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Research article

What drives farmers' behavior under climate change? Decoding risk awareness, perceived impacts, and adaptive capacity in northern Italy

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ABSTRACT

Understanding climate change in a precise and timely manner may assist in gauging the occurrence and seriousness of its impacts, thereby boosting the adaptive capacity and responsiveness of farmers. This investigation looks into farmers' knowledge of climate change, their perception of risks and impacts, and the strategies they anticipate to tackle the challenges of adaptation. A well-structured online survey covering risk awareness, perception, and adaptation was used to randomly sample 460 respondents from 12 irrigation districts in northern Italy. Descriptive and multivariate statistics, including structural equation modeling, were employed to outline the profiles of farmers, explore the drivers shaping their behavior, and disentangle the magnitude and direction underpinning their adaptive capacity. Findings revealed that farmers recognize changes in climate and perceive its variability and effects, such as rising temperatures, extreme heat events, and irregular precipitation. Farmers blend adaptive measures, including climate services and insurance, with preventive mechanisms like reducing fertilizer use, rotating and diversifying crops, and introducing soil conservation techniques. However, they encounter obstacles such as poor government assistance, expensive investments and overlay intricate regulations. Regarding decision-making processes, the structural model demonstrated that 1) recognizing climate change can sensibly predict alterations in farmers' behavior concerning climate impacts while 2) there is a lack of correlation between perceiving risks and implementing risk adaptation measures. Interestingly, factors such as farming experience, farm size, area under irrigation, and primary crop type significantly influence how risks are perceived and what measures are adopted. In light of these results, we offer guidance for upcoming research.

1. Introduction

In their pursuit of agricultural activities, farmers interact with a multifaceted combination of human and natural elements, which are defined by various factors including politics, economics, institutional, cultural, and biophysical conditions [1]. They have consistently navigated risks, yet the challenges associated with farming have escalated in recent years as a result of climate change affecting agricultural practices [2]. The fluctuating rainfall patterns, rising temperatures, and the amplified occurrence and severity of

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climatic extremes are negatively affecting agricultural productivity and food security, along with the oversight of water resources and the ecological balance in rural areas [3]. Crop yields are strongly influenced by the foreseeability of temperatures, which encompass both the timing and supply of rainfall, especially at vital stages of plant growth. While gradual temperature increases may lead to improved growing conditions for some crops in specific areas, these potential yield increases are likely to be restricted by severe weather episodes, such as intense heat, drought, and erratic rainfalls during the flowering period [4].

Accurate statistics and modeling are commonly used to tackle climate change, but it tends to be seen in an abstract light, differentiating it from other threats as it happens over an extended period, which makes it challenging to recognize the disruptions in real-time [5]; that is, it can be challenging to separate the effects of global climate change from the fluctuations of local weather patterns [6]. When there is a gap in time between observations, the accuracy of personal and collective memories can be compromised [7], making it difficult to differentiate between new information (semantic) and past experiences (episodic) [8]. When examining the wider picture, the traditional approach of studying climate change often centers on semantics (for instance, is a 1 in a 1000-year occurrence typical?), while experiential and narrative or storytelling approaches look at the episodic (for example, have we witnessed this in the past and what might the next occurrence be?) [9]. Subsequently, climate change is not easily perceived, although it may seem to be subject to personal observation and judgement. Moreover, the lack of interest or trust in institutions and experts also hinders the transmission of climate change facts from researchers to the broader community, managers, and decision-makers, often resulting in a limited exchange of information and facts [10].

It is crucial to bear in mind that personal interpretations of climate change are embedded in a wider context [11], suggesting that farmers do not simply absorb climate change information, but that their views are shaped by their values and beliefs [12]. In this context, it is essential to have a thorough comprehension of the farmers' perspectives and outlooks for ensuring sustainability and resilience of modern agriculture schemes [13,14]. Furthermore, investigating local wisdom can facilitate the recognition of farmers' concerns and aspirations, thus granting fresh prospects to hone in on initiatives for enhancing climate change actions and interventions tailored to the local context [15]. Farmers' perception regarding climate change uncertainty, potential impacts and risks at the local level is crucial because i) their experience and knowledge can be shared and compared to identify common trends and end users that can be conveyed to decision-makers, and ii) delving into their attitude and interventions to face climate change is the initial move towards adaptation [16]. In this regard, the way farmers respond to climate change tends to be more influenced by their beliefs and attitudes than by the real climate trends themselves [17]. Believing in climate change and worrying about its effects spur adaptation, however some barriers can restrict the application of solutions in the near and distant future. Furthermore, adaptation decisions are also influenced by farmers' risk behavior and other internal (e.g., socio-demographic and experiential, farming characteristics) or external (e.g., institutional support or access to information) cognitive factors [18,19]. Indeed, the farmers' risk attitude is a decisive element in determining their response to changes in climate [20].

Climate change is often viewed as a far-off psychological risk [21], with effects that vary across space and time [22]. It is assumed that impacts will resonate with people who are not only far away in space and time but also from different generations [23]. As climate change has a heterogeneous character regarding space, temporal variability, and distribution, studies tend to identify key local factors for specific geographical areas. Most research on farmers' cognitive stressors regarding climate variability has been focused on the Global South and developing countries [24], in which extreme events are expected to severely affect agricultural production [25]. On the contrary, fewer attempts have been made to target farmers' perspectives from global north regions. For example, at the European level, studies have been interested in the benefits of higher temperatures for more suitable crop conditions and longer growing seasons in northern European regions [26,27], while less attention has been put on reporting perceived crop production impacts on Europe's southern and Mediterranean regions [28], where there is estimated that crop and livestock production will be reduced, and maybe even have to be discontinued [29].

This paper employs a survey-based approach to blend the cognitive processes of climate change behavior, combining knowledge and drivers from belief information and outcome assessments of farmers' attitudes and perspectives in the Lombardy region, in northern Italy, a section of the most extensive and productive irrigated area in Europe. The research backs up the latest findings that emphasize a triple-loop strategy in understanding farmers' actions towards climate change [e.g., 30, 31] and puts forward proposes three major interdependent research questions (RQs):

RQ1. Do farmers recognize climate change and their contribution to its occurrence and severity?

RQ2. What are the impacts that most farmers perceive, and which effects are more evident?

RQ3. How significantly do farmers change their methods due to climate change, and what barriers exist that restrict their capacity to adapt more effectively?

Additionally, we enhance the current body of research by broadening a robust framework to examine or predict farmers' attitudes (e.g., [32–36]). Therefore, the research aims to check the potential influence and predictability between the three dimensions of farmers' behavior (awareness, perception, and adaptive capacity), that is, if awareness could anticipate the variance in perceived impacts, and if perceived impacts could, in turn, determine the variance in taking adaptation measures.

The layout of the research is outlined as follows. Section 2 provides the conceptual framework of the triple-loop on awareness of climate change, perceived impacts, and adaptation measures and barriers. Section 3 describes the case study and outlines the research methodology, including data collection (survey design and variables) and data analysis (descriptive and multivariate statistics) processes. The findings are presented in Section 4, followed by a discussion in Section 5. The concluding remarks in Section 6 cover research limitations, potential policy implications, and further research recommendations.

2. Conceptual framework

The concept of risk, conceptualized as the potential negative outcomes linked to socioecological systems [37], is pivotal to this work as it identifies the primary impacts of climate change concerning probability, uncertainty, and significance [38]. In order to tackle climate change, three primary steps need to be considered: (i) observing changes in the external environment; (ii) evaluating whether such changes necessitate transformative behavior to ensure resilience; and (iii) enacting adaptation measures to reduce vulnerability [39]. Therefore, local insights and experience, awareness and understanding, and perspectives and viewpoints are deeply intertwined and interactively contribute to perform climate change adaptation. While the first issue is derived from knowledge and social learning, the following ones combine individual interpretations and responses to individual occurrences or processes (such as climate change) [40].

Theory suggest that farmers who feel well-informed, competent, and resourced tend to be less stressed regarding the threats that climate change poses to their farming practices [41]. Hence, researchers are increasingly recognizing the range of influences and concerns that inspire adaptive behaviors related to climate change, in line with the notion of 'realistic farmers' [42], with the aim to gain insight into the cognitive functions that underlie behavior instead of merely considering the rationality of farmers [22]. The rest of the section provides an overview of the triple-loop approach of farmers' behavior, which include the explanatory factors determining farmers' attitudes and perspectives: risk awareness, risk perception, and risk adaptation.

2.1. Risk awareness

Numerous researchers have explored how being aware of climate change can serve as a significant motivator in shaping managers' understanding of climate-related risks and responses [43]. Notably, these academics assert that awareness is biased; instead, it includes a range of evaluations of climate effects, which can be either advantageous or detrimental, ultimately affecting the formulation of climate action initiatives [44]. Therefore, risk awareness is a fundamental aspect for managing farming susceptibility during the early stages of adaptation [45], even a critical and tacit feature in anticipating pro-environmental farmers' action. Considering the far-reaching nature of awareness as a social construct, there is a lack of clarity in regards to how awareness is formed, the steps taken in its development process, the actions required to shift from one step to the next, and who should drive these actions [46]. Awareness is both a pre-requisite and a requirement during the process of constructing resilience, as it is the force that drives transformation [47]. It is mainly defined from five attributes: beliefs, understanding, willingness to act, commitment, and collaboration [48]. Attention has largely centered on 'beliefs' as a way to capture how aware individuals are of the influence of climate change on their thoughts and decisions [49]. In the same line, some authors stated that the convictions held by farmers about climate change are essential for evaluating the probability of potential adaptation strategies [50], while ignorance and doubt can lead to inaction or even dismissal of these threats [51].

Several socioeconomic factors, such as farm characteristics, location and geographical elements, or institutional support and services, as well as access to information and knowledge regarding advanced technologies or climate projections, affect the awareness of climate extremes [40]. Farmers may recognize climate change as a result of their personal experience or through professional and social networks. For example, farmers who have had unexpected exposure to extreme events such as droughts and floods, temperature fluctuations or erratic precipitations in the past tend to have greater awareness of changes in climate and its potential effects on agriculture compared to those who lack such risk experiences [52]. Likewise, the literature also revealed that awareness of climate change and trusting the climate information providers can motivate conservation-oriented behaviors [53]. Paradoxically, being more aware of climate change may lead to a lower sense of risk, shich could stem from risk normalization [54]: sustained awareness and exposure to hazardous situations foster the creation of tactics that diminish the perceived level of risk, although such tactics do not contribute to solving environmental threats and challenges.

2.2. Risk perception

Although awareness by itself can motivate and lead to adaptation steps [55], the way farmers perceive the impacts of climate change plays a vital role in their approach to dealing with climate-related risks and opportunities. How farmers respond to risk perception will determine their adaptation alternatives, the steps to be taken, and the final outcomes arising from the adaptation process [56]. Perceived risk reflects how farmers evaluate the potential adverse effects of climate change on their practices. It can be evaluated through individual or collective beliefs [57], which contributes to identifying the main hazards while deepening their associated risks [58]. Moreover, it is widely interpreted as assessments that individuals form about the characteristics and intensity of risks, the way in which information or stimuli from the environment is received, converting it into psychological awareness, and behaving in accordance with their experiences, insights knowledge, and trust levels [30]. In essence, it serves as a cognitive representation, an individual's perspective on the implications of a contextualized climate extreme, along with a subjective evaluation of the magnitude of a menace [23].

Some authors, such as [59], make a distinction regarding how climate change is perceived over short and extended periods (e.g., extreme events in the last year versus those over the last two decades). When it comes to short-term extreme weather events, farmers must take quick action, while long-term climate change necessitates resilient, costly strategies that can be adopted over time. The relevance of risk perception, considering both the near and far future, tend to be influenced by their past encounters, their current set of values, needs, memories, emotions, social circumstances and expectations. Therefore, individuals, managers, and decision-makers might display a temporal bias by showing a preference for immediate risks, considering them to be more significant than those associated with a longer timeframe.

In this sense, the way an individual or social group behaves in climate change is influenced by their knowledge, interests, cultural factors, and other societal forces, which can shape their reactions to particular events or situations [60,61]. The way farmers perceive risk is influenced by their constant observations of the surrounding environment and the local narratives from social learning experiences [62], which can differ significantly from the usually abstract climate models and projections managed by scientists and experts in the field [63]. As a result, if farmers misjudge the risks related to climate change, they could either be unable of introducing the necessary adaptation measures or might engage in maladaptive practices, also motivated by fatalism, denial, and wishful thinking, leading to greater vulnerability to climate threats [64,65].

2.3. Risk adaptation

Farmers are constantly adapting to shifting conditions, making it challenging but essential to determine whether climate change is the main catalyst for their adaptive strategies [66]. The choices farmers make on the farm are based on a combination of external cues (weather conditions, market forces, government policies) that are integrated into a single decision-making process. Variations in adaptation responses can arise from a multifaceted relationship between socioeconomic, environmental, and institutional drivers [67], which encompasses four distinct adaptation categories: (i) advancements in technology and innovation, (ii) governmental initiatives and insurance schemes, (iii) on-farm production improvements, and (iv) financial oversight [68]. Studies have examined the determinants motivating the deployment of each adaptive strategy to face climate change (e.g., [69]), and based on which one is the main driver, adaptation actions vary from dealing with change to small alterations and total system transformation [70]. However, despite the varied nature of adaptation categories, and due to the multifaceted repercussions of climate change, it is expected that will adopt several strategies rather than relying on just one adaptation action to address climate impacts [71].

In this regard, researchers categorize adaptation into two forms: incremental and transformative. Incremental adaptation involves developing strategies and actions that minimize negative impacts or improve the advantages of environmental shifts and making appropriate adjustments to new climate circumstances. Conversely, transformative adaptation refers to a process that leads to changes in the biophysical, social, or economic aspects components by introducing changes to regulate the system's performance [72]. Knowing how farmers discern and apply adaptation measures is essential for enhancing behavior transformation, as they are the key players in determining the best options to guarantee agricultural productivity in a changing climate [73,74]. Nevertheless, some studies indicate that adaptation has become a standardized part of effective management practices, which is something that a 'good' farmer should embrace, no matter their stance on climate change [75].

Risk awareness and risk perception positively influence the adaptive capacity of farmers [76]. According to Ref. [77], when farmers perceive a high risk to their physical health, finances, or productivity from climate change, they have an increased intention to adapt. Furthermore, when farmers recognize the efficacy of adaptive actions and feel empowered to take them, adaptation intention is further boosted [78]. The literature similarly recognizes that farmers can also adapt without engaging their beliefs concerning climate causality. This suggest that farmers' beliefs and awareness did not directly influence, at least in a tangible and measurable way, their adaptation efforts or how they perceive risk [23,34,79,80].

3. Material and methods

3.1. Case study

Situated in northern Italy, the Po Valley stands out as a highly productive agricultural region in Europe, accounting for a third of the country's total agricultural output. The Lombardy region (latitude 45.585556N and longitude 9.930278E) alone contributes over 10 % of this production, supported by approximately 47,000 farms spread across less than one million hectares [81]. About 40 % of the regional surface is dedicated to farming, with the leading crops including maize, rice, wheat, grasslands, and soybeans. Water supply depends on an intricate and ancient interconnected network comprising rivers, regulated lakes, reservoirs, and advanced irrigation systems, which together support 25 % of the national irrigated land and about a third of the water employed for irrigation purposes. Characteristic of subalpine regions, the area's hydrometeorological regime is distinguished by periods of dryness in winter and summer, with moisture peaks during late spring and autumn, resulting from snowmelt and rainfall. From May to July, the primary contributor to seasonal water reserves is the melting snow, which is later employed during the summer months to fulfill the increased demand for irrigation [82].

Italy is ranked 21st in the global climate risk index, indicating how much the country has suffered from extreme weather phenomena [83]. It is anticipated that by the end of the century, climate change will greatly influence geo-hydrological instability, driven by increased temperatures, changes in rainfall patterns, and a rise in the frequency and duration of severe weather events. Therefore, it is predicted that the rise in average temperature, evapotranspiration and low rainfall will lead to a significant decrease in flow rate: a 40 % reduction by 2080 [84]. [85] foresaw a gradual decline in average discharge rates and an earlier reduction in peak spring flows, caused by alterations in the snow accumulation and melting dynamics in the Alpine regions. This will likely lead to more severe consequences regarding both the strength and timing of flows, as well as an increase in low flows throughout the summer. Likewise, as rainfall periods tend to be more intense but less frequent, severe water stress for the agricultural districts is expected [86]. Projections suggest that by the end of the century, the worth of farms in Lombardy may drop by nearly 80 % as a consequence of changing climate conditions [29], being rice and wheat production especially sensitive to changes in seasonal climate parameters [87].

In addition, there has been a rise in extreme weather occurrences, with the Centre for Research on the Epidemiology of Disasters

[88] noting that the past two decades have seen a series of hydrological (such as flash floods), climatological (including droughts and convective storms), and meteorological (cold waves and heatwaves) phenomena. For example, the spring-summer season of 2022 experienced what is deemed the most severe drought in seven decades, attributed to a significant reduction in winter snowfall, an extended heatwave, and a 120-day absence of rain. This led to unusual soil moisture levels and caused August weather patterns to shift forward by six weeks, as reported by the Po River District Basin Authority.

3.2. Data collection

An internet-based survey was employed to collect responses from farmers concerning their understanding of climate change perception and their attitudes towards adaptation (for specifics, refer to Table A.1 in the supplementary materials). The analysis focuses on individual farmers since decisions regarding risk management and adaptation often originate at the level of the farm or household. A total of 12 irrigation districts confined to the regional irrigation districts' union (ANBI Lombardy) collaborated in the development and implementation of the survey (e.g. managers from two irrigation districts pre-tested its suitability and applicability for individual farmers, ensuring that essential information was not overlooked, sensitive data was protected, and the time required for completion was accurate. In accordance with the ethical guidance outlined by the Declaration of Helsinki and adhering to EU Regulation 2016/679 (General Data Protection Regulation), the survey received approval from both the Ethics Committee and the Data Protection Office, ensuring the confidentiality and safety of all personal data belonging to participants. Additionally, every participant received information regarding the survey's objectives and was asked to provide their consent through an online form to engage in the study.

Data was gathered using the Microsoft Forms platform, collecting 511 samples between January and April 2022, with 460 being validated, surpassing the sample size deemed representative according to Cochran's formula for finite populations [89], which results in 382 samples given a farm population of 47,000, a confidence interval of 95 % and a margin error of 5 %. Each farmer took 13 min on average to answer the survey questions. The survey was delivered in Italian and contained 75 closed-ended questions of different nature (e.g., single/multiple-answer, dropdown, Likert) divided into six blocks combining descriptive factors (farmers characteristics and farming features) with cognitive factors (climate change knowledge and comprehension, perceived effects, adaptation strategies and hindrances). The selection of explanatory variables is summarized and operationalized as shown in Table 1 following an in-depth literature review (e.g., [90–92]).

A wide array of independent variables covers farmers' characteristics and farming features as influencing farmers' attitudes towards adapting to climate change. Nevertheless, certain factors which have not been taken into consideration in this analysis may limit the outcomes (e.g., lack of farm income data). In the same way, dependent variables are outlined from the literature to summarize farmers' knowledge of the changing climate and their derived attitudes, perceived effects and risk behavior, choices regarding adaptation options, and the obstacles they face in adapting.

Categorical, continuous, and dummy responses were used to determine farmers' and farming' characteristics; 5-point Likert scale measuring responses from *Strongly disagree* (1) to *Strongly agree* (5) to delve into farmers' attitudes regarding risk awareness, and dummy responses (1 = yes/0 = no) were used to recap farmers' experiences on perceived impacts and risk adaptation options. As climate change can be difficult to perceive and considered an abstract issue, the 'I do not know/No answer' option (2) was included when asking about the triple-loop on risk behavior (awareness, perception, adaptation) to minimize non-attitude respondents or those respondents without a strong opinion, even doubting about climate change effects and management [93]. The combination of dependent variables aims to holistically assess climate change risk behavior by considering multiple stressors. Preliminary analyses such as normality and outliers were also computed. Cronbach's alpha based on standardized items was recorded to test survey reliability, obtaining an overall score of 0.76. This value suggests that the survey tool demonstrates a satisfactory level of internal consistency, indicating that the responses from participants were dependable and appropriate for additional examination. Furthermore, the Average Variance Extracted (AVE) was used to assess convergent validity, with a value exceeding 0.5 being necessary to account for the error variance. In this research, the obtained value for all the constructs was between 0.501 and 0.836.

3.3. Data analysis

Statistical analysis, both descriptive and inferential, was performed using IBM SPSS Statistics v.27 and Origin Pro 2022 packages. Basic descriptive statistics, encompassing mean, frequency, and standard deviation, were derived for the attributes of farmers and their farming activities (independent variables) paired with their awareness of climate change risks, the main effects, and the primary adaptation strategies and barriers they face (dependent variables). Combining approaches from similar research (e.g., [94–96]) complemented with specific regional issues, independent variables include a total of nine farmer characteristics (age, gender, education, farming experience, labor force, farmers' union membership, irrigation district membership, off-farm income, and succession intention) and eleven farming singularities (farm size, production system, main crop, livestock, fertilizers use, farming practice, irrigated surface, irrigation method, water source, renewable energy use, and non-conventional water sources use) (e.g., [97–99]). The survey also asked to indicate the municipality where the agricultural activity was carried out, and the water rotation period (i.e., the time interval between two successive water deliveries to the farm by the irrigation district). However, both variables have been discarded for in-depth analysis given the high diversity of responses obtained. Dependent variables related to risk awareness include ten questions summarizing farmers' beliefs, exposition, responsibility, and technological ingenuity (e.g., [100,101]), while variables defining perceived risk are fourteen, combining impacts on crops with experienced weather changes (e.g., [102–104]). Risk adaptation perspectives include twenty adaptation measures related to changes in crop planting, water supply, conservation, land use and

Table 1
Overview of the descriptive statistics for the independent variables utilized in examining the farmers' profiles.

Explanatory variables		Category	Mean ± SD	Mode (%)	Description and measurement
Farmers' characteristics	Age (FE1)	Continuous (groups)	3.25 ± 1.19	4 (29.1)	Less than 35 years (1), 35–44 (2), 45–54 (3), 55–64 (4), 65 years or more (5)
	Gender (FE2)	Categorical	1.22 ± 0.45	1 (80.0)	Male (1), Female (2), Not specified (prefer not to say) (3)
	Education (FE3)	Categorical	2.97 ± 0.88	3 (38.3)	Illiterate (0), Elementary (1), Secondary (2), Tertiary (3), Vocational training (4)
	Farming experience (FE4)	Continuous (groups)	3.93 ± 1.26	5 (49.6)	Less than 5 years (1), 5–10 (2), 11–20 (3), 21–30 (4), More than 30 years (5)
	Labor force (FE5)	Categorical	1.91 ± 0.93	1 (48.7)	Family members (1), Non-family members (2), Both family and non-family members (3)
	Farmers' union membership (FE6)	Categorical	1.57 ± 0.68	2 (58.7)	Coldiretti (1), Confagricoltura (2), Confederazione Italiana Agricoltori (3), COPAGRI (4), No membership (0)
	Irrigation district membership* (FE7)	Categorical		0 (26.1) Oglio Mella (20.7)	From 1 to 12 being associated with an irrigation district, No membership (0)
	Off-farm activity (FE8)	Dummy	0.31 ± 0.46	0 (69.3)	Off-farm job (external income) (1), Not off-farm activity (0)
	Succession intention (FE9)	Dummy	0.62 ± 0.64	0 (46.7)	Identified a successor (1), If do not (0), Does not know (2)
Farming characteristics	Farm size (FA1)	Continuous (groups)	4.27 ± 1.51	6 (29.1)	Less than 1 ha (1), 1–5 (2), 6–10 (3), 11–20 (4), 21–50 (5), More than 50 ha (6)
	Agricultural production system (FA2)	Categorical	1.48 ± 0.96	1 (75.2)	Conventional (1), Organic or agroecological (2), Transiting to organic (3), Mixed (4)
	Main crop** (FA3)	Categorical		2 (70.2) Cereals–maize (66.3)	From 1 to 26 considering the preeminent irrigated or rainfed crop
	Livestock (FA4)	Categorical	1.07 ± 1.53	0 (48.0) Cattle (34.6)	Cattle (1), Goats (2), Horses (3), Pigs (4), Poultry (5), Rabbits (6), Sheep (7), Buffaloes (8), Not livestock (0)
	Fertilizers use (FA5)	Categorical	1.04 ± 0.82	1 (77.8)	Mineral, compound or organic (1), Natural (2), Soil correctives (3), Amendment (4), Not use (0)
	Renewable energy use (FA6)	Categorical	1.65 ± 2.27	0 (63.0)	Biogas (1), Biomass (2), Hydroelectricity (3), Methane (4), Solar (5), Other (specify) (6), Not use (0)
	Farming Practice (FA7)	Categorical	0.95 ± 0.52	1 (72.2)	Rainfed (0), Irrigated (1), Mixed (2)
	Irrigation surface (FA8)	Continuous (groups)	3.57 ± 2.13	6 (24.8)	Less than 1 ha (1), 1–5 (2), 6–10 (3), 11–20 (4), 21–50 (5), More than 50 ha (6), Rainfed agriculture (0)
	Irrigation method (FA9)	Categorical	2.02 ± 2.10	1 (52.4)	Surface (1), Drip (2), Drip by sub-irrigation (3), Sprinkler by pivot or ranger (4), Sprinkler by roll (5), Mixed (6), Rainfed agriculture (0)
	Water Source (FA10)	Categorical	2.49 ± 1.55	2 (37.8)	Aqueduct (1), Canal (2), Well (3), Mixed canal and well (4), Pipe (5), Rainwater (6), River (7), Rainfed agriculture (0)
	Non-conventional water use (FA11)	Dummy	1.66 ± 0.74	2 (82.8)	Use of alternative water resources (1), Not use (2), Rainfed agriculture (0)

Notes: Irrigation district membership: Est-Sesia, Est-Ticino Villoresi, Muzza Bassa Lodigiana, Media Pianura Bergamasca, Dugali Naviglio Adda Serio, Oglio Mella, Chiese, Garda Chiese, Territori del Mincio, Navarolo AgroCremonese Mantovano, Terre dei Gonzaga in Destra Po, and Burana. Main crops include cereals (maize, wheat and spelt, barley), permanent grasslands (pastures and meadows), temporary forages, and vineyard.

livestock change, cooperation, and weather forecast (e.g., [105–106]), while nine barriers are defined distinguishing between those associated to farmers' attitudes and those corresponding to external support (e.g., [107, 108]).

Statistical inference was used to assess the potential connections and (in)dependence of trending attributes and cognitive patterns. Bivariate analysis integrates both parametric and non-parametric correlation techniques, such as Pearson's r, Kendall's tau, and Spearman's rho, along with logistic regression approaches. It incorporates distribution tools, one-way ANOVA, and post hoc assessments to investigate differences among respondent groups and to identify the internal drivers influencing the formulated hypotheses. Evidence from earlier investigations indicates that farmers are more likely to adopt a mix of adaptation measures to tackle climate-related challenges and constraints, instead of depending of just one strategy [109]. Therefore, the choice made by a farmer can be seen as a multivariate, interdependent, and simultaneous decision [110]. For this reason, binary logistic regression was used to determine how explanatory variables affect farmers' choices regarding the adoption of strategies to lessen climate-induced risks [111]. In addition, Structural Model Evaluation (SEM) was applied to examine the potential causal links between observed data and latent variables associated with constructs related to risk awareness, perception, and adaptation. SmartPLS v.4.0.8.8 was used to develop a partial least squares path modeling (PLS-SEM), which serves as a technique for estimating intricate cause-and-effect relationships in path models that involve latent variables from our triple-loop approach. Construct analysis and bootstrapping are used combining different metrics to delve into the predictor capability of the endogenous or dependent variables (path coefficient β, effect size f^2, indexes of significance t-value and p-value, R^2 as coefficient of determination and Q^2 as predictive relevance) [112]. The aim is 1) to represent how endogenous or dependent variables could be causally related to one another, and 2) to predict observed and unobserved influence and inter-relationship between the set of variables on risk awareness, perceived impacts, and adaptation measures [31] (Fig. 1).

4. Results

This section looks at descriptive data related to farmers and their farm characteristics to evaluate their understanding, perception, and reaction to climate change. Afterward, an assessment was conducted on the drivers that shape farmers' behaviors and actions across each dimension of the triple-loop approach.

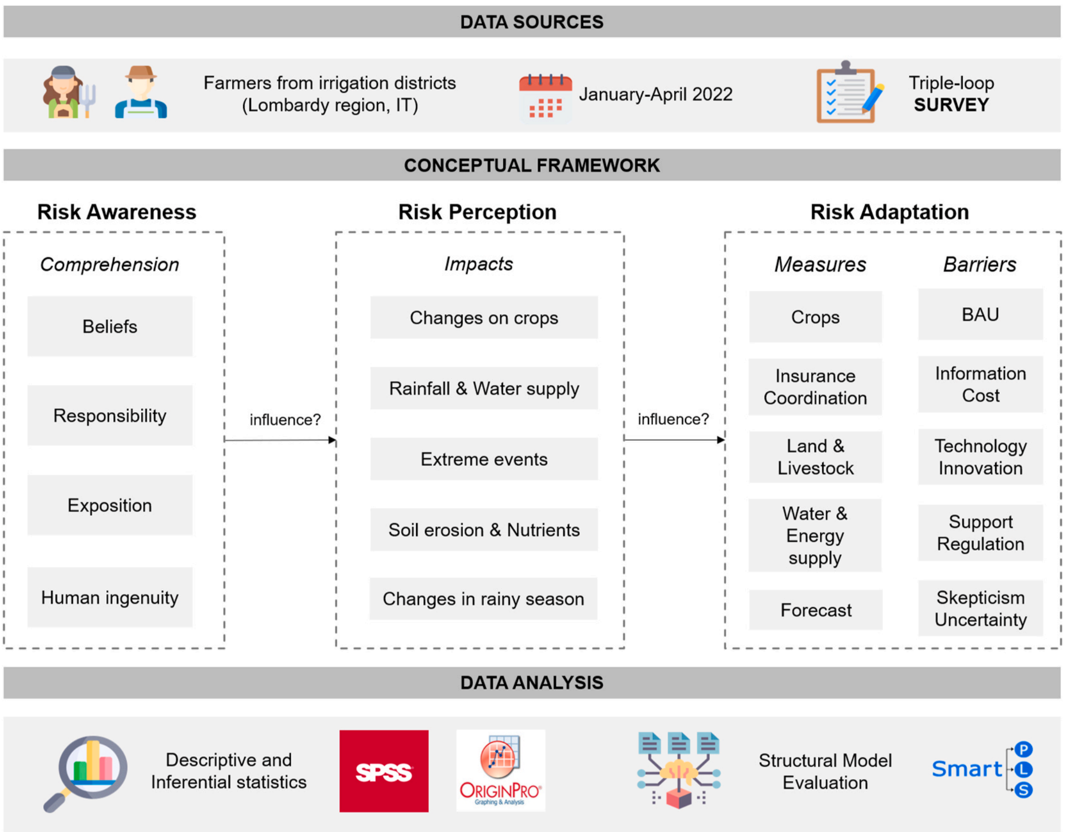

Fig. 1. Data sources, conceptual framework with main constructs defining the path analysis of the triple-loop approach on climate change risk behavior, and data analysis.

4.1. Farmer and farm characteristics

Descriptive statistics revealed that most respondents are males (80 %), and just over half (55.4 %) of the respondents are aged between 45 and 64 years, whereas only 9 % are under 35. Regarding education level, 38 % farmers sampled had completed tertiary studies, and 32 % had vocational training. Moreover, nearly half (49 %) of those surveyed possess over three decades in farming, while about 5 % to be considered young farmers with less than five years of experience. Non-family members manage only 12 % of the farms and a significant 49 % of farms rely exclusively on family members for labor, whereas a mix of family and non-family workers is prevalent in 39 % of the farms. Most farmers are involved with a farmers' union, with Confagricoltura (58.7 %) and Coldiretti (33 %) being the most relevant. At the same time, three out of four farmers are also associated with an irrigation district; the most representative of those are Oglio Mella (21 %), Muzza Bassa Lodigiana (15 %) and Chiese (13 %). Considering the data provided by 85 % of farmers who have specified their location, 164 municipalities are hosting sampled farmers, two-thirds of the respondents are from Brescia and Lodi provinces, while 15 % of the farmers are from the provinces of Cremona, Milan and Mantova. Regarding off-farm activities (non-farm income), 69 % of the farming households do not have any members working on non-farm activities. Meanwhile, there is almost a technical tie regarding succession intention to guarantee the transition from the current farming generation to the next (47 % without confirmed succession, 45 % with it).

The results also revealed that the landholding size held by the sampled farmers is higher than 50 ha for 29 % of the respondents, while 20 % of farmers have between 21 and 50 ha, and 19 % between 11 and 20 ha. Further, it was observed that merely 2 % of farmers fall into the category of marginal plots, which are less than 1 ha in size. Conventional agriculture dominates the sample (75 %), being organic or agroecological production systems applied by 11 % of farmers and a mix of both production systems considered by10 % of the respondents. Interestingly, about 5 % of the farmers are applying for a transition to organic. The farmers essentially cultivate cereals, maize being the first crop option for 66 % of the sample (plus 4 % of farmers planting as a secondary or tertiary option), combined with temporary forages (35 %). Secondary crops are wheat and spelt (28 %) or barley (18 %), while some farmers also apply for permanent grasslands, pastures and meadows (21 %) related to the livestock accounted in over half of the farms (52 %), being cattle (35 %), pigs (11 %) and poultry (7 %) the most dominant. A significant majority of farmers (85 %) utilize fertilizers, which can be mineral, compound or organic (78 %), applied as soil amendments (5 %) and correctives (2 %), or opting for using natural fertilizers, even they are used in a testimonial way (0.4 %). Even though 63 % of farmers do not use renewable energy, those that do opt for solar energy (29 %), biomass (5 %) or hydroelectric (2 %).

Farming practice is mainly irrigated (72 %), and most of the farmers irrigate a surface of more than 20 ha (51 %), while 17 % irrigate less than 5 ha. Surface irrigation is the most used method (63 %), combined with mixed methods by one in five farmers (20 %). Likewise, drip (plus sub-irrigation) and sprinkler (by pivot/ranger or roll) irrigation techniques are applied by the same proportion of farmers, 7 %. The primary water source comes from canals (46 %) (e.g., Naviglio Grande, Muzza) or a combination of canals and wells (34 %). However, farmers who only use wells are about one in seven (15 %). Regarding the range of irrigation turns for a season, almost half of the irrigators (49 %) use between five and twenty turns, while 42 % require less than five turns to achieve their water requirements. Although it is not a common practice, some farmers irrigate daily or weekly (less than 3 % of the farmers in both cases), but 99 % do not use alternative water sources (e.g., reclaimed water).

The probit model provides interesting correlations for the exploratory factors associated with the farmers' profiles and farm

Table 2
Farmers' knowledge levels concerning climate change (in %).

Code	Item	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	I do not know/No answer	Mean	SD
AW1	Climate change stands as the foremost issue that the world must tackle	1.3	6.1	7.6	44.3	39.1	1.5	4.09	1.03
AW2	The challenges posed by climate change are manageable, as human creativity will allow us to adjust to new conditions	14.8	35.9	27.4	10.9	2.4	8.7	2.24	1.17
AW3	Climate change should be seen as beneficial and not detrimental to agricultural activity	32.4	36.5	12.6	5.4	2.6	10.4	1.78	1.13
AW4	European Union and governments are responsible for tackling climate change	3.0	4.3	14.8	42.6	21.3	13.9	3.33	1.61
AW5	Economic sectors (business, industry, agriculture) are responsible for tackling climate change	2.2	7.6	17.8	46.5	15.4	10.4	3.34	1.14
AW6	Individuals and communities are responsible for tackling climate change	1.1	2.4	7.6	52.6	25.9	10.4	3.68	1.45
AW7	Crops that rely solely on rainfall are vulnerable to the impacts of climate change	1.3	3.0	6.7	45.7	33.0	10.2	3.75	1.49
AW8	Crops that are watered through irrigation face the impacts of climate change	0.7	4.3	7.4	53.5	23.0	11.1	3.61	1.47
AW9	Livestock is exposed to climate change	0.9	1.7	11.1	49.1	25.9	11.3	3.63	1.48
AW10	Multifunctionality (landscape, biodiversity, recreational) is exposed to climate change	0.9	1.5	4.3	53.0	28.0	12.2	3.69	1.52

characteristics (see supplementary material, Tables A.2 and A.3 for details). Some results confirm expected significant interactions. For instance, age is significantly and positively correlated with farming experience (*p*-value 0.01 and coefficient 0.629) but negatively correlated with education level and succession intention (*p*-value <0.001 and coefficients −0.118 and −0.269, respectively). Gender is significantly and negatively correlated with farming experience (*p*-value <0.001 and coefficient −0.259) and irrigation district membership (*p*-value 0.023 and coefficient −0.106). This means women have less farming experience and less involvement in managing irrigation districts. The educational level of farm households shows a significant and positive correlation with off-farm activities (*p*-value 0.033 and coefficient 0.099). More educated farmers combine agricultural activity with income other than farming. Interestingly, those less experienced farmers and those farms involving family members as the main labor force tend to introduce off-farm activities (*p*-value 0.004 and coefficient −0.135). Similarly, there is a strong and positive correlation between the workforce and farmers' union membership (*p*-value 0.002 and coefficient 0.142) as well as the possibility to continue the family farming legacy (*p*-value <0.001 and coefficient 0.177). Farm size is significantly correlated with all farming characteristics, mainly in a positive sense, except for the agricultural production (*p*-value 0.017 and coefficient −0.111) and the main crop (*p*-value <0.001 and coefficient −0.428), which means that the larger the farm, the more predominance of conventional agriculture and cereal (maize), and also the more irrigated surface (*p*-value 0.001 and coefficient −0.185). The use of fertilizers is significantly and positively correlated with farming practices, irrigated surface, and water sources (including non-conventional resources), which means fertilizers use increases when farms are irrigated or mixed (*p*-value 0.005 and coefficient 0.131), with a larger irrigated surface (*p*-value 0.010 and coefficient 0.121), and the primary water source is a mixed-use of canals and wells (*p*-value 0.004 and coefficient 0.134).

4.2. Awareness

Table 2 illustrates the perspectives of farmers on climate change. The findings reveal that a significant number of farmers (83 %) view climate change as the most challenging issue, capable of harming agricultural activity (69 %), for which human ingenuity does not seem to be enough to face climatic changes (51 %). Farmers firmly assert that the responsibility for tackling climate change lies predominantly with individuals and collectives (78 %); also, 62 % of them are aware of the liable acting of the economic sectors (including the agricultural activity), while less attention is placed on governments and institutions such as the European Union. Finally, farmers must evaluate if crops, livestock, and multifunctionality (e.g., landscaping, biodiversity, recreational activities) are exposed to climate change. Results display similar agreement on the exposition of crops (79 % for rainfed and 76 % for irrigated) and livestock (75 %). However, according to 81 % of the sampled farmers, multifunctionality is the most exposed to climate impacts.

According to the findings from the multivariate probit model (refer to Table A.4 in the supplementary material for further information), the attributes of the farm play a more critical role than the traits of the farmers in determining their awareness of climate change. Farmers' characteristics do not show a meaningful relationship with the belief that climate change is the most critical issue to be solved. Nevertheless, there is a strong positive relationship between age and the potential benefits of climate change, indicating that older farmers are more likely to view climate change as having some beneficial aspects for farming practices (*p*-value 0.036 and coefficient 0.098). It is noteworthy that both gender and workforce composition affect the belief in human creativity to tackle climate change; farms employing non-relatives or a combination of relatives and non-relatives tend to have greater faith in the importance of innovation and technology in addressing climate issues (*p*-value 0.001 and coefficient 0.148). At the same time, women are less confident (*p*-value 0.033 and coefficient −0.099). Likewise, larger irrigated farms using fertilizers in conventional agriculture are the most persuaded of the benefits of modernization when addressing climate change impacts.

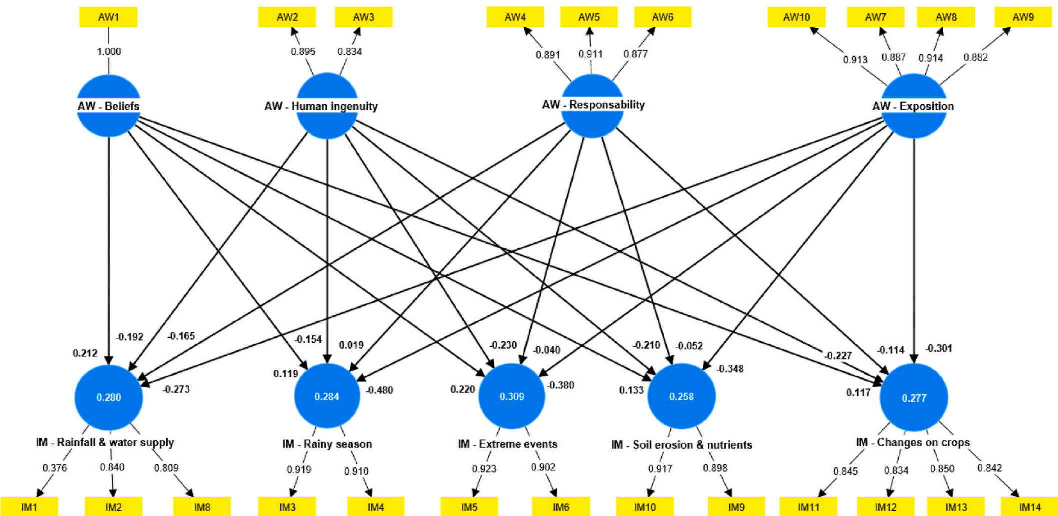

Fig. 2. SEM with the predictive capacity between latent variables and constructs on risk awareness (the top circles) and risk perception (the bottom circles). Note: values are expressed as coefficient of determination (R^2). Legend: AW = 'Awareness' items, IM = 'Impacts' items.

The findings also portrayed how farming experience, labor force, and farmers' union membership are significantly correlated with the responsibility to face climate change. Less experienced farmers identify institutions and individuals as those in charge of facing climate change, while those members of a farmers' union highlight the role of the economic sectors. Different farmer and farming characteristics intervene when comparing climate change exposition among crops, livestock, and multifunctionality. The association between farming experience and labor force is strongly linked to both irrigated and rainfed crops, as well as livestock and multifunctional practices. This suggests that farmers with limited experience and those who employ non-family labor are more attuned to the effects of climate change on their crops and livestock, along with the associated biodiversity risks, which are of particular concern among union farm memberships. Moreover, farm size and irrigated surface are positively and significantly correlated with irrigated crop vulnerability, that is, larger and irrigated farms are more aware of the potential risks affecting irrigated crops.

The structural model was applied to analyze if endogenous or dependent variables can predict farmers' behavior, that is, if awareness could anticipate perceived impacts. The SEM revealed a moderate correlation between risk awareness and risk perception constructs, suggesting that understanding of climate change can reasonably predict variations in how farmers respond to perceived effects ($Q^2 = 0.241–0.280$, that is, awareness predicts between 24 % and 28 % of the variance in risk perception) (refer to Fig. 2 and Table A.5 in the supplementary material for further details). For example, the findings revealed that having faith in climate change as the foremost critical issue greatly enhances the perception of its impacts, especially during instances of extreme weather events ($\beta = 0.220, t = 3.077, p = 0.002, R^2 = 0.309, Q^2 = 0.280$) and changes in rainfall patterns ($\beta = 0.212, t = 4.031, p = 0.000, R^2 = 0.280, Q^2 = 0.256$), while the path analysis illustrates a negative association between being exposed to climate change and consider human innovation as determinant of perceived impacts. Moreover, higher values for the coefficient of determination ($R^2 = 0.81–0.92$) have been obtained for all control variables except for one indicator of the construct 'Rainfall and water supply' (IM1, increased rainfall or extended rainy season, $R^2 = 0.376$), which can be related to a more substantial prediction capacity of the rest of the indicators of the construct.

4.3. Perceived impacts

A vast majority of farmers reported experiencing changes in extreme weather conditions related to meteorological and hydrological risks and, to a lesser extent, biological hazards (Fig. 3). The most prominent effects include rising temperatures and heatwaves, as well as a higher occurrence or severity of droughts (88 % and 87 %, respectively). Similarly, farmers are acutely aware of more unpredictable rainfall trends, noting a rise in the frequency or severity of floods (76 %) alongside a reduction in overall rainfall or a briefer rainy season (73 %). This situation is aggravated by an unreliable water supply scenario (71 %) and increased soil erosion (60 %).

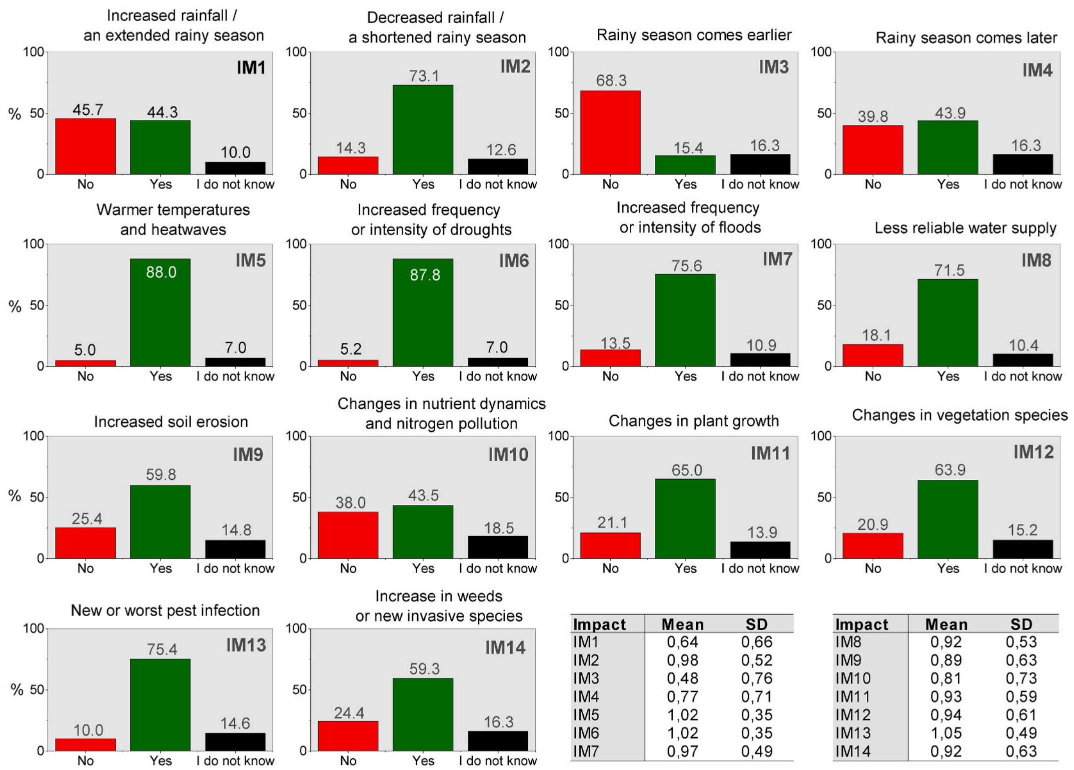

Fig. 3. Farmers' concern regarding main observed changes in climate variables. Note: Box results are presented in percentages. Mean and SD are provided for each listed impact (IM1-IM14), being the values 0 (No), 1 (Yes) and 2 (I do not know).

Farmers mostly associate significant weather changes with the emergence of new or more severe pest infestations, as well as a rise in weeds and invasive plants (75 % and 60 %, respectively). They also note alterations in plant growth (65 %) and shifts in vegetation types and biodiversity (64 %). Interestingly, there is only one listed impact that most farmers do not identify: a preview of the rainy season (68 %). While over 80 % of farmers hold strong views on the anticipated effects of climate change, certain impacts raise questions, including shifts in nutrient dynamics or heightened nitrogen pollution (18 %) and alterations in the distribution of rainy seasons (16 %).

The findings from the multivariate probit model (refer to Table A.6 in the supplementary materials for additional information) highlight that some personal characteristics such as education, labor force and the province affected farmers' perception of main weather changes. The three factors are negatively and significantly correlated with changes in rainy season patterns, that is, less

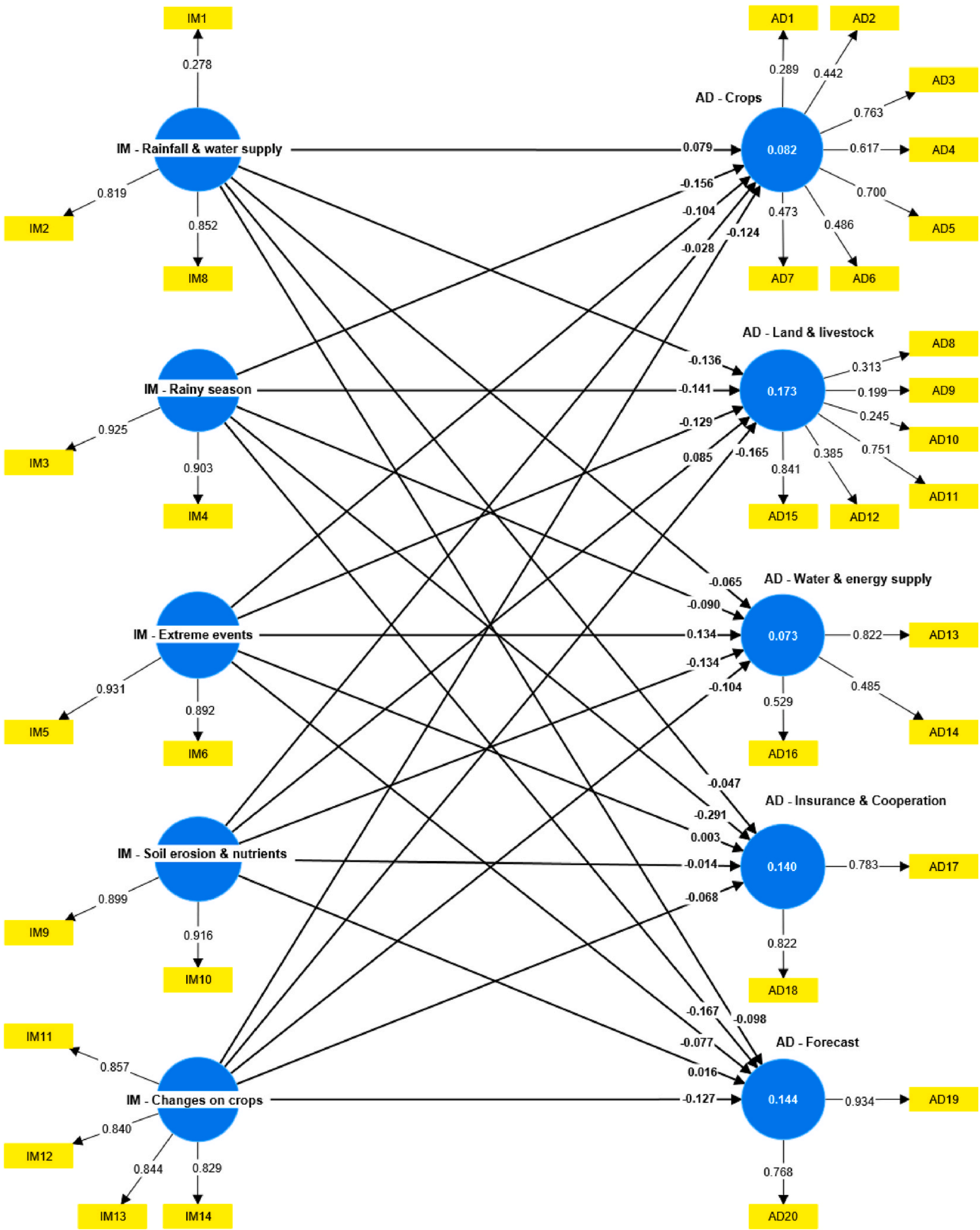

Fig. 4. SEM with the predictive capacity between latent variables and constructs on risk perception (circles on the left) and risk adaptation (circles on the right). Note: values are expressed as coefficient of determination (R^2). Legend: IM = 'Impacts' items, AD = 'Adaptation' items.

educated farmers (particularly from Como and Brescia provinces) and farms employing only family members perceive rainy season comes earlier or later. In the same way, farms that include relatives report a heightened frequency or intensity of flood occurrences (p-value 0.032 and coefficient −0.100). Contrary to what expected, age and farming experience are not significantly correlated with any of the parameters defining weather changes. However, both factors are linked to the effects on crops, such as shifts in plant species and biodiversity. This means that younger and less experienced farmers tend to notice greater impacts on plant diversity and associated biodiversity losses.

Regarding farm characteristics, findings suggest that farm size is the most influencing factor in determining both weather changes and impacts on crops, being negatively and significantly correlated with erratic rainfall patterns (e.g., shortened or differently distributed rainy season), less water supply, and an increase in soil erosion, alongside alterations in nutrient dynamics and variations in plant growth. This suggests that smaller farms (including those mainly irrigated) have a greater capacity to identify weather changes and related impacts on crops. Using fertilizers is also negatively and significantly correlated with changes in plant growth (p-value 0.013 and coefficient −0.116) and increasing weeds or new invasive species (p-value 0.022 and coefficient −0.107). Most farmers who use fertilizers are unaware of the impacts affecting plant development or the appearance of invasive species. Even though only a limited number of farmers adopt renewable energy options, this element stands out as the only one that is significantly and negatively linked to the awareness of increasing temperatures, heat waves, and the heightened occurrence or intensity of droughts. Thus, most farmers recognize fluctuations in temperature and associated severe weather extremes.

The structural model was applied to analyze if perceived impacts could explain the variance in adaptation measures promoted by farmers. The SEM revealed a moderate to weak capacity to associate the constructors of risk perception and risk adaptation (Fig. 4 and refer to Table A.7 in the supplementary material), that is, perceiving climate change partially explains the predicting nature of the variance in climate change adaptation ($Q^2 = 0.052–0.147$, that is, perception only anticipate between 5 % and 15 % of the variance in risk adaptation). According to the results from the path analysis, most of the perceived impacts are negatively associated with adaptation, being the construct of 'Rainy season' the one with the highest significance ('Rainy season' > 'Insurance and Cooperation' t-value = 5.025, p-value = 0.000). Interestingly, the model identifies a very low predictive relevance between perceived extreme events and taking out insurance or cooperating with other farmers, obtaining a positive coefficient but not significant ($\beta = 0.003$, $t = 0.049$, $p = 0.961$, $R^2 = 0.140$, $Q^2 = 0.119$), which means that farmers are not directly considering the occurrence or frequency of extreme events as a driver for insurance or coordination promotion. At the internal level of the constructs, preventive adaptation measures (AD17-AD20) related to 'Forecast' and 'Insurance and Cooperation' obtained the highest values for the coefficient of determination ($R^2 = 0.77–0.93$), which can be related to their robustness in prediction capacity.

4.4. *Adaptation measures and barriers*

4.4.1. *Adaptation strategies*

Being aware of how climate change is affecting their activity, farmers adopt different strategies at the farm scale (Fig. 5). At least half of the farmers apply 7 of the 20 proposed measures. In response to adverse effects, the most common actions taken care are decreasing fertilizer usage or enhancing their effectiveness (70 %), implementing crop diversification and rotation (67 %), and encouraging soil conservation techniques such as cover cropping and tillage practices (54 %). Likewise, some actions are preventive in

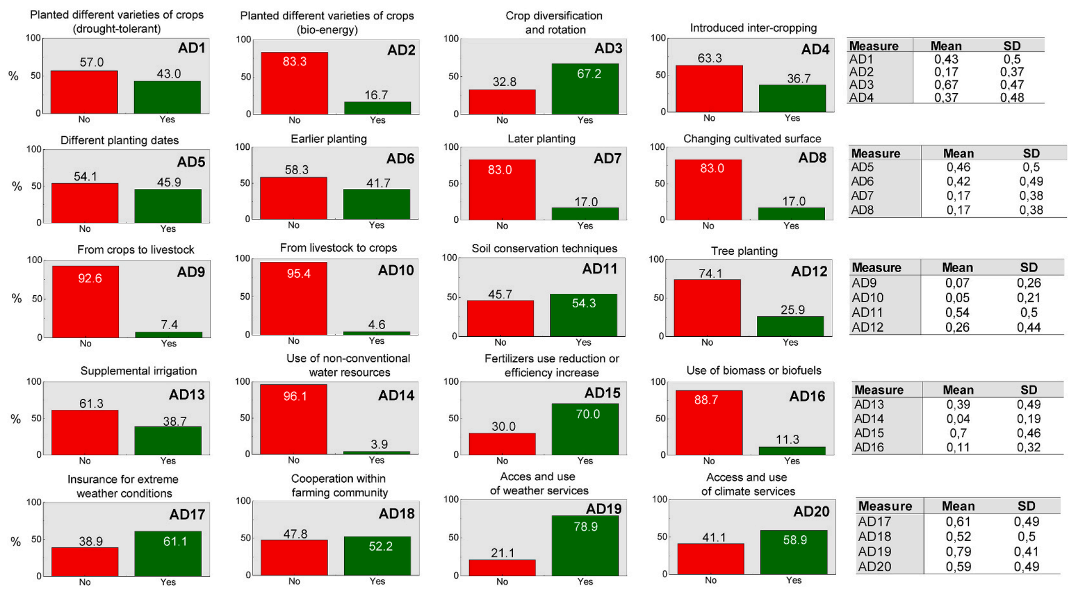

Fig. 5. Adaptation measures undertaken by farmers. Note: Box results are presented in percentages. Mean and SD are provided for each listed adaptation measure (AD1-AD20), being the values 0 (No) and 1 (Yes).

nature: using weather or climate services to recap knowledge on short-term or seasonal forecasts (79 % and 59 %, respectively), contracting insurance to face extreme weather conditions (61 %), and promoting cooperation within the farming community to share best practices (52 %). Interest is also shown in measures related to the crop planting process (changing dates, planting earlier, or introducing different varieties or crops being drought-tolerant), which are applied by about 40 % of the farmers. Likewise, results show those measures outside the farmers' mitigation or adaptation strategy. More than 90 % of the farmers have not considered exchanging crops for livestock and vice versa, while more than 80 % of respondents discarded planting bio-energetic crops and later planting, and around 70 % ruled out shading and sheltering or tree planting options. Interestingly, a significant number of farmers have not considered utilizing alternative water sources, such as reclaimed water, with 96 % not exploring this option. Additionally, 61 % have not implemented supplementary irrigation to combat water scarcity, and a staggering 89 % of respondents have dismissed the idea of integrating biomass or biofuels for their energy requirements on the farm.

The outcomes of the multivariate probit model (see Table A.8 in the supplementary section for specifics) reveal that crop-related actions, including the introduction of new varieties, crop rotation, or alterations in the planting calendar, are predominantly influenced by the characteristics of the farm, such as the size of the farm, the primary crop cultivated, the main farming practices, and the irrigated area. For example, larger and irrigated farms cropping cereals (mainly maize, wheat and barley) opt for crop diversification and earlier planting. To a lesser extent, some farmers' characteristics, such as age (*p*-value 0.002 and coefficient −0.142) and gender (*p*-value 0.012 and coefficient −0.117), are negatively and significantly correlated with planting drought-tolerant crops and applying crops rotation, being male and younger farmers those more predisposed to introduce changes in crops varieties. Further, farms with livestock prioritize planting bio-energetic crops (*p*-value 0.018 and coefficient 0.110).

Change from crops to livestock is positively and significantly correlated with farmers' union and irrigation district memberships, farm size and irrigated surface but negatively and significantly correlated with age. In other words, younger farmers with the largest irrigated farms and those counting on the support of a farmers' union and an irrigation district see livestock as a better adaptation option than crops. Soil conservation techniques are positively and significantly correlated with farming experience, farm size, and irrigated surface. In other words, experienced farmers leading larger and irrigated farms introduce mechanisms to reduce soil erosion. Likewise, tree planting is promoted by smaller and rainfed farms from conventional agriculture, while supplemental irrigation is prioritized by larger and irrigated farms (particularly those using sub-irrigation or sprinkler methods). Interestingly, the use of non-conventional water resources is negatively and significantly correlated with farming practices (*p*-value 0.020 and coefficient −0.108), which means that rainfed farms are planning to use non-conventional water resources to address warmer temperatures and drought episodes. Interest in reducing or improving the use of fertilizers is positively and significantly correlated with farm size, farming practice, irrigated surface, and using non-conventional water resources. As a result, extensive and irrigated farms may be inclined to reassess the benefits or improve the efficiency of fertilizer application as a means of adapting to the challenges posed by climate change.

The findings indicate a strong and meaningful relationship between the size of farms and the implementation of additional preventive adaptation strategies, such as insurance, collaboration, and climate-related services. That is, the larger the farm size (particularly for those irrigated), the greater the use of forecasting tools. Insurance is the most correlated measure, particularly with farm characteristics related to water supply (e.g., irrigated surface, irrigation method, water source). Further, male, older and experienced farmers choose insurance as the priority measure to reduce crop vulnerability. Farm size, irrigated surface, labor force, and farmers' union membership are positively and significantly correlated with cooperation within the farming community. For example, farmers from larger (*p*-value <0.001 and coefficient 0.216) and irrigated farms (*p*-value 0.022 and coefficient 0.107) are sharing local knowledge with the neighborhood to reinforce their adaptation capacity. In addition, using weather and climate services shows a significant positive correlation with both the scale of farming operations and membership in farmers' unions. This indicates that larger farms and those backed by farm unions are especially inclined to rely on forecasting services to guide their choices. Moreover, weather services are also positively and significantly correlated with the irrigated surface, water sources (including non-conventional resources), and fertilizers used. Therefore, farmers with larger irrigated farms (particularly from canals) and those using fertilizers opt for using weather services to recap rainfall and temperature information in the short-term.

Table 3
Barriers to implementing adaptation measures.

Code	Item	No (%)	Yes (%)	I do not know/No answer (%)	Mean	SD
BA1	Climate change denial or skepticism	31.5	59.6	8.9	0.77	0.59
BA2	Limited awareness of danger (I won't be directly impacted)	30.0	54.8	15.2	0.85	0.66
BA3	Business-as-usual scenario: 'This is how we've consistently approached things, it's our established method, and it's what we are accustomed to'	30.2	54.4	15.4	0.85	0.68
BA4	Lack of information about risks and vulnerability	38.7	47.4	13.9	0.75	0.68
BA5	High cost related to capital outlay at the farm level	11.3	77.0	11.7	1.00	0.48
BA6	Limited availability of drought-tolerant crop varieties	27.4	54.1	18.5	0.91	0.67
BA7	Insufficient availability of advanced solutions to bolster resilience against climate change	33.2	50.9	15.9	0.83	0.68
BA8	Inadequate governmental assistance and disorganized management efforts	9.1	79.3	11.5	1.02	0.45
BA9	Regulations and rules are too complicated	11.6	75.2	13.3	1.02	0.50

Note: Mean and SD are provided for each listed adaptation barrier (BA1-BA9), being the values as 0 (No), 1 (Yes) and 2 (I do not know/No answer).

4.4.2. Adaptation barriers

Many farmers concur on challenges to increase their resilience and adaptive capacity (Table 3). About 80 % of the respondents have been able to confirm or deny the listed barriers, placing the unknown level at 14 % on average. A major obstacle is the insufficient backing from the government together with ineffective management coordination (79 %). High investment costs at the farm stage (77 %) and the bureaucracy entailing climate change policies and regulations (75 %) are identified as critical barriers. Climate change denial or skepticism (including low-risk perception), business-as-usual scenario, or distrust in innovation and new technologies to promote drought-tolerant crop varieties have been identified as key barriers by almost one in two farmers, while the absence or quality of information about risks and vulnerabilities at the farm scale does not surpass the fifty percent threshold of validation.

The results derived from the multivariate probit model (see Table A.9 in the supplementary material for comprehensive details) shed light on the characteristics of farmers, including their gender, experience in agriculture, and off-farm engagements, which are significantly linked to climate change denial. Specifically, women, farmers with minimal experience, and those with external income sources regard skepticism about climate change as a major barrier to their adaptation strategies. Likewise, farming practices and irrigation methods are negatively and significantly correlated with low-risk perception and lack of information about farming risks and vulnerability, which means that rainfed farmers identify this barrier as one of the most relevant. The business-as-usual scenario is positively and significantly correlated with gender and negatively and significantly correlated with labor force, farmers' union membership, farm size, and irrigated surface. In other words, farms led by women, rainfed, small in extension, with only family members, and without the support of a farmers' union recognize that the ordinary way farmers take care of their agricultural activities can be an obstacle to promoting adaptation. The substantial expenses associated with farming operations are inversely and notably linked to factors such as the age of the farmer, the farm size, the application of fertilizers, main agricultural techniques, the area under irrigation, the irrigation method, and main water sources, including alternative options. Thus, younger farmers from smaller farms (mainly rainfed) and non-using fertilizers are the main ones concerned with the investment required to face climate change impacts. In addition, the limited access to drought-resistant crop types, paired with the absence of new technological advancements to bolster crops' adaptability to climate change, is significantly and negatively linked to irrigation district participation, the scale of farms, fertilizer usage, farming methods, and the adoption of unconventional water resources. Difficulties in obtaining more resilient crop varieties to face warmer temperatures and drought conditions are highly experienced by farmers from smaller and rainfed farms, but also by farmers non-using fertilizers and not affiliated with an irrigation district. Finally, lack of government support and poor coordination, combined with too complicated regulations and rules, is negatively and significantly correlated with labor force, farmers' union membership, main crop, renewable energy use, and water source. Consequently, rainfed farms, with only family workers, without the support of a farmers' union, having cereals as the main crop, and without using renewable energy sources are those profiles asking for more public support from institutions at the regional and national scale.

5. Discussion

The intricacies of human behavior are multifaceted, limited in rationality, and difficult to depict due to its influential and influenceable nature [113]. A wide range of conceptual frameworks and theories has emerged to investigate individual beliefs and perspectives, showcasing different influences and hidden assumptions with implicit assumptions to manage complex systems in climate change scenarios [114]. Social learning has been promoted as a fundamental feature for complex system management and governance, in which past experiences are used to deal with future challenges [115]. In this line, our study aimed to reinforce existing frameworks by considering a triple-loop approach on farmers' behavior able to combine risk awareness, risk perception, and risk adaptation issues. The approach elicited a strong comprehension of farmers' behavior to encourage knowledge co-production tailored to local contexts [116]. Our findings provided relevant background on farmers and farming characteristics, being able to identify within the heterogeneity of the sample, a dominant profile: a man between 45 and 64 years old, with higher education and more than 30 years of farming experience, affiliated with both a union farm and member of an irrigation district but without off-farm activity and succession intention, who developed farming activity in farms larger than 20 ha and irrigated mainly by canals, combining livestock and conventional crops (maize) and using fertilizers (mineral, compound, or organic). This profile indicates that a significant number of farmers have been engaged in farming for an extended period and were in a better position to identify long-term changes because they understand their environment in time horizon [117,118].

Raising comprehension and awareness is frequently viewed as crucial during the initial phases of adapting to climate change effects, helping to lessen the susceptibility and vulnerability of farmers. In line with recent research [119,120], our field observations revealed that farmers largely recognize global warming, viewing climate change as the primary challenge impacting both crops and livestock, particularly in terms of multifunctionality. Farmers were assertive in pointing out that, in the context of assigning responsibility for climate change and its repercussions, the focus should be on individuals and communities rather than on economic sectors, including agriculture, or on governmental and institutional entities. This view diverges from the conclusions drawn in recent research by Refs. [60,121], where farmers stated that their main priority was to reduce climate emissions. As noted by Ref. [122], if farmers do not view managing climate change as a key priority, this could represent a significant turning point in their attitudes. Furthermore, the insights from the SEM offer a reliable and practical exploratory framework by identifying a moderate to strong ability to anticipate a positive association between the drivers of risk awareness and perception. This suggests that recognizing climate change can partially foresee changes in farmers' behaviors related to perceived impacts, since increased awareness among farmers is likely to bolster their responses, similar to observations made in the research by Refs. [30,123].

According to the conceptual review conducted by Ref. [124], this mutual influence between climate change awareness and perceived impacts can be explained by different elements, including experience (from events during farming activity) and memory (from farmers' recall of the potential impacts enhanced by climate change). In other words, a more accurate and prompter understanding of risks led to improved assessments of both the occurrence and intensity of risks at the farm scale [125]. Our findings confirmed that farmers notably experienced climate changes, recognizing rising temperatures along with more climate extremes, including heatwaves and droughts, but also more erratic rainfall patterns, corroborating outcomes from recent studies [126–129]. The results from the multivariate probit model highlighted that age and farming experience are not significantly correlated with perceiving weather changes, although both factors are correlated with impacts on crops, that is, younger and less experienced farmers perceive larger impacts on plant growth and biodiversity. In this sense, our findings oppose the conclusions of [130,131], which suggested that age serves as an indicator of farming experience, as it is the more experienced farmers who are better at noticing changes in climate. Regarding farm characteristics, findings suggest that farm size is the most influencing factor in determining weather changes and impacts on crops, contrary to previous studies by Ref. [132], in which farm size is considered a limiting factor.

Grasping how farmers conceive scientific knowledge is crucial for co-designing climate-related policies including local dependent adaptation measures [133]. Moreover, how farmers perceive climate change can be used as a proxy for upcoming adjustments and decisions. In this line, the findings from the SEM could only confirm a moderate ability to discern an association between drivers conditioning risk perception and adaptation, that is, perceiving climate change partially explains the predicting nature of the variance in climate change adaptation. These results are less robust than those presented by past studies [134], in which the mediating effects between constructs were also considered. We explored farmers' adaptation practices and main adaptation barriers to delve into this direction. The results showed that farmers utilize various adaptation techniques concurrently, such as reactive strategies for dealing with post-disaster impacts and preventive actions implemented before climate-related hazards, which is consistent with findings from recent research [135]. The highest scores were obtained among preventive actions (e.g., weather and climate services, insurance, and cooperation within the farming community). Our results confront some studies in which inaccurate weather prediction increased farmers' exposure and vulnerability and hindered adaptation strategies [136]. Furthermore, a majority of farmers preferred to implement responsive strategies like minimizing fertilizer application, enhancing efficiency, practicing crop rotation and diversification, as well as employing soil conservation methods [137–139]. Likewise, sampled farmers have not chosen to implement changes in the planting dates and introduction of dry-resistant and bio-energetic crops. However, both are common strategies adopted in response to changes in rainfall patterns [140,141].

Farmers frequently mentioned obstacles to adapting, including insufficient government assistance, inadequate management coordination, expensive investments, and overly complicated regulations, echoing the political and economic challenges noted by Ref. [142]. Interestingly, while previous studies primarily identified insufficient information and limited services as key obstacles to adaptation [143–146], our findings emphasized the significance of cognitive challenges, including skepticism or denial regarding climate change and a tendency to maintain the status quo. Various factors influencing farmers' behavior have been highlighted in the literature, which can either hinder or facilitate their willingness to adapt. Our findings revealed various types of farmers and agricultural characteristics that shape their views and reactions to climate change. Key elements such as prior experiences, the scale of their farms, primary crops grown, the area under irrigation, and fertilizer usage significantly affect how farmers perceive climate change and their ability to adapt, consistent with earlier research conducted by Refs. [147–150]. However, variables such as gender, education, succession intention or off-farm income were less relevant, contrasting previous results [151–153].

We acknowledge certain limitations in our study and suggest avenues for further investigation. First, the use of a survey to collect information helps in acquiring standardized and contrasted knowledge, but it might constrain the study's narrative as participants often rely on their recollections, which are generally obtained retrospectively [154]. Likewise, it could lead to unclear data or information bias because answer options may be interpreted differently by respondents [155]. The application of a mixed or multi-methods research (e.g., quantitative, qualitative) can address the shortcomings of cross-sectional studies when it comes to establishing causal inferences and providing flexibility: the quantitative analysis could indicate the strength and direction of associations, while the qualitative analysis can provide insights into the reasons those associations occur [156]. Additionally, there is still a lack of understanding regarding how farmers adapt their actions in response to climate change, including significant changes in their capacity to perceive impacts and identify strategies for adaptation. Likewise, future research should combine farmers' behavior evaluation with precise and prompt observed data on climate hazards to overpower climatic risks and improve farm management strategies design. Authors like [157] have strongly advocated for distinguishing between preemptive and reactive adaptation strategies to enhance the formulation of climate policies. Similarly [158], emphasized that the examination of climate data should go beyond seasonal variations and include intra-seasonal weather patterns, which are crucial for farmers. They are particularly interested in the timing of rainfall, the length of the growing season, and the likelihood of dry spells. Moreover, presenting historical cases of extreme weather events as representations of inter-seasonal climate fluctuations could help farmers recognize the consequences of climate change, lessening the mental distance to climate-related dangers and rendering them more applicable to their daily routines [159,160]. By doing so, farmers will be more confident and trusting due to information sharing from farming experiences, and adaptation strategies could be implemented more efficiently at the farm scale while increasing the feasibility and effectiveness of the adaptation strategies promoted by farmers [161]. Ultimately, even though climate change adaptation occurs on a global scale, the strategies employed are largely dependent on individual circumstances and shaped by regional differences and farmers' sensitivities. A recent study [24] pointed out that the distribution of case studies on farmers' responses and actions regarding climate change is skewed, predominantly in low-income areas and the Global South. In this regard, although our results are limited to the Lombardy region, its implications may be much more far-reaching, particularly at the European level to reinforce the roadmap for adaptation defined by the European Climate Adaptation Platform (Climate-ADAPT), and at the Mediterranean context, considered a climate crisis hotspot [162].

6. Conclusion

There is an expanding interest in studying farmers' responses to climate change, as recognizing their perceptions and attitudes is vital for anticipating their adaptability. This insight can inform the adjustment of adaptation measures and policies to better suit local challenges. This research sought to enhance the current literature in this area by producing fresh insights through social learning and bottom-up approaches. Our research indicates that a majority of farmers recognize the effects of climate change and are able to differentiate between atypical variations in temperature and precipitation and the rising occurrence and severity of extreme weather events. Farmers tackle the obstacles of climate change by integrating both preventive responses—like climate and weather services and insurance—and proactive strategies, which encompass practices such as minimizing fertilizer application, rotating crops and diversifying varieties, and conserving soil. Still, major constraints obstructed their adoption efforts, primarily stemming from economic and institutional challenges. The SEM analysis confirmed that knowledge of climate change can reliably predict how farmers might change their behavior based on perceived effects, although the connection between risk perception and adaptation strategies was found to be less robust. In addition, the outcomes of the binary logistic model demonstrate that drivers such as the farming expertise, the dimensions of the farm, the irrigated land area, and the main type of crop are essential in determining both risk perception and the implementation of relevant adaptation measures. These issues are imperative to consider when implementing and monitoring actions to enhance climate change adaptive capacity among farmers. Therefore, it is essential for policymakers to acknowledge the unique backgrounds of farmers and their distinct reactions, as these factors can impact their ability to modify their agricultural techniques for greater resilience. Additionally, it can be relevant for policymakers to focus on the cognitive drivers that shape farmers' narratives and actions regarding climate change awareness, perception, and their adaptation strategies. These actions can support a more comprehensive perspective on the triple-loop framework related to agricultural practices and contribute to enhance risk management approaches and reduce maladaptive responses.

CRediT authorship contribution statement

Sandra Ricart: Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Claudio Gandolfi:** Writing – review & editing, Validation, Supervision, Resources, Conceptualization. **Andrea Castelletti:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Data availability statement

No additional data was used for the research described in the article. Raw and complementary data from datasets generated during the study are available from the corresponding author on reasonable request.

Ethics declaration

The Politecnico di Milano's Data Protection Officer, following an assessment by an ethics committee, verified that the research met the standards outlined in the European Code of Conduct for Research Integrity. The participants in the survey were properly briefed about the purpose of the study, as well as the methods for gathering and handling data by being informed through the initial page of the online questionnaire. The survey was anonymous and no sensitive nor identifiable data was obtained from the participants. All participants gave their consent to participate in the study.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e41328.

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