (ISTAT, 2014). The regional authority oversees 12 irrigation districts, which are public entities responsible for maintaining hydraulic security and supporting water for irrigation by holding primary water rights (Fig. 1). Under the Regional Association of Irrigation Districts (ANBI Lombardy), irrigation districts and five lake regulatory agencies provide support, guidelines, and training for the effective implementation of water-related activities and reclamation efforts to boost rural development. In this context, it is important to examine the attitude of irrigation districts' managers, given (i) the amount of authorized water detour (over 800 m^3/s) faced with multi-objective water scenarios, and (ii) their historical perspective resulting from centuries of extension of their activity in constant interaction with farmers.

The hydrometeorological regime of the area is typical of subalpine regions, featuring dry spells in the winter and summer months and peaks in the late spring and autumn seasons, nourished by snowmelt and rainfall, respectively (Giuliani et al., 2020). The annual precipitation ranges from 700 to 1,200 mm/year, with the highest levels occurring during the autumn and spring seasons. Snowmelt between May and July serves as the primary water source for accumulating seasonal water storage, which is later used for summer irrigation (Giuliani et al., 2020). However, progressive reductions in average flows and earlier declines in high spring flows are attributed to shifts in snow accumulation and melting dynamics, alongside a strengthening of low summer flows (Casale et al., 2021). In addition, precipitation events are becoming less frequent, yet more intense, which could lead to severe water stress for agricultural areas, exacerbated by increasing temperature that alters the hydrological regime (Vezzoli et al., 2015). In 2020, the country experienced almost 1500 severe weather events, a significant increase from previous decade where there were less than 400 events, as reported by the European Severe Weather Database (ESWD, 2022). Over the last two decades, the Lombardy region has experienced a succession of hydrological disasters such as flash floods, climatological events like convective storms and droughts, and meteorological phenomena such as cold and heat waves, according to the Centre for Research on the Epidemiology of Disasters (EM-DAT, 2022). The Po River Observatory has identified certain occurrences as extraordinary events, including the 2022 drought during spring/summer.

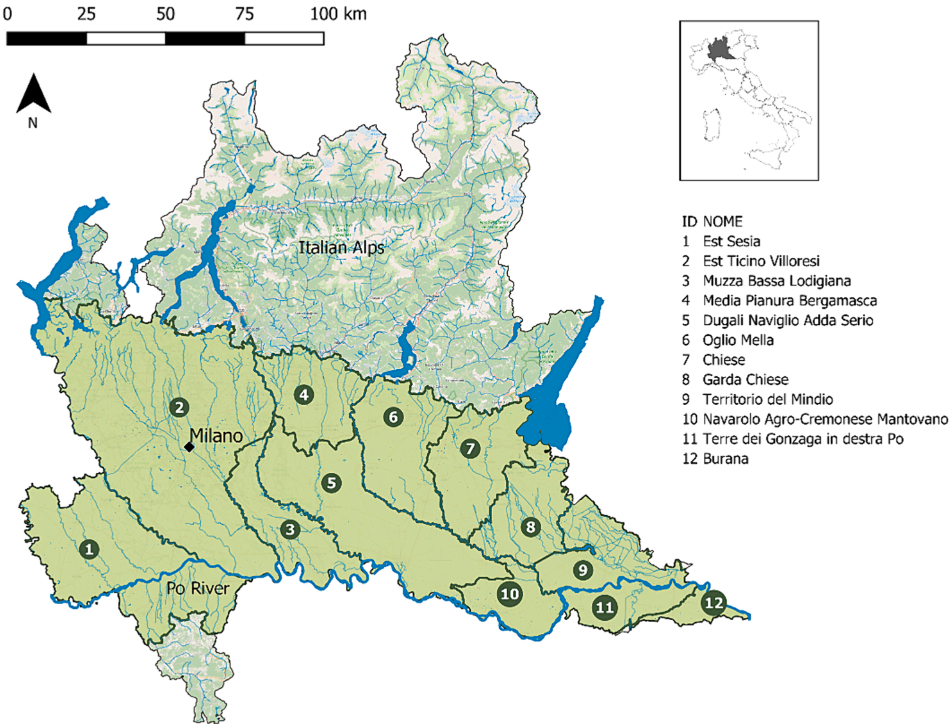

Fig. 1. The Lombardy region with irrigation districts area.

This drought, which was the most severe in 70 years, followed a 70 % decrease in winter snowfall, a prolonged heatwave (with July temperatures exceeding the average in 2.3 °C), and a significant drop of 52 % in precipitation in comparison to the average levels recorded between 1991 and 2020, including no rain for more than five months. The first evaluation of 2023 is not encouraging: water levels in the major lakes were noticeably lower than seasonal levels, and the Po River's flow does not seem to be recovered from the severity of the drought in 2022. The aftermath of this situation is expected to increase consciousness of the impacts posed by severe droughts to the fulfillment of agricultural water requirements (Bonaldo et al., 2023).

3. Data and methods

3.1. *Data collection*

It is increasingly recognized that effective climate risk assessments benefit from well-crafted processes of knowledge co-production involving key stakeholders (André et al., 2023). Accordingly, we followed a stakeholder engagement approach to recap the way in which irrigation districts managers perceive and respond both individually and as influenced by their social interactions to promote cognitive feedback (Hovardas, 2021) and contribute to reinforcing social learning processes based on potential changes in the system performance and a shared vision for collective actions (Eriksson et al., 2019; Ricart and Kirk, 2022). We adopt a mixed-methods approach (O'Connell and Osmond, 2022), beginning with a qualitative, semi-structured interview with irrigation district managers to recap their views on climate change risks and management, as well as using a triple-loop questionnaire to systematically gather information on their awareness, perceived impacts, adaptation actions, and barriers. We interviewed the director of the irrigation district's board or, alternatively, the water operations and field service manager who is in closest contact with the farmers, in order to gain a comprehensive overview of both policy and technical expertise. The entire public irrigation districts in the region (12 in total) were interviewed: Est Sesia (D1), Est Ticino Villoresi (D2), Muzza Bassa Lodigiana (D3), Media Pianura Bergamansca (D4), Dugali Naviglio Adda-Serio (D5), Oglio Mella (D6), Chiese (D7), Garda Chiese (D8), Territori del Mincio (D9), Navarolo AgroCremonese Mantovano (D10), Terre dei Gonzaga in Destra Po (D11), and Burana (D12) (see full details of irrigation districts' characterization in Table A1).

The data collection process was divided into two parts. For the first part (interview), we devised a script to gather details on 1) the attributes of irrigation districts, 2) primary concerns regarding climate change scenarios and water supply, and 3) awareness and experiences of extreme weather events, including narratives and assessments of potential risks. The content was shaped by open-ended questions, which encouraged detailed and thorough answers (Veisi et al., 2022). The script was pre-reviewed and pre-tested by technicians from two irrigation districts in order to ensure its effectiveness and appropriateness. Part two encompassed a concise questionnaire addressing perceived effects of climate change, methods for adaptation, and main obstacles to adaptation. We reviewed the literature (e.g., Ado et al., 2020; Assan et al., 2020; Singh, 2020) to identify the most common drivers related to each dimension for the period 2010–2020. In light of the geographical and climatic factors affecting our specific study area, we have formulated a standardized list of statements outlining the predominant perceived impacts (14), adaptation actions (20), and barriers (9). The objective was to reinforce and evaluate its coherence (in terms of resemblance) with the overarching statements acquired during the interview (particularly, the risk assessment segments). Response options were scored as 'Yes', 'No', and 'I do not know' for convenient comparison between irrigation districts profiles.

Managers were contacted by phone or email, with some previous and additional recruitment provided by ANBI Lombardy. During the initial contact, the purpose of the study was explained in general terms and managers were asked to participate in the study, obtaining their informed consent. Each manager was interviewed individually and virtually. The interviews, which were held in Italian, took place during February and March 2022 and lasted for 50 to 90 min each. They were recorded for transcription, translation, and coding purposes.

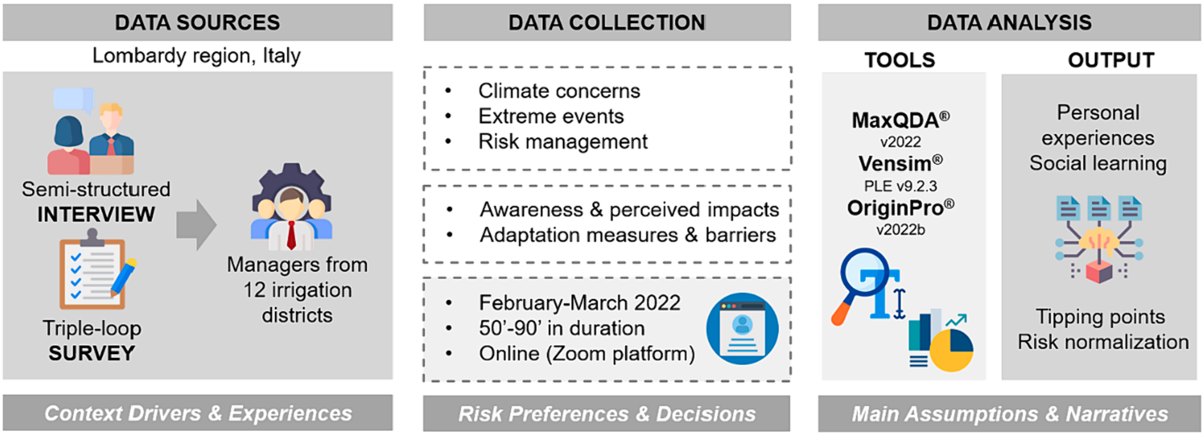

Fig. 2. Methodological process.

3.2. Data analysis

The research employs a mixed method of qualitative and explanatory comparative analysis, incorporating a case-based (or horizontal) and issue-based (or vertical) approach (Thomann et al., 2022) (Fig. 2). The first approach focuses on managers' behaviors to bolster conclusions drawn from cross-case comparisons, while the second approach emphasizes greater knowledge sharing and reliance between their perspectives. Both approaches require that the interviews be transcribed verbatim (by a professional service provider) and translated into English, followed by coding through MaxQDA® software (v22). The iterative technique was applied, with the analysis including three concurrent procedures: 1) Identifying key themes and subthemes from the narratives, 2) Synthetizing inputs from these themes and subthemes (i.e. main ideas or concepts found in data) to create a list of codes, and 3) Cross-checking inferences and correlations among codes to verify prominent findings, recurring ideas, and common trends across managers' narratives (Jenkins et al., 2023; Tofu et al., 2022).

The coding process followed an inductive approach (Azungah, 2018) used to create a codebook with a preliminary list of codes identifying main themes and subthemes before reaching a theme saturation (i.e. the point when no additional issues are identified and the codebook begins to stabilize) that allowed us to build the foundation for grounded theory (Saunders et al., 2018). In the coding process, we applied an *open coding* process, in which data is reviewed segment by segment to identify themes and emerging patterns and concepts without predetermined categories, and marked segments of text are directly recorded in numerous new codes. Then, we applied an *axial coding* process, which involves a more focused and systematic examination of the data to identify relationships between codes identified during the *open coding* phase. This process aims to establish linkages between concepts, exploring how they relate to each other and contribute to underlying the structure that emerges from the data. A list of 44 codes (subthemes) was identified and grouped into six categories (themes) to standardize managers' narratives and the range of factors influencing their views: 1) farming characteristics, 2) concerns, 3) extreme weather events, 4) perceived impacts and awareness, 5) adaptation actions, and 6) risk management (see coding details in Figure A1). To determine intercoder reliability (ICR), codes and sub-codes were carefully reviewed by an external researcher after being coded by the first author, and a few discrepancies were noted (e.g., sentence expansion, code assignment). ICR was calculated using Cohen's kappa, with a value of $k = 0.89$, indicating very high intercoder reliability of code system categorization.

The triple-loop questionnaire was examined using OriginPro 2022® in order to document the distribution, central tendency, and variability of the managers' responses. We incorporated descriptive statistics, including mean, frequency, percentage, and standard deviations to depict potential disparities in perceived impacts, adaptation measures, and barriers. In parallel, mental models (MMs) were employed to pinpoint managers' perceptions (Clements et al., 2021) underlying their views, social construction, and management of climate change risks (Findlater et al., 2019) as a first step toward developing effective risk management strategies. As a result, we developed a causal loop diagram (CLD) using VENSIM® by merging insights from interviews and questionnaires to visually represent the key assumptions and cause connections that shape managers' views on climate change (Coletta et al., 2021), then be considered a fundamental basis for constructing an articulated theory of behavior simulation (Hensel et al., 2023).

4. Results

The codification process resulted in a total of 510 quotes (see Table A2 to check the top3 most frequently cited subthemes and narratives for each irrigation district). The subsequence sections showcase key messages that encompass the primary narratives, each corresponding to a designated manager identifier (D#). To start off, we outline contrasting problem environments that influence the actions and decisions of managers, including internal (agricultural sector) and external (multifunctionality of water) factors. Then, we recapitulate narratives of extreme weather events by illustrating the most frequent episodes and statements. Storylines on drought and flood events and their plausible connection to perceived climate change impacts are then analyzed to raise awareness of climate change. By synthetizing the input data, we bring attention to the main options and barriers for adapting to climate change. Finally, we identify farmers' heuristics as tipping points to explore the prevalence of both hard and soft adaptation pathways, as well as strategies to enhance risk management.

4.1. Concerns

The majority of managers see agriculture as highly vulnerable to physical impacts of climate change (D4) and also socially at risk due to uncertain generational change (D10) and a lack of recognition for farmers' role in the agri-food chain (D7). Some managers believe that not only farming practices, but also the rural environment and associated landscaping, are at risk (D5) if substantial and well-planned investments are not taken to secure a reliable water supply (D3). Within this scenario, most managers believe that water supply is becoming limited as the irrigation session grows longer. This is largely attributed to the rise in horticultural production (e.g., tomatoes), which may not use a significant amount of water but still requires it on a daily basis (D8), often starting in February or March rather than waiting until May (D12). The latest developments in rice farming techniques to improve water efficiency have not gone unnoticed by managers. However, the implementation of the alternate wetting and drying (AWD) irrigation method aggravates water shortages as it has resulted in a shift in peak water consumption for rice to the summer session, coinciding with that of maize, making it challenging for the irrigation district to maintain sufficient water supply during the irrigation campaign (D2).

Moreover, certain managers are concerned about the impact of water-saving techniques on groundwater levels, as replenishing aquifers and spring wells in a timely manner is necessary for preserving environmental integrity (D1). Managers unanimously acknowledge the importance of incorporating the environmental dimension into irrigation practices, especially in relation to the ecological river flow. Nevertheless, the controversial issue concerns the method employed by the regional authority in revising the ecological river flow rates for water distribution points, including irrigation canals. Some managers have expressed frustration with the public administration's lack of empathy towards the agricultural sector, citing not enough discussion during the implementation of the new methodology (D3). This is further exacerbated by the fact that some managers are willing to share their experimental findings from pilot studies (D2, D3). Within this scenario, many managers stress the utmost value attributed to the river, while neglecting the role of the irrigation canal network and even the role of the farmer in preserving a harmonious ecosystem (D2). Some managers are concerned that the new criteria may pose a threat to the agricultural sector (D7), particularly if irrigation water needs to be reduced in the summer months (D5).

The increased demand for water in summer exacerbates this scenario as long as the main crops are cereals and horticulture, which are water-dependent. Moreover, the last 20 years have witnessed the expansion of irrigation practices in previously untapped areas, driven by the cultivation of new crops (watermelon, melon) (D9), while clayey soils must be kept moist for most of the day during summer to prevent soil cracking (D12). Some managers argue that the water-saving policy advocated by the irrigation district (D7) falls short in addressing the growing water demands, as they struggle to secure new water supplies (D5). Therefore, managers reiterate the importance of improving water efficiency through initiatives like investing in maintenance of water networks and pinpointing locations in the district where irrigation techniques can be switched without disrupting environmental and groundwater dynamics (D7), as well as moving toward an "Agriculture 4.0", which enables farmers to use water more efficiently, ensuring water accessibility for all (D4). This last point, however, demands that farmers become more sensitive in optimizing water systems and rationalizing water usage (D3), as well as considering energy costs, which are considered a constraining factor by one-third of managers because water is generally required to be pumped in the southern part of the area or generally pressurized for water distribution at the farm level (D8, D9, D11, D12). Likewise, the competing upstream and downstream water demands enhance tensions between agriculture and hydropower, with a tendency to prioritize the needs of hydropower production over irrigation and the environment (D1).

4.2. *Extreme weather events and related storylines*

Over the past decade, managers have observed a rise in the intensity and severity of extreme weather events, resulting in more destructive episodes impacting the region (D3), particularly during the summer season (D6). Some managers noticed a recurrent

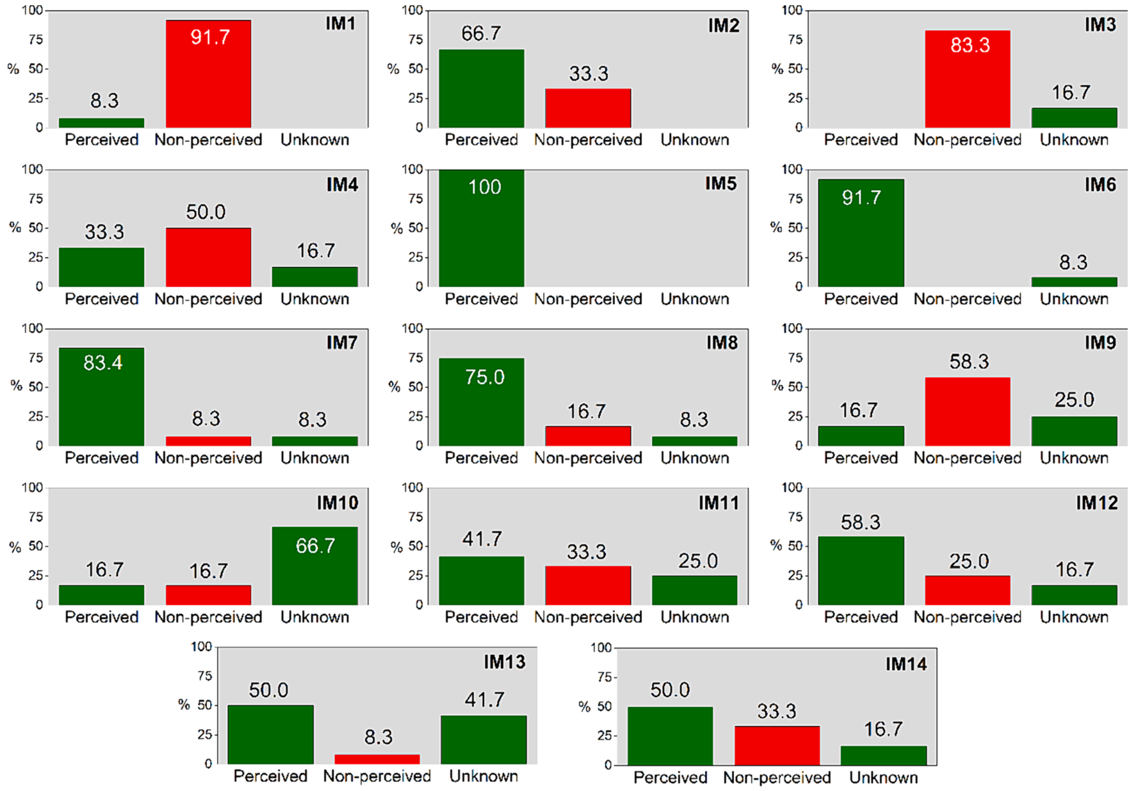

Fig. 3. Types of impacts (IMs) perceived by irrigation districts' managers *Legend on IMs (Impacts): IM1 (Increased rainfall / an extended rainy season), IM2 (Decreased rainfall / a shortened rainy season), IM3 (Rainy season comes earlier), IM4 (Rainy season comes later), IM5 (Warmer temperatures and heat waves), IM6 (Increased frequency or intensity of droughts), IM7 (Increased frequency or intensity of floods), IM8 (Less reliable water supply), IM9 (Increased soil erosion), IM10 (Changes in nutrient dynamics or nitrogen pollution), IM11 (Changes in plant growth), IM12 (Changes in vegetation species and biodiversity), IM13 (New or worst pest infection), IM14 (Increase in weeds or new invasive species).

pattern of catastrophic events each year (D11), with each year surpassing the previous one in severity (C7). Extreme weather events can occur in isolation (D8) or follow a contemporaneous pattern in which two or three extreme events occur during the year and determine the success or failure of the irrigation season (D10, D12). For some managers, the patterns of extreme events are not apparent to the farmers (D2) because for some of them nowadays crops are more water-intensive and consequently more exposed to risk (D5).

The most commonly perceived extreme weather events are droughts and floods. The general consensus is that droughts are becoming more frequent than in the past (D5, D7), even appearing during winter (D12) and pointing towards a sustained period of high temperatures for multiple weeks, which was not the norm two decades ago (D6). Managers place great significance on the shift in drought patterns, characterized by shorter yet more severe occurrences (D10). These events are often viewed as unpredictable (D12) and have notable spatial impacts across multiple counties over a medium timeframe (D3). In contrast, floods and intense rainfall patterns are typically confined to specific areas (D6) and have the potential to greatly disrupt agricultural production in just a few hours (D9). Likewise, when flash floods occur, the challenge is compounded by the inadequacy of the outdated water infrastructure to cope with heavy rainfall or overflowing rivers (D1). In contrast to drought management, floods demand immediate decisions that involve farmers on a personal and physical level, and managers on a technical and operational level (D3).

The droughts of 2003 and 2005 were unanimously recognized by managers as the most remarkable episodes since the 1976 drought, which primarily impacted the Adda River basin. The event of 2003 is widely regarded as the most disastrous and critical, prompting the lighting of wells on May 1st and their uninterrupted operation until September 15th to preserve water supply during the growing season. Some managers recall droughts in 2009 (D5), 2013–2014 (D9, D10), and 2017–2018 (D2, D5, D10). As for flooding, less than half of the managers cited specific examples of major events, including flash floods in 2014 and 2015 (D3, D8, D10) or a heavy rainfall episode in the spring of 2006 that brought a quarter of the average seasonal rain (D12).

4.3. Perceived impacts and climate change awareness

Managers are experiencing warmer temperatures and heatwaves, and most of them have noticed a rise in frequency or intensity of extreme weather events such as droughts (92 %) and floods (83 %), as well as an unreliable water supply (75 %) due to a decreased rainfall or a shorter rainy season (67 %) (Fig. 3). In contrast, changes in rainfall distribution patterns are not perceived by managers, meaning that the rainy season does not arrive earlier (83 %) or later (50 %), and soil erosion is not on the rise (58 %). Likewise, managers are unaware of the impact of climate change on nutrient dynamics or nitrogen pollution (67 %) and the appearance of new pest infections (42 %).

As expected, impacts are not uniformly recognized among the irrigation districts. While half of the managers acknowledge nearly half of the potential impacts, there are notable differences in their observations. For instance, D1 is aware of 86 % of the suggested impacts, whereas D8 only perceives two main effects: warmer temperatures and heat waves, and a rise in flood frequency or intensity). The varying attitudes of managers towards diversity of perceived impacts play a significant role in determining the levels of awareness and uncertainty within irrigation districts (Table 1). Generally, managers of irrigation districts located upstream of the river basin are more cognizant of the perceived impacts than those located downstream (along the Po River). D1, D2 and D12 rank at the top for irrigation district awareness, while D5, D9, and D10 have the most uncertainty. Interestingly, there are three managers who have no doubt regarding the impact on their irrigation district (D1, D11 and D12).

During interviews, managers offered interesting context for understanding most perceived impacts. Half of them observed a significant decline in rainfall since the start of the century. In certain instances, the impact is severe enough for managers to quantify a reduction of two-thirds in annual precipitation from usual levels (D3), causing a direct effect on spring groundwater supplies (D1) and

Table 1
Awareness and uncertainty of impacts by irrigation district managers.

Irrigation districts	Awareness		Uncertainty	
	%	Perceived impacts (IMs*)	%	Doubtful impacts (IMs*)
Est Sesia (D1)	85.7	2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14	0	
Est Ticino Villoresi (D2)	64.3	2, 4, 5, 6, 7, 8, 11, 12, 13, 14	21.4	7, 9, 10
Muzza Bassa Lodigiana (D3)	57.1	1, 2, 5, 6, 7, 8, 12, 14	14.3	10, 13
Media Pianura Bergamasca (D4)	57.1	2, 4, 5, 6, 7, 8, 10, 11	7.2	14
Dugali Naviglio Adda-Serio (D5)	42.9	2, 5, 6, 7, 8, 12	42.8	3, 4, 10, 11, 13, 14
Oglio Mella (D6)	50	2, 5, 6, 7, 12, 13, 14	7.1	10
Chiese (D7)	57.1	2, 5, 6, 8, 9, 11, 13, 14	14.3	10, 12
Garda Chiese (D8)	14.3	5, 7	28.6	6, 8, 10, 13
Territori del Mincio (D9)	28.6	5, 6, 7, 8	35.7	9, 10, 11, 12, 13
Navarolo AgroCremonese Mantovano (D10)	35.7	2, 5, 6, 7, 8	42.9	3, 4, 9, 10, 11, 13
Terre dei Gonzaga in Destra Po (D11)	35.7	5, 6, 7, 12, 13	0	
Burana (D12)	64.3	4, 5, 6, 7, 8, 11, 12, 13, 14	0	

*Legend on IMs (Impacts): 1 (Increased rainfall / an extended rainy season), 2 (Decreased rainfall / a shortened rainy season), 3 (Rainy season comes earlier), 4 (Rainy season comes later), 5 (Warmer temperatures and heat waves), 6 (Increased frequency or intensity of droughts), 7 (Increased frequency or intensity of floods), 8 (Less reliable water supply), 9 (Increased soil erosion), 10 (Changes in nutrient dynamics or nitrogen pollution), 11 (Changes in plant growth), 12 (Changes in vegetation species and biodiversity), 13 (New or worst pest infection), 14 (Increase in weeds or new invasive species).

stored surface water storage in regulated lakes (D6). Similarly, managers hypothesize that the strength of precipitation has been altered due to intermittent and unpredictable inflows, resulting in less consistent and unforeseen rainfall (D1) characterized by variations in location and timing (D12). The transitions from heavy rainfall to flash floods have been noticed by some managers: precipitation records that took five or six days to reach a decade ago are now achieved in just five or six hours (D4, D10). Some managers look back on heavy rainfalls as a valuable method of distributing water throughout the district without causing significant destruction. Nowadays, however, managers are aware that most farmers 'cross their fingers' when heavy rainfall hits (D11), especially during the summer season as heavy rainfall can cause significant disruptions in the crop production cycle (D2). Rainfall variability is often perceived as random, with sudden shifts from extreme floods to extended periods of drought occurring within a few weeks or months (D9). This results in increased water insecurity throughout the year, as erratic rainfall patterns move from the fall-winter to the summer season (D10, D12).

Concerns about precipitation variability are matched by concerns over the decreasing snow accumulation and retreating glaciers in the Alpine mountains (D6). The melting process of glaciers tend to occur rapidly, lasting only a matter of days or weeks (D3), due to rising temperatures, which directly impact maize and rice production (D7). However, warmer temperatures have another effect: the proliferation of algae in irrigation canals, making water distribution more challenging (D2). Despite these impacts are well-known by most managers, some of them believe that farmers have historically underestimated the effects of climate change on water supply and crop production (D4). From their experience, changes in precipitation and temperature can serve as a wake-up call to motivate direct actions (D12), empowering farmers to verify the significance of these impacts on crop production, both on a seasonal and yearly basis (D5). However, some managers assume that most farmers can perceive climate change as an abstract or intangible issue, without delving into effects on the farm level (D5). In the same vein, managers agree that farmers are not currently taking climate change into consideration when making decisions, but this may soon change if glaciers continue to melt at high speed, to the point that they risk disappearing altogether (D5). Some managers perceive that farmers have a limited understanding of the potential impacts of climate change and related extreme weather events on their activities (D3), which in turn demotivates the adoption of measures to increase

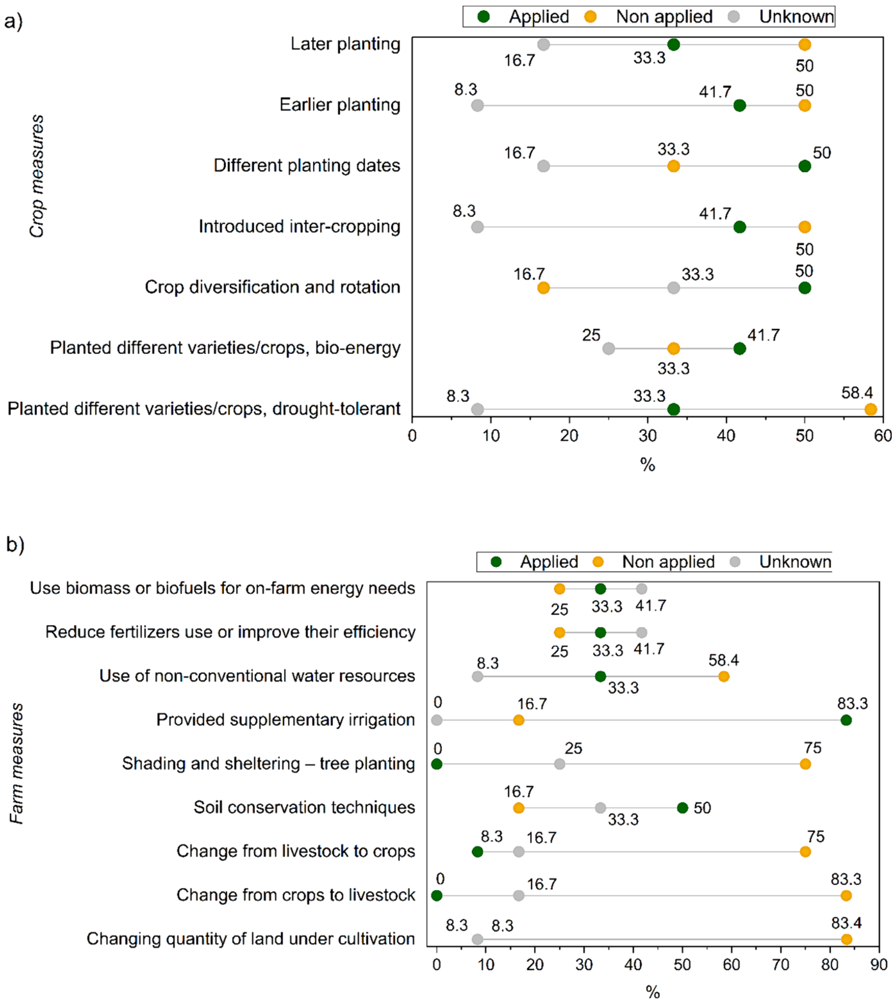

Fig. 4. Crop (a) and farm (b) adaptation measures promoted by farmers according to managers' experiences.

their resilience (D3, D10).

4.4. *Climate change adaptation measures and barriers*

According to managers, farmers are primarily taking steps to strengthen their ability to withstand the effects of climate change through farm practices. This includes crop diversification and rotation, introducing inter-cropping, and modification of planting dates (Fig. 4a-b). Climate change is accelerating the trend of growing more Mediterranean crops (D12), particularly those that are considered water-saving or less intensive crops (D4). Despite its potential benefits, some managers are reluctant to pursue it as maize, rice, and vegetables, all of them water-intensive crops, are deeply rooted in the region's food culture and value chain (D3). Similarly, farmers encourage the cultivation of crops that can withstand extreme weather events (D4, D6), the transition to energy-producing crops (e.g. biogas) (D10), and the introduction of different crop varieties (D5). However, managers are aware that some crop changes require a change in irrigation system, especially from flood to drip or sprinkler irrigation (D6, D10), which means an extra effort in investment by farmers that could be challenging without financial support (e.g. subsidies) (D1, D3). Furthermore, some managers point out which will be the consequences of increasing water efficiency in terms of groundwater storage and environmental functions (D6, D9).

Following different strategies, most managers concur that water infrastructure is vital in mitigating the inflow/outflow imbalance exacerbated by projected climate change scenarios in the area. For example, some managers suggest elevating the designated operating level of the Lake Como by half a meter (D1), or implementing flood retention basins to collect surplus precipitation during heavy rainfall and gradually discharge it through the irrigation canals network (D6). Others suggest implementing groundwater storage initiatives to cope with heavy rains and flash floods (D4), contributing to a threefold goal: 1) resolving hydrogeology challenges, 2) providing new sources of water for irrigation, and 3) restoring degraded areas from a landscape and environmental perspective (D7). As stated by a third of the managers, improving water storage methods would give farmers more irrigation options. The rise in demand for supplemental irrigation (83 %) is driven by the necessity for thermal comfort and alleviating crop water stress (D2), but also to reaching new crop production standards (D7). Some managers noticed that farmers who had never used irrigation before started implementing it as a way to enhance soil conservation techniques (50 %) or else face the potential loss of their crop production (D12). Similarly, a third of managers recognize that farmers tend to rely on non-conventional water sources in order to guarantee water supply during water shortage scenarios (D6). Despite this, most managers recognize the need for further discussion before considering this option as an alternative to ensure additional irrigation requirements that are not currently being fulfilled by conventional water sources, particularly during the summer when urgent measures must be implemented to tackle water shortages or droughts.

As of today, managers employ various strategies to rationalize water distribution, with the prevailing option being to reduce irrigation timing or amount. This is particularly beneficial in irrigation districts that operate on a set schedule. One option was to implement the red hour system, where irrigation time is cut in half without compromising water volume (D7). Alternatively, managers opt to combine different options, such as reducing flow to 70 % while maintaining the same number of irrigation days, decreasing irrigation time, or extending the frequency between irrigation rounds (D8). Likewise, some managers prefer to allocate less water to all farmers to prevent certain farmers from being disproportionately affected (D3). Interestingly, managers also mentioned taking proactive steps to anticipate farmers' decisions and handle any potential climate impacts. For example, the vast majority of farmers (92 %) invest in insurance plans that protect against extreme weather events. Furthermore, they use weather and climate services to inform their decisions based on both short-term and seasonal forecasts for rainfall and temperature (92 % and 75 %, respectively). In certain

Table 2
Main adaptation barriers by type and according to main managers' observations.

Type of barriers	Barriers	Observed (%)	Non-observed (%)	Uncertain (%)	Identified by districts (D#)
Internal	Climate change negationism or skepticism	0	91.7	8.3	
	Low risk perception ("I will not be directly affected")	25.0	66.7	8.3	2, 3, 9
	Business-as-Usual scenario	33.3	66.7	0	3, 7, 8, 9
External (technological)	Lack of information	8.3	66.7	25.0	2
	High cost of investment at the farm level	75.0	16.7	8.3	1, 2, 4, 5, 6, 7, 8, 10, 12
	Limited availability of drought-tolerant crop varieties	75.0	16.7	8.3	1, 2, 5, 6, 7, 8, 10, 11, 12
	Limited access to new technologies and innovation	41.7	58.3	0	2, 4, 5, 8, 11
External (institutional)	Lack or poor government support	66.7	8.3	25.0	1, 2, 3, 4, 7, 10, 11, 12
	Too complicated regulation and rules	58.3	25.0	16.7	2, 3, 4, 5, 6, 7, 11

*Legend (D#): Est Sesia (D1), Est Ticino Villoresi (D2), Muzza Bassa Lodigiana (D3), Media Pianura Bergamasca (D4), Dugali Naviglio Adda-Serio (D5), Oglio Mella (D6), Chiese (D7), Garda Chiese (D8), Territori del Mincio (D9), Navarolo AgroCremonese Mantovano (D10), Terre dei Gonzaga in Destra Po (D11), and Burana (D12).

cases, managers can offer technical guidance to identify the most suitable weather information systems and applications.

However, from managers' expertise, there are still obstacles impeding farmer adaptation (Table 2). The most critical barriers include: 1) costly investments at the farm level and limited access to drought-resistant crops (75 % each), 2) insufficient support and coordination (67 %), and 3) complex rules and regulations (58 %). The main barriers to progress are typically attributed to external forces (technological and institutional), while internal barriers related to farmers' attitudes are rarely considered and others are not even observed (e.g., climate change negationism or skepticism). It is worth noting that managers do not face the same obstacles when it comes to adaptation: most managers do not consider low-risk perception, business-as-usual scenario, and lack of information as barriers to adaptation.

4.5. Heuristics and risk management

In the eyes of managers, there are four key factors influencing farmers' perspectives on climate change and conditioning their attitudes towards managing risk. First, (small) farmers tend to imitate their neighbors' actions, particularly by implementing water-saving techniques or supplying extra irrigation to tackle water scarcity (D9, D12). Second, farmers tend to be conservative, and their outlook can be influenced by their personal experiences with long-standing challenges, especially when there are potential economic repercussions in the near future (D1). Third, young farmers are at the forefront of driving the modernization and innovation process in agriculture, specifically in the implementation of water efficiency techniques, predominantly supported by larger farms (D10, D11). Finally, farmers rely on managers to take charge and implement water supply and management measures that are not feasible to be implemented individually due to high costs or limited technological criteria (D2).

Some of these attributes determine the ability to normalize risk. One commonly held belief among managers is that experiencing both water scarcity (droughts) and water abundance (floods) in quick succession can contribute to risk normalization: "In 2013, a national drought management commission was established, but just a year later, the region was hit with a flash flood, prompting the appointment of a national flood management commission. In consequence, farmers quickly incorporated both extremes in their daily routines and accept the increasing occurrence and intensity of both extreme weather events" (D9). In this context, many managers strive to promote and combine a mix hard and soft adaptation measures to reduce risk normalization and reinforce farmers' resilience to extreme weather events. Lake regulation is the most important upstream solution for maintaining water supply and ensuring hydraulic safety. As mentioned by some managers, a key advantage is that farmers confirm lake regulation as the best option to manage heavy rainfalls and flash flooding, even in the worst-case scenarios (D2). Likewise, some managers support the implementation of some water expansion tanks to work in conjunction with lake management and mitigate the effects of flash floods (D8, D10). Maintenance programs and carry out preventive actions within the canal network are the primary focus of managers at the downstream level. These efforts are essential in minimizing flood risk and maintaining a reliable water supply for agriculture (D7, D12). Managers agree that most structural interventions require significant funding and medium-term development plans (D3, D5), while direct interventions can offer operational versatility, making it easier to switch to an alternate water source during a crisis (D2, D3) or increase energy efficiency by replacing energy-intensive pumps (D9). Most of these downstream strategies make use of network monitoring systems, which include real-time updates on water levels and flow rates at key locations within the water network (D5). In some cases, a remote monitoring system with level, pressure, and pump sensors is also used to identify irregularities in normal patterns and trigger a cell phone alert system (D9, D11).

Half of the managers use climate data from regional or national weather centers and national meteorological services, along with real-time measurements and three-day bulletins, to strengthen network monitoring. Likewise, forecasts are consulted to gather information on the water levels in reservoirs (D2) and snow levels upstream (D8). Similarly, managers concur that it is crucial to have prompt updates on temperatures and precipitation for the upcoming days in order to determine whether to reduce water allocation to farmers (D8, D12), adjust water distribution mechanisms, and enforce conservation strategies, such as agricultural insurance management (D11). For some managers, climate services should be integrated into a holistic approach that encompasses multiple measures and actions to develop a robust strategy for tacking climate change (D3). This requires managers to gain a clear understanding of the data and establish credibility with farmers to encourage their acceptance of forecast-driven decisions (D6). At the local level, the biggest drawback of climate services is their reliability, as weather patterns can differ greatly within the irrigation district. For example, it may rain in one area but remain dry just 10 km away (D9). In contrast, weather events have become increasingly unpredictable, making it challenging to grasp their location and intensity after 48–72 h (D11).

All managers agree on the benefits of collaboration in risk management. However, there is no active and formal collaboration between irrigation districts except for when ANBI Lombardy arrange round table discussions about extreme weather event pro-active management (D2). Effective collaboration is prioritized in handling emergencies that could impact multiple irrigation districts (D11). Moreover, some managers exchange information and insights regarding common challenges, including ecological flow, hydraulic safety regulations, technical knowledge, and administrative requirements, as these issues are frequently comparable across all irrigation districts (D9, D10). In general, managers observe their neighboring districts and occasionally imitating practices with those who are alike or close by (D3, D12).

5. Discussion and conclusion

The impacts of climate change are scientifically proven and socially perceived, such as rising temperatures, irregular and unpredictable rainfall patterns, and more frequent and intense extreme weather events (Bednar-Friedl et al., 2022). In the face of climate change-induced challenges, irrigation district managers have a crucial role to play as they must navigate through stressors and unexpected events, and provide context-specific solutions to farmers (Cisternas et al., 2023). This research applied a qualitative and explanatory approach in order to unravel the intricacies of irrigation district managers' perspectives and pinpoint the key cognitive drivers that influence their ability to enhance risk management and support farmers' adaptive capacity. The findings shed light on multiple issues, including the challenge of encouraging water-saving practices without disrupting groundwater dynamics, the impact on farming water supply when adopting new ecological flow standards, and potential solutions for addressing tensions between upstream and downstream water demands. Based on firsthand accounts from managers, it appears that the ability to withstand climate risks is aligned with their experience in observing the adverse effects of extreme weather events, particularly droughts and floods, which are escalating in both intensity and severity (Alimonti et al., 2022). Managers' decisions are influenced by personal experiences with extreme weather events. Therefore, those managers who are directly impacted by severe weather events believe that the chances of these events recurring are fairly high (Egger et al., 2023; Kunimitsu et al., 2023). Furthermore, managers who have experienced life-threatening events tend to be more inclined to reinforce risk management, as hypothesized by Budhathoki et al. (2020).

In terms of effective adaptation, different time frames can be considered within which adaptation occurs. Combining short- and long-term strategies is a major hurdle for managers looking to improve adaptation, especially when factoring in the need of pathways that can handle long-term scenarios, recurring weather anomalies due to climate variability, and extreme occurrences, like droughts and floods (Thomas et al., 2021). In line with the findings of Wheeler and Lobley (2021) and O'Neill and Boyer (2023), our study revealed that certain managers held a (techno-) optimistic view towards different strategies and opportunities for enhancing agriculture's adaptability and response to changing conditions. This was particularly evident in their emphasis on local efforts to tackle water scarcity and drought. In this scenario, managers noticed that most farmers are driven to implement water-saving practices or encourage the cultivation of less water-intensive crops, as a means of avoiding or diminishing the impact of water rationing policies. According to managers' experience, farmers prefer crop-level interventions (such as diversification, intercropping, and timing of planting) over changes made at the farm level (like changes in land use, livestock management, or tree planting). This is consistent with widespread research that indicates farmers tend to favor more direct measures for their crops, rather than promoting labor-intensive or expensive farm-level options (Khanal et al., 2018; Aidoo et al., 2021; Roy et al., 2021; Bedeke, 2023). In parallel, managers employ a mix of hard and soft adaptation measures to effectively manage the inflow-outflow imbalance. Water infrastructure measures, such as maintaining irrigation canals or supporting water interventions downstream, take center stage as hard adaptation measures, while soft measures rely on using climate services and foster collaboration for knowledge exchange and emergency response. Nevertheless, managers reported obstacles for farmers when promoting adaptation, including costly investments, a lack of drought-resistant crop varieties, low public support, and overly complex regulations, which aligns with the findings of Talanow et al. (2021) and Mitter et al. (2019).

Fig. 5 provides an overview of key factors influencing managers' narratives, considering main drivers from climate change awareness, perceived impacts, and adaptation measures and barriers. Reinforcing and balancing loops recapitulate findings on perceived impacts and adaptation actions. The former represents increasing or decreasing actions, while the latter illustrate self-correcting mechanisms that oppose and counteract change. Their analysis can support the characterization and relevance of tipping points in climate change adaptation based on factors influencing managers' decisions when facing risk management. At a

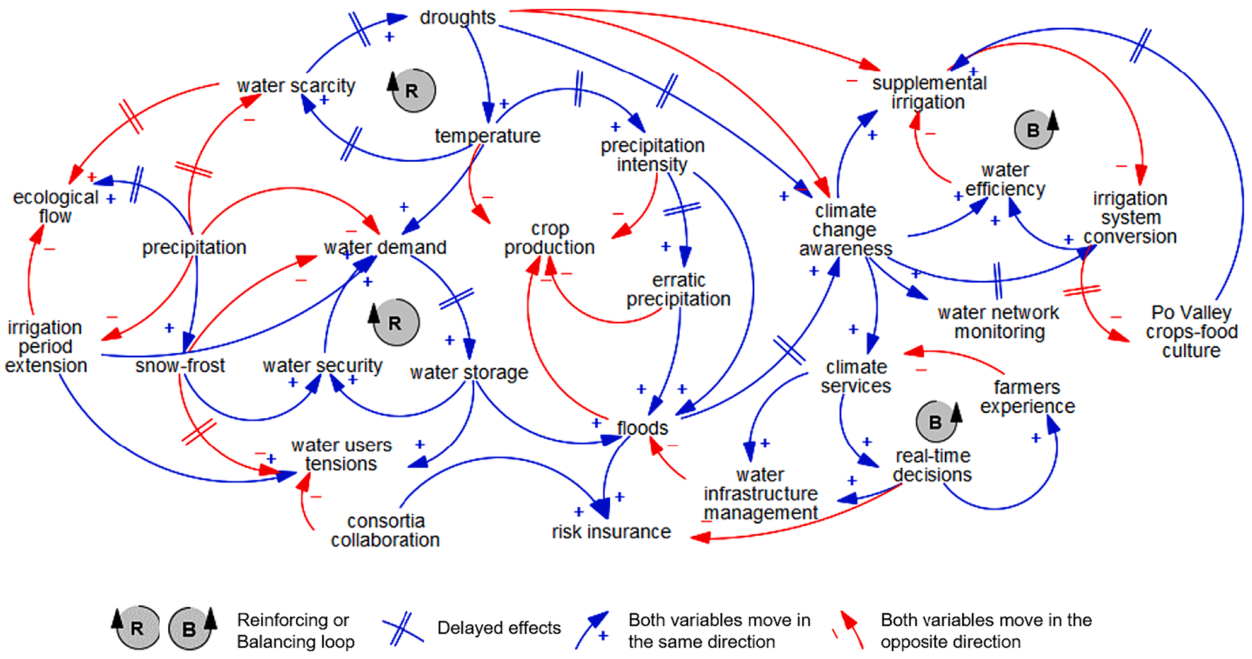

Fig. 5. Causal loop diagram on drivers conditioning climate change perception and adaptive capacity.

critical transition (tipping point), the system shifts to a new state of self-organization, where perturbations and shocks that could previously be absorbed lead to system failure (Berglund et al., 2023). Tipping points are typically reached when boundary conditions are forced in a direction that strengthens positive (reinforcing) feedbacks and/or weakens negative (balancing) feedbacks (Milkoreit et al., 2018). Characterizing tipping points in complex water systems influenced by extreme weather events can provide early warning signals to be used as an opportunity for deliberate system transformation (Lenton, 2020). However, there is a high degree of uncertainty regarding their timing and impacts as well as social responses to tipping points (van Beek et al., 2022). It is no wonder that the identification of tipping points in the water cycle has been listed as one of the top 23 Unsolved Problems in Hydrology (UPH) by the International Association of Hydrological Sciences (IAHS) (Blöschl et al., 2019).

In this regard, expert knowledge from irrigation districts managers can be used to delve into tipping points at the local scale, because managers are aware of the normal behavior of the system, both before and after a regime shift. Reinforcing loops can support the contextualization of both climate and social tipping points by considering those variables influencing the system dynamics (Juhola et al., 2022). Our research revealed two primary reinforcing loops: 1) rising temperatures and droughts leading to heightened water scarcity (attributed to changes in snow accumulation and melting patterns, as perceived by a majority of managers), and 2) growing water demand has prompted a need for investment in water storage (related to the construction of flood retention basins to capture excess precipitation during heavy rainfall, as suggested by some managers). In contrast, balancing loops can be seen as methods of risk normalization where managers strive to find a balance between two dichotomies: 1) the use of climate services versus farmers' experience (considering the challenges of using climate services in a specific area due to the varying weather conditions within the irrigation district, as mentioned by several managers), and 2) the emphasis on water efficiency versus meeting the rising water demand for supporting irrigation (highlighted by some managers for its potential consequences on groundwater storage and environmental functions).

We recognize some limitations of our study and provide potential directions for future research. Although semi-structured interviews effectively gathered essential information from irrigation district managers and highlighted key issues in their interactions with farmers, it was assumed that managers have a complete understanding of farmers' attitudes and management practices, which may be debatable. Moreover, the widespread acknowledgment of the effects of climate change by irrigation districts with almost no exception (albeit with differing levels of intensity) can be used to support the need for a complementary survey to gather farmers' experiences. This will allow for the detection of any potential disparities in perspectives between managers and farmers. This limitation is mainly due to the use of cross-sectional data, while a longitudinal approach would allow an exploration of how adaptation might change among managers and farmers over time (Graskemper et al., 2021). As Sinha et al. (2022) suggested, validation from focus group discussions could constitute the starting point for policy co-design, while allowing full control for time-invariant unobserved heterogeneity, such as cultural factors or the neighborhood effect that may influence adaptation behavior among farmers (Skevas et al., 2022). Effective knowledge exchange and mutual understanding between managers and farmers on perceived impacts and adaptation actions can assist in devising specific downstream strategies and preventing maladaptation at the local scale (Ghazali et al., 2021). Since managers and decision makers are unlikely to identify individual strategies because farmers are far from homogeneous (Bartkowski et al., 2022), collaboration between managers and farmers is key to avoiding generic and vague adaptation initiatives (Yeleliere et al., 2022).

Another limitation of the study is that climate change observations is often spread out over time, and personal and collective memory of past events may be flawed or uncertain, making it difficult to differentiate between knowing factual knowledge and emotional recollection (Sambrook et al., 2021). One way to bridge this gap is by integrating managers' behavioral assessments with accurate and timely observed data on climate hazards. This would help mitigate climatic risks and enhance the design of management strategies at the irrigation district level. In this context, authors suggest distinguishing ex-ante and ex-post adaptation to improve risk assessment (Hou et al., 2023) or to encompass a more farmer-centric approach focused on intra-seasonal climatic episodes instead of considering inter-seasonal climatic events: farmers are concerned about when it is going to rain, the duration of the season, and the potential of dry spells during the season (Dakurah, 2021). Similarly, upcoming research should focus on developing a shared vision to addressing the potential trade-offs between climate adaptation strategoes and food security outcomes (Zurek et al., 2023), in which managers' perspectives and timely farmer observations could be used to overwhelm climatic risks while contributing to promote transformative pathways for managing uncertainty at the local level. In this sense, proactive adaptation measures that consider the behavior of target groups —managers and farmers— could effectively bolster the shift towards risk assessment and resilience (De Lauwere et al., 2022; Biswas and Rahman, 2023). This scenario will strengthen the adaptation pathway outlined by the European Platform for Climate Adaptation (Climate-ADAPT), focusing on up-to-date knowledge, shared understanding, and multifaceted strategies for addressing climate change risks.

CRediT authorship contribution statement

Sandra Ricart: Conceptualization, Formal analysis, Funding acquisition, Investigation, Writing – original draft, Writing – review & editing. **Claudio Gandolfi:** Resources, Supervision, Writing – review & editing. **Andrea Castelletti:** Funding acquisition, Supervision, Writing – review & editing.

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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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2024.100598.

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