frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 16 July 2025
DOI 10.3389/fenvs.2025.1540818

Characterizing adaptation responses to drought risk of livestock farmers in the Spanish *dehesa* agroforestry system

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RECEIVED 06 December 2024
ACCEPTED 27 June 2025
PUBLISHED 16 July 2025

CITATION
Ropero Szymańska N, Hernández-Mora N and De Stefano L (2025) Characterizing adaptation responses to drought risk of livestock farmers in the Spanish *dehesa* agroforestry system.
Front. Environ. Sci. 13:1540818.
doi: 10.3389/fenvs.2025.1540818

Climate change adaptation is primarily a local endeavor in response to impacts that are specific to regions, communities and ecosystems. Assessments of adaptation action must take into consideration the specific socioeconomic and environmental contexts where it takes place. This study aims to understand how context-specific attributes influence the adaptive capacity of implemented measures. Building on the work of other authors, we developed a mixed methods approach to characterize drought and climate risk management measures and adaptation strategies that take into consideration farmer input and local context. We applied this methodology to the response of extensive dryland livestock farmers in a *dehesa* agroforestry system in southcentral Spain during a prolonged drought. Qualitative data was collected through interviews, focus groups and workshops, and coded and analyzed through deductive content analysis and complementary statistical correlation and multicriteria analysis. Measures were classified to place them along a coping-adaptation spectrum. They were further characterized in terms of their basic features, effectiveness, enabling conditions and feasibility requirements. The analysis helped identify potential barriers and opportunities to enhance strategies that reduce vulnerability to future climate-driven impacts. In the face of climate crisis, farmers will often tend to choose coping measures that have immediate effectiveness and are useful to swiftly address an unexpected critical situation, while more adaptive measures often need years or decades to achieve full effectiveness. Our work showed that the adaptive capacity of specific measures are context- and timing- dependent so that, for instance, some coping measures such as seasonal rental of *dehesa* for pasture or acorns or purchase of water tanks can help address short-term impacts to allow for devising more long-term adaptive strategies. Results highlighted the important role that cooperatives played in helping farmers face climate-related impacts. Inadequate information or limited understanding of local conditions constrains the ability of farmers to design effective adaptation strategies. These must build on an understanding of local priorities, values, socioeconomic and institutional contexts and local conditions to ensure their success. Applicability of adaptation strategies across case studies requires a careful adjustment of adaptation "success stories" documented in other regions to the multifaceted local reality.

KEYWORDS

drought, dehesa, adaptation, dryland, livestock

1 Introduction

Anthropogenic climate change is causing fast and irreversible changes. The frequency and intensity of extreme weather events are increasing, leading to widespread adverse impacts on the health and functioning of vital ecosystems and livelihoods (IPCC, 2022). While curbing emissions remains a critical policy goal, there is an urgent need to develop effective adaptation strategies to complement mitigation actions and adapt to the inevitable effects of a warming climate (Ray Biswas and Rahman, 2023). The 2023 UAE Framework for Global Climate Resilience (UNFCC, 2023) emphasized the need to accelerate adaptation action to reduce vulnerability, enhance adaptive capacity and resilience, protect livelihoods and economies, and ensure preservation and regeneration of natural ecosystems.

Adaptation efforts are addressing the escalating impacts of climate change on economic sectors through the implementation of a variety of context-dependent strategies (Berrang-Ford et al., 2021). Understanding human-driven adaptation to climate change is important to support the long-term sustainability of socioecological systems in the face of climate risks and impacts (Berrang-Ford et al., 2021). While climate change adaptation research is a growing field (Biswas and Rahman, 2023; Berrang-Ford et al., 2021; Schipper, 2020), some research areas, such as the assessment and characterization of adaptation action, need further attention (Fischer, 2019). Significant work is still needed to track, report, and assess the potential effectiveness of adaptation measures and strategies (Beauchamp and Józefiak, 2023; Berrang-Ford et al., 2021; Birkmann, 2011; EC, 2021; Fischer, 2019; Miao and Malikov, 2025).

The literature provides multiple conceptual frameworks and analytical tools to characterize adaptive action (e.g.,: Birkmann, 2011; Fischer, 2019; Magnan et al., 2020; Wise et al., 2014). These approaches aim to understand societal responses in terms of the capacity of measures to reduce long-term vulnerability to climate risks (Berrang-Ford et al., 2021; Fischer, 2019). Responses to climate change result from an iterative process of risk management conditioned by environmental, social and spatiotemporal changes (Magnan et al., 2020) that leads to different types of adaptation strategies.

Climate change adaptation is primarily a local endeavor in response to impacts that are specific to particular regions, communities, and ecosystems. Therefore, assessments of adaptation action must take into consideration the specific socioeconomic and environmental contexts where it takes place (Burgess et al., 2022; Quandt et al., 2023). If specific actions or strategies increase the current or future vulnerability of an individual, community or socioecological system, they can lead to maladaptation (Ali et al., 2022). In the context of this paper, adaptation is understood as the current or future adjustment of managed socio-ecological systems to climate impacts (Ali et al., 2022), while coping refers to short-term, uncoordinated and temporary actions that can increase risk and lead to maladaptation in the medium to long term (Birkmann, 2011; Fischer, 2019).

Due to the inherent variability of natural hazards and the different sensitivities of ecosystems and societies to such hazards, adaptation action should not be understood and characterized as a dichotomy between adaptive and or maladaptive responses (Magnan et al., 2016). Rather, it should be understood as falling somewhere along the adaptation-maladaptation spectrum (Fischer and Denny, 2024; Schipper, 2020). Moreover, it is relevant to use context-specific attributes of measures to interpret and discuss their adaptation/coping orientation, as a means to identify barriers and opportunities towards more adaptive strategies.

The Mediterranean region is a hotspot for highly interconnected climate risks. Temperatures are increasing 20% faster than the global average with impacts on precipitation, heat waves, availability of water resources and increase in the frequency, intensity and duration of droughts (Ali et al., 2022; MedECC, 2020). Within the Mediterranean region dryland farming systems are particularly vulnerable to global warming, with impacts on yields, productivity and soil fertility. Climate change also affects livestock farming in drylands. Heat stress, water shortages, and reduced forage availability can impact animal health and productivity, leading to economic losses for farmers.

This study focuses on adaptation strategies of extensive livestock farmers in the traditional Iberian *dehesa* agroforestry system of Los Pedroches, a region in southcentral Spain. The Iberian *dehesas* are savannah-type agroforestry systems composed of scattered holm oaks and pasture and considered as one of the most biodiverse and multifunctional ecosystems in Europe (Moreno et al., 2018; Moreno et al., 2018). They are a representative of high natural and cultural value farming system (Moreno et al., 2018; Strohbach et al., 2015) recognized and protected by the European Union's Habitat Directive (European Commision, 2013).

The increased frequency and severity of droughts and heatwaves impact pasture and acorn productivity in the *dehesa*, increase the occurrence of pests and diseases that damage the holm oaks (Carbonero and Fernández-Rebollo, 2014; Plieninger et al., 2021), and reduce water availability, thus increasing farmer dependence on external resources and impacting farming profitability. Actions taken in the face of climate-related challenges affect the long-term viability and sustainability of the *dehesa* socioecological system (Lomba et al., 2020).

The management of *dehesa* systems is deeply rooted in traditional land use practices that have shaped and maintained these semi-natural habitats of exceptional biodiversity. However, studies of *dehesa* farming practices often fail to include the perspectives of farmers. Furthermore, adaptation studies in the agricultural sector in Europe, often focus on technical and infrastructural adaptation efforts (Berrang-Ford et al., 2021), so that knowledge on how farmers respond to climate change impacts is limited (Quandt et al., 2023). Research involving farmers is needed to understand how the management of the *dehesa* socioecological system adapts to the effects of climate change (Plieninger et al., 2021).

In this study, we aim to contribute to the field of climate change adaptation studies by proposing and applying a methodological framework to identify and characterize measures adopted by farmers to address climate impacts, as well as the influence of local context and conditions on the design of adaptation strategies. To do so, we combine and further develop the methodological approaches proposed by Fischer (2019), Fischer and Denny (2024) and Magnan et al. (2020) to characterize adaptation action. Our framework also incorporates additional

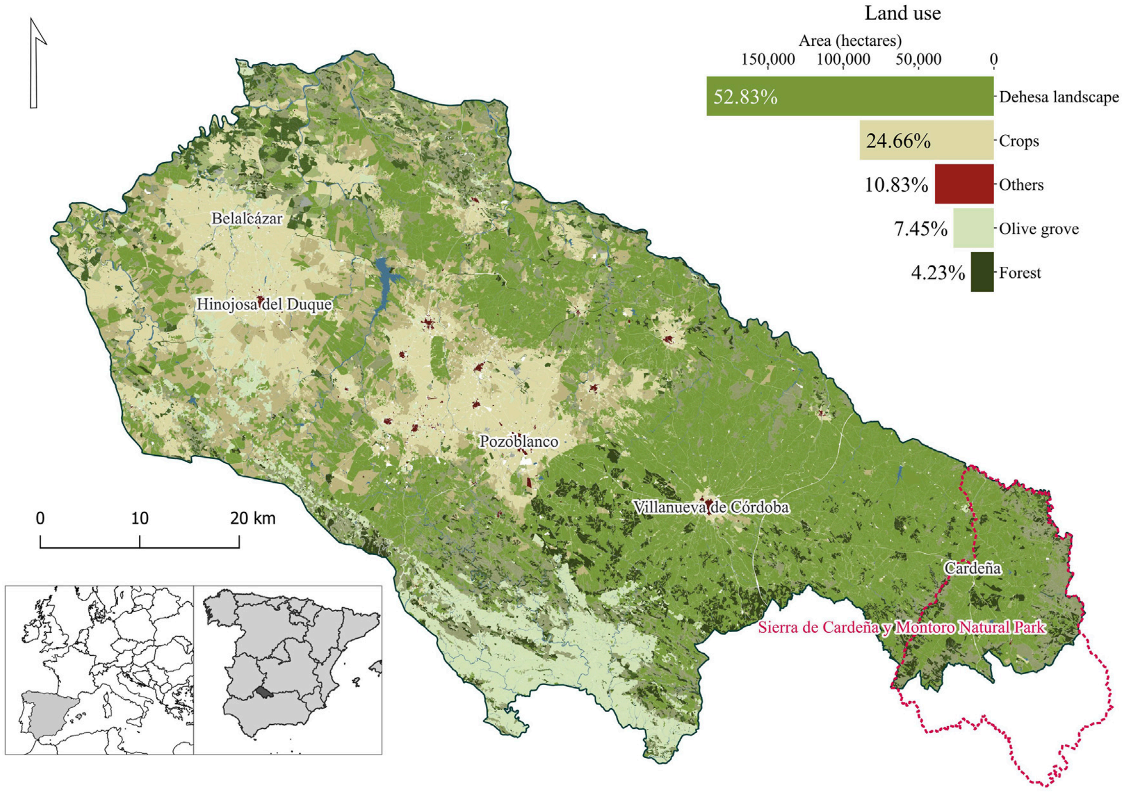

FIGURE 1
Los Pedroches region in north Córdoba, Andalucía (Spain).

attributes that emerged as relevant in the context of the case study. Thus, the objective of this work is twofold: a) to develop a methodological framework for characterizing drought and climate risk management measures and adaptation strategies that takes into consideration farmer input and local context; and b) to contribute to advance the study of climate adaptation strategies in the specific context of extensive livestock farming in the dryland *dehesa* agroforestry system by applying our methodological framework to Los Pedroches region, in Spain.

2 Materials and methods

2.1 Case study

Los Pedroches is a rural area in northern Córdoba, Southcentral Spain (Figure 1). It covers a territory of 3,612 km^2 with 51,900 inhabitants distributed in 17 municipalities. The landscape can be divided into two main areas: the *dehesa,* characterized by an undulating topography, with thin soils over a granite rock formation, where groundwater-dependent springs and temporal streams are the primary source of water for livestock and wildlife; and the Mediterranean woodlands of the sierra Morena in the south and east of the region, where the unique sierra olive groves are cultivated in a more abrupt terrain where more permanent rivers flow. The region's altitude ranges between 209 m and 957 m above sea level. The granitic area on which the *dehesa* is established consists of a heterogeneous, shallow, and fractured aquifer recharged by rainfall.

The climate in Los Pedroches is temperate with large intra- and interannual precipitation variability according to the Köpen-Geiger classification. The northwestern part of the region is gradually experiencing an expansion of the arid climate corresponding to the cold steppe (BSk) (Chazarra Bernabé et al., 2022). Rainfall varies significantly across the region due to the influence of the southern Sierra Morena Mountain range. The higher elevation areas receive an average annual rainfall of 700 mm, while the western, flatter areas, receive about 300 mm/year (Cabrera et al., 2020). Annual temperatures are rather uniform across the study area, with a sharp contrast between cold winter months (mensual average of 11°C) and very hot summer months (mensual average of 33°C).

The livestock sector, dedicated to a mix of Iberian pigs, sheep, goats, beef and dairy cattle, and agriculture, including olive groves, cereals and other crops, sustain the economy of Los Pedroches (Ballesteros and Vacas, 2020; Broekman et al., 2022). In this study, we have focused on the study of the drought management responses of extensive *dehesa* livestock farmers, responsible for approximately 50% of the agricultural output in the region.

Los Pedroches represents the largest livestock farming area in Andalusia, accounting for more than half of existing livestock farms in the province of Córdoba (Broekman et al., 2022). There are approximately 1,200 farms, 98% of which are family-owned (ADROCHES, 2021) and have an average size of 224 ha (Maroto-Molina et al., 2018). Most farms (84%) manage multiple

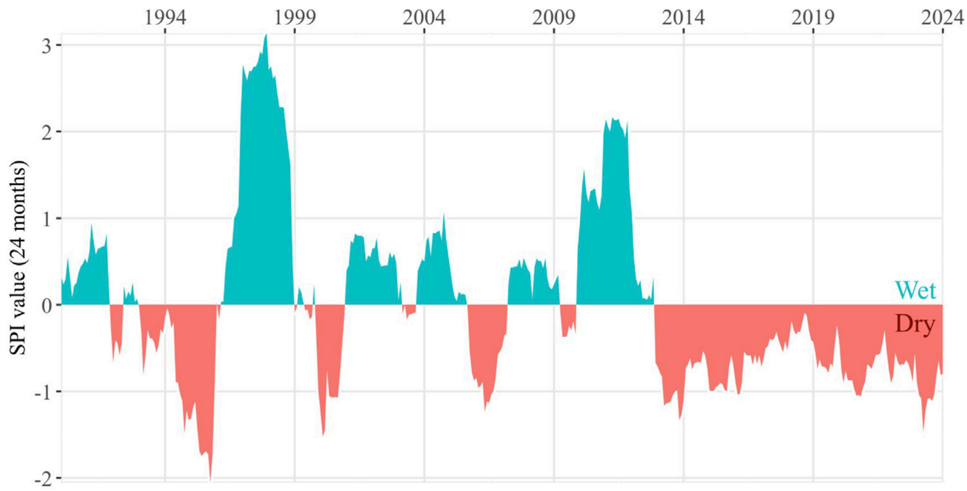

FIGURE 2
Evolution of the 24 months Standardized Precipitation Index (SPI-24) in the meteorological station of Villanueva de Córdoba (Los Pedroches) showing the dry (red) and wet (blue) tendency of the period (UCM, CREAF, 2023).

species, with cattle-porcine and cattle-sheep-porcine combinations being the most common. Iberian pigs are the most profitable livestock, favoring their presence in 40% of the farms (Maroto-Molina et al., 2018). Land dedicated to *dehesa* pasture occupies 190,662 ha (52%) of the region (Figure 1).

Extensive *dehesa* livestock farms are based on an integrated production system that combines free-ranging Iberian pigs fed with a combination of acorns and pasture. The proportion of acorns that makes up the pigs' diet has a direct relation with the final price of meat products, so that primarily acorn-fed Iberian pig products are highly valued. The period when acorns fall from the trees and are fed to the pigs, typically between October and November, is known as *montanera*. Pig rearing is combined with a mix of livestock for meat production or the sale of animals for breeding.

The profitability of this production system is highly dependent on the availability of water, acorns, and pasture, which are largely weather dependent. Traditional water sources for livestock relied on temporary streams and shallow wells. Changes in rainfall patterns have gradually increased the dependence on livestock ponds and boreholes, especially in the summer months. Between July and September the herd's diet must be supplemented with feed due to reduced availability of natural pasture (Iglesias et al., 2016). Pasture productivity is also limited by the type of soil in the region, characterized by its acidity and low organic matter content (ADROCHES, 2021).

As a primarily rainfed production system, Los Pedroches is particularly vulnerable to droughts. The sustainability of the *dehesa* agroforestry system is threatened by the increasing intensity and duration of droughts and heat waves. These can lead to an increase in oak tree mortality, reduced natural pasture availability, reduced acorn and crop production, and impact on livestock breeding periods due to heat and water stress.

Over the past decade Los Pedroches has experienced a prolonged drought that affected local water supplies and agricultural, acorn and pasture productivity. The drought was alleviated by particularly rainy springs in 2024 and 2025. The evolution of the Standard Precipitation Index (SPI) between 1990 and 2024 reflects a strong precipitation deficit starting in 2013 (Figure 2).

2.2 Methodological framework

Our methodological framework builds on the work of Fischer (2019), Fischer and Denny (2024) and Magnan et al. (2020) to characterize adaptation action. The unit of analysis in our work are the individual measures implemented by *dehesa* livestock farmers in Los Pedroches to deal with the impacts of droughts. We apply a three-step approach to (Figure 3): (a) place measures along the adaptation–coping continuum by calculating the adaptation ratio developed by Fischer and Denny (2024); (b) characterize measures based on four sets of features that we called "BEFEc attributes" after their initials (Basic features, Effectiveness, Feasibility requirements and Enabling conditions); and (c) analyze relationships between the adaptation ratio and the BEFEc attributes and among the different attributes using statistical methods.

In the first step of our study, the adaptation ratio developed by Fischer and Denny (2024) was calculated based on three characteristics that can contribute to vulnerability reduction: purposefulness (autonomous or planned action), timing (reactive or proactive), and scope (incremental or transformational) (Fischer and Denny, 2024; Ara Begum et al., 2022) (Figure 3). Based on this classification, when a response is planned, proactive and transformational, it leads to adaptation, and when it is autonomous, reactive and incremental, it is considered coping behavior that can lead to potential maladaptation. The calculation of the adaptation ratio, with values that range between 0.25 and 4.0, can help identify actions that have a higher potential to contribute to adaptation and long-term risk reduction.

In the second step of the study, the characterization of each measure according to its BEFEc attributes sheds light into the

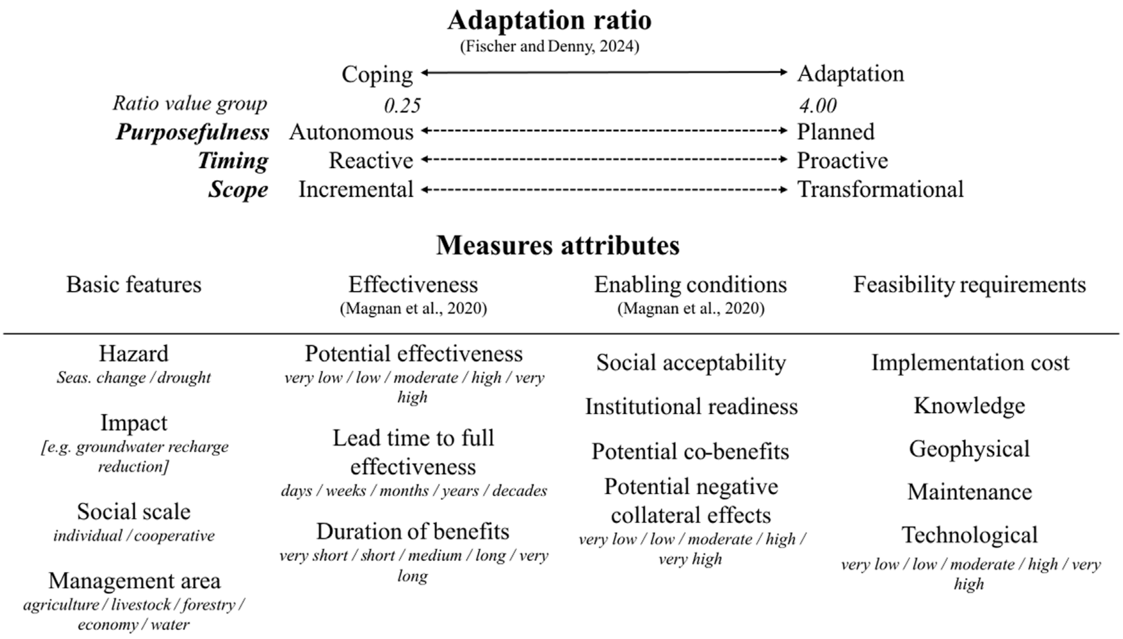

FIGURE 3
Methodological framework for the characterization of measures to address climate change impacts. Adapted from Fischer and Denny (2024); Magnan et al. (2020). *In italics the range of values used to categorize each attribute.*

reasons behind the selection (or not) of each measure and into how to address possible barriers or identify and enhance existing leverages to support adaptation in the field. The Effectiveness and Enabling conditions attributes are borrowed from the work of Magnan et al. (2020), while the Basic features and the Feasibility requirements were identified and defined by the authors in the context of this study, as they provide critical information to understand the local conditions for the implementation of each measure.

The Basic features (B) attributes refer to: (a) the climate hazard addressed (e.g., droughts or changes in the seasonality of precipitation and temperature); (b) the climate impact addressed (e.g., decreased groundwater recharge or reduced acorn production); (c) the social scale at which the measure is implemented (individual *versus* collective or cooperative response), and (d) the management area it addresses (e.g., economic viability of the farm, water availability, livestock management, feed production or oak management).

The Effectiveness (E) attributes (Magnan et al., 2020) include: the ability of a measure to reduce climate impacts (potential effectiveness); the lead time to full effectiveness, that is, the time required for an action to reach full implementation and impact; and the duration of benefits once the measure is implemented.

The Feasibility requirements (F) provide key information about barriers to implementation. They include implementation costs; knowledge or technical expertise needed for implementation; technical, operational and/or financial maintenance needs for the action to remain effective over time; geophysical requirements that are location-dependent; and the necessary advances in technological or infrastructural development for measure implementation.

The Enabling conditions (Ec) (Magnan et al., 2020) include the social acceptability of a measure, understood as the ability of a social group to support its implementation; its institutional readiness, that is, the feasibility of its implementation in a specific institutional context; the potential co-benefits in addition to direct reduction of climate impacts; and the potential negative side effects, which are the observed or potential adverse consequences of the measure on the socioecological system.

The proposed methodological framework was implemented using a mixed methods approach (Creswell and Creswell, 2022; Johnson and Onwuegbuzie, 2004) that is described in the next two subsections. Qualitative data was gathered through interviews, focus groups, and workshops. All participants received and completed an informed consent form before participating in any research project activity. We sequentially used both qualitative (deductive content analysis) and quantitative (descriptive statistics, correlation analysis and multiple correspondence analysis) tools to characterize adaptation measures and explore patterns in the attributes of measures in relation to their capacity to contribute to adaptation.

2.3 Data collection

Data collection was conducted between February 2022 and November 2024 and followed a multi-phase and multilevel approach (Table 1; Figure 4). A first scoping phase involved actors from different sectors active in the case study region, including livestock farmers, both extensive *dehesa* and milk producers, olive growers, farming cooperatives, hunters, research institutions and natural area and water managers. In a second phase (zooming in) we focused on the *dehesa* extensive livestock farming sector and, in a final phase (zooming out), we again included different actors from the whole region to enrich the sector-specific perspective. We used three qualitative data gathering

TABLE 1 Data collection methods, number and type of participants.

Type of participant	Data collection method				
	Scoping interviews (February 2022)	1st workshop (October 2022)	In-depth interviews	Focus groups (november 2023)	2nd workshop (March 2024)
Livestock sector	2	4	17	6	2
Olive growers	1	2	-	-	1
Rural development	1	1	-	-	1
Local research institute	-	2	-	-	2
Water Authorities	-	2	-	-	-
Others	3	12	-	-	7
Total	**7**	**23**	**17**	**6**	**12**

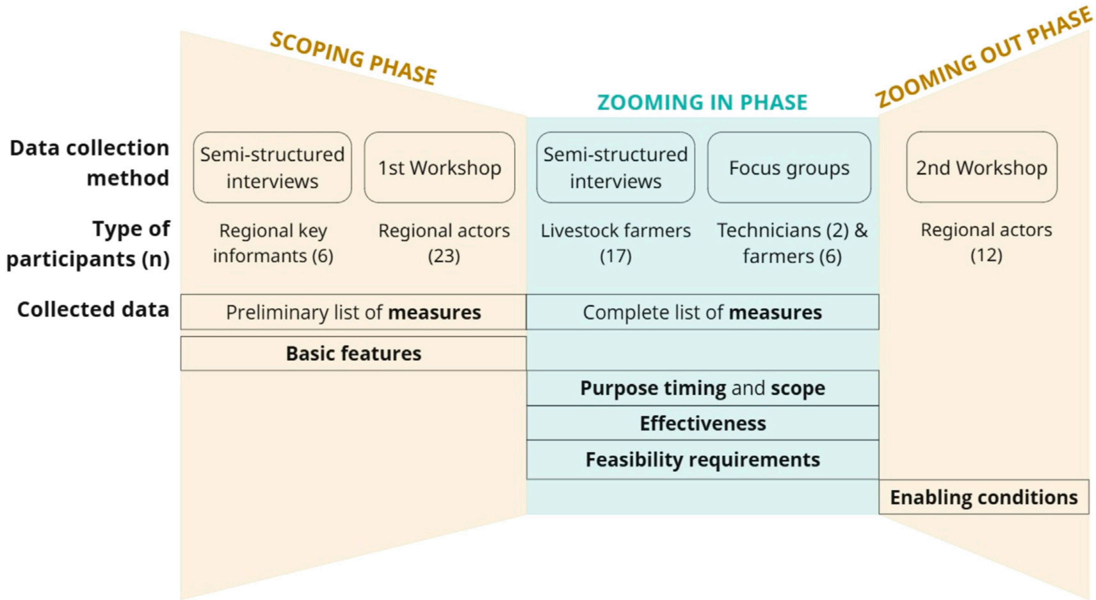

FIGURE 4
Diagram of the workflow process involving the data-gathering methods, type and number of participants and type of data collected.

methods: semi-structured interviews, workshops, and focus groups. In total, 49 distinct stakeholders participated in the data collection process at some point during the research (Table 1).

In the scoping phase, key actors belonging to different public and private organizations active in the study area were interviewed through semi-structured interviews to identify the main climate-related risks experienced in the region, the measures implemented to address them, and the climate information used to inform those decisions. Interviewees were selected based on the researchers' prior knowledge of the region and belonged to different sectors: water and natural area management, livestock and olive farmers and cooperatives, and a local rural development organization. The first round of interviews yielded a preliminary list of measures implemented to respond to drought and climate change risk and provided information for the characterization of their Basic features. Moreover, using a snowball sampling technique (Parker et al., 2019), the scoping interviews served to identify other relevant actors to involve in subsequent phases of the work. The preliminary list of measures and their Basic features were discussed in a workshop with 23 participants from this broader set of regional actors (Table 1). The workshop served to validate the list of measures and their Basic features, identify additional measures, and explore the Feasibility requirements for their implementation from a regional perspective.

In the 'zooming in' phase, we focused on the *dehesa* livestock farming sector. The characterization of the Basic features in the scoping phase revealed two levels of decision-making in the livestock sector: individual, that is, measures taken by each livestock farmer, and coordinated, that is, measures taken by a local livestock farming cooperative. In this second phase, we targeted both levels of decision making. We conducted seventeen semi-structured interviews with extensive individual *dehesa* livestock farmers to complement the list of measures and further characterize them in terms of their Effectiveness and Enabling conditions. The farmers interviewed were selected using snowball sampling techniques and based on their geographical location to include farmers from throughout the region, and on their availability and willingness to participate in the study. In addition, we conducted two focus groups, one with *dehesa* agricultural extension agents of the cooperative and one with *dehesa* farmers belonging to the cooperative. The focus groups served to validate and complement the information gathered in the interviews using decision-making timelines for a regular year and for the full duration of the 2013–2024 drought period (De Stefano et al., 2023). Decision timelines provide a structured framework to understand the sequence and timing of decisions and allow for the temporal mapping of the decision making process (Luyts et al., 2023).

In the final 'zooming out' phase, a workshop with the main actors in the region served to validate the complete list of measures and discuss the Enabling conditions for their implementation from a multisectoral regional perspective. Using a world cafe approach (Brown et al., 2005), participants were asked to rotate through three thematic tables corresponding to the three main typologies of measures identified – ecosystem sustainability, economic viability of the farm and water management –, contributing their perspectives on the effectiveness and potential externalities (both positive and negative) of each measure on other sectors and on the environment.

2.4 Data processing and analysis

Qualitative data was transcribed and manually coded into a database through successive iterations using a deductive content analysis (Elo and Kyngäs, 2008) based on the methodological framework. The results of the coding informed the assignment of values to the attributes of each measure (see Figure 3 for the range of values). Coding and initial valuation was conducted by the lead author of the study and validated through complementary individual assessments of each characteristic and attribute by each of the coauthors. Potential differences in the assessment of the attributes or their values were discussed, validated with the coded data and resolved.

The assessment of the adaptation ratio characteristics—purposefulness, timing and scope—allowed placing each measure along the adaptation-coping spectrum. The resulting ratio offers discrete values ranging from 0.25 for fully coping responses and 4.00 for fully adaptive responses (Supplementary Figure S1). Possible values for the BEFEc attributes ranged from 'days' to 'decades' in the case of temporal attributes, except for duration of benefits. This attribute was classified as 'very short' (days-weeks), short' (months-years), 'medium' (years to one to 3 decades), 'long' (from three to 5 decades), 'very long' (5 decades to a century). For the remaining attributes the values ranged from 'very low' to 'very high' (Figure 3).

For the quantitative analysis of the coded data, a database was generated with the ratio values and the attribute values for each of the 31 measures identified (Supplementary Table S1; Figure 1). The goal of the statistical analysis was to explore patterns in the attributes of the measures in relation to their capacity to contribute to adaptation.

Descriptive statistics were calculated to show the frequency of each attribute in each adaptation ratio group. We then used R software (R Core Team, 2023) with Factoshiny package (Vaissie et al., 2024) to analyze the correlation between each adaptation ratio group and each attribute, and between pairs of attributes, to find statistically significant patterns between our variables (adaptation ratio and BEFEc attributes). This offered additional insights into the narrative provided by the qualitative data. Considering the sample size of the measures (n = 31), we performed a chi-square test of independence and a Fisher's exact test for the *post hoc* analysis (Lydersen et al., 2009). When relationships were found to be statistically significant, we conducted an analysis of Pearsons' residuals to determine whether those relationships were positive or negative. This analysis was also used to confirm that the statistical tests performed are appropriate for the characteristics of the sample, and their results were validated.

To corroborate the one-to-one correlation analysis, we also performed a Multiple Correspondence Analysis (MCA) between the 31 measures and the 68 categories that result from the combination of each attribute with their possible values. This means, for instance, that for the Effectiveness attribute, we considered five categories (Eff_very low; Eff_low; Eff_medium; Eff_high; Eff_very high). MCA can identify multiple simultaneous relationships among variables and therefore describe more complex patterns than those found with one-to-one correlation analysis.

3 Results

3.1 Identification and characterization of implemented measures

Data collection led to the identification of 31 measures implemented during the 2013–2024 drought period to address climate impacts in Los Pedroches (Table 2; full description in Supplementary Table S1). Measures were categorized into five areas of intervention ('management area' in the Basic features attribute): water management, feed supply, livestock management, economic viability of the farm, and oak forest management. Although some measures—e.g., holm oak reforestation and pruning or rotational grazing–are part of normal farming practices, their timing or intensity changed during drought.

In the early stages of the drought, water-related impacts were perceived as manageable. However, from 2017 onwards, water availability was compromised, jeopardizing livestock farming activities. This led to the implementation of different measures seeking additional sources of water in the farm (e.g., drilling of new wells and boreholes, rainwater harvesting, construction of water tanks), reducing water demand through water reuse and improved water efficiency, or bringing water from outside the farm by truck. The cooperative also fostered the reduction of water use through different measures such as the design of more efficient livestock watering systems or facilitating access to off-farm water resources

TABLE 2 Measures identified in the study area, grouped by management area and with their values of the adaptation ratio (0.25 = coping, 4 = adaptation) Column 'Purpose': Autonomous (A); Planned (P). Column 'Timing': Reactive (R); Proactive (P). Column 'Scope': Incremental (I); Transformative (T).

Management area	Measure	Purpose	Timing	Scope	Adaptation ratio value
Water management	Borehole drilling	A	R	I	0.25
	Digging wells	A	R	I	0.25
	Use of public wells and/or boreholes for livestock	A	R	I	0.25
	Water supply by water trucks	A	R	I	0.25
	Construction of water deposits	P	R	T	0.67
	Cooperative water storage tanks	P	R	T	0.67
	Coordinated use of public reservoirs for livestock	P	R	T	0.67
	Diversification of water sources on the farm	P	P	I	1.50
	Rainwater harvesting and storage	P	P	I	1.50
	Design of efficient livestock water troughs	P	P	I	1.50
	Water reuse	P	P	I	1.50
	Small-sized dam construction	P	P	T	4.00
Feed production	Adaptation of the crop operations calendar	A	R	I	0.25
	Use by-products for feed	A	R	I	0.25
	On-farm forage production	A	R	I	0.67
	Sustainable shrub management	P	P	I	1.50
	Rotational grazing	P	P	I	1.50
	Construction of multifunctional warehouses	P	P	T	4.00
	Diversify feed crops in dehesa	P	P	T	4.00
	Improve soil quality and structure	P	P	T	4.00
Livestock management	Livestock slaughter or early sale	A	R	I	0.25
	Redistribution of livestock combination	P	P	I	1.50
	Strategic adaptation of the stocking rate	P	P	T	4.00
	Community feedlots	P	P	T	4.00
	Reduction of the stocking rate in *montanera*	P	P	T	4.00
	Reduction of the livestock load	P	P	T	4.00
Forest management	Holm oak reforestation	P	P	I	1.50
	Holm oak pruning	P	P	I	1.50
Farm Economy	Rental of farms for *montanera*	P	R	I	0.67
	Collective purchase of supplies	P	R	I	0.67
	Request for financial aid for the improvement of water infrastructures	P	P	I	1.50

e.g., by obtaining a collective permit to access water from a nearby reservoir or building collective water deposits and access points.

To ensure the availability of sufficient fodder, the cooperative encouraged farmers to diversify planted feed crops or to adjust livestock ratios and stocking rates. Farmers also adapted the cropping calendar to climatic conditions and optimized rotational grazing patterns. In the most acute phase of the drought (2023), the scarcity of spring rainfall further extended the supplementary feeding period, raising operational costs. Due to worsening conditions, the cooperative implemented additional measures, such as constructing a community feedlot.

Increased management costs related to the adverse impacts of the drought caused significant pressure on the financial viability of farms. Several measures were implemented to reduce costs and seek financial aid to cover part of the expenses involved in ensuring water availability. For instance, farmers rented oak tree plots to ensure the

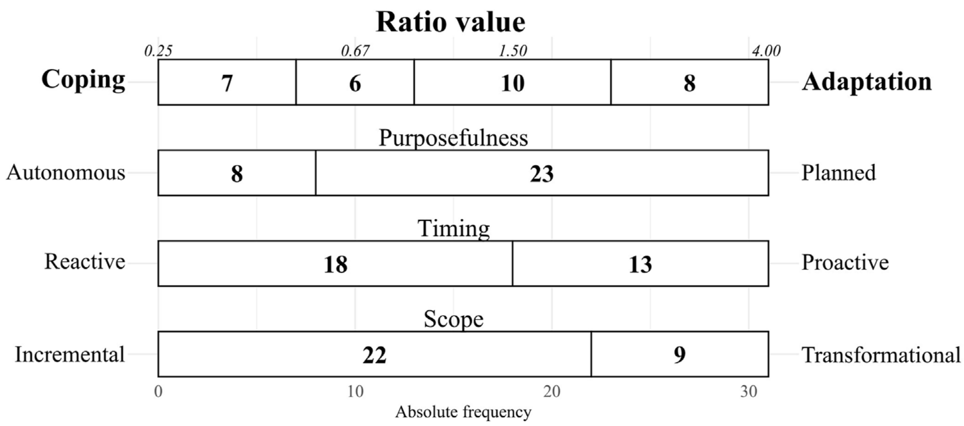

FIGURE 5
Absolute frequency distribution of adaptation ratio values and purposefulness, timing and scope values distribution.

availability of sufficient acorns for the pigs during the *montanera*, the cooperative negotiated the collective purchase of feed supplies and other inputs and promoted the use of by-products for livestock feeding. Despite these efforts, increased operational costs due to the simultaneous scarcity of feed and water led some farmers to sacrifice or sell part of their livestock.

Preserving the holm oak tree population is a critical part of regular *dehesa* farming practices. However, climate change processes are increasing the appearance of pests and the life cycle of the holm oak, so that reforestation of the species has become a challenge. Thus, forest management measures focus on improving pruning practices and reforestation rates. Due to their slow growth, it is crucial to have a long-term plan for tree replacement, which is constrained by drought periods.

The calculation of the adaptation ratio value showed that seven of the 31 measures were classified as coping and eight as adaptive (Figure 5). Sixteen fell somewhere between coping and adaptation, with intermediate values of 0.67 (6) and 1.5 (10). Most measures were planned (23), reactive (18) and incremental (22). The results for each individual characteristics of the adaptation ratio (purposefulness, timing, scope) can be found in Table 2 above.

Half of the fully adaptive measures were implemented in the areas of livestock management (four out of eight) and feed production (3). These measures were related to land transformation, such as diversifying the mix of feed crops in the *dehesa*, improving soil quality and structure, or changing livestock management practices like reducing livestock density or creating community feedlots. Coping measures were often focused on water management (four out of seven fully coping measures), such as borehole drilling and water supply by trucks. Measures with intermediate ratio values are present across all the management areas. Some of those measures were planned and reactive – for example, the rental of farms for *montanera*, collective purchase of supplies, or the construction of water reservoirs and water storage facilities. Others, though planned or proactive, were not transformational, such as diversifying on-farm water sources, redistributing livestock combinations and reforesting of holm oak trees.

Figure 6 shows the absolute frequency of the values of the BEFEc attributes (X-axis) in each adaptation ratio value (Y-axis). Implemented measures often addressed multiple climate-related impacts simultaneously. The main impacts driving the implementation (D in Figure 6) were the reduction in surface water availability, the reduction in acorn and pasture productivity, and the reduction in rainfed crop productivity. Reduced groundwater recharge, increased oak mortality, and changes in soil moisture also triggered several actions. These impacts were linked to the occurrence of drought and seasonal climate changes. Most of the implemented measures focused on drought (19), while about one-third of the measures (9) addressed seasonal changes in precipitation and temperature patterns, and six addressed both types of hazards (A in Figure 6).

In terms of the social scale of measures (B in Figure 6), 21 were implemented at an individual scale and 10 were coordinated by the cooperative at the regional level. All measures classified as coping were implemented at the individual scale, while those implemented by the cooperative are distributed across the other three adaptation ratio groups. Adaptive actions mainly target livestock management and feed production, while water management measures are rarely adaptive.

In terms of lead time to full effectiveness (F in Figure 6), most of the implemented measures (21) required months or longer to fully deliver their expected results. Measures with a lead time of days were mostly coping, while those with a lead time of months or more were placed on the adaptive side of the spectrum. Once measures are in place, their benefits are expected to last several years or longer, particularly in the case of adaptive or adaptation-oriented measures, while coping and coping-oriented measures have shorter-lasting benefits (G in Figure 6).

Most measures were perceived as being suitable to achieve their intended goals, as indicated by the fact that 21 out of 31 have high or very high potential effectiveness (E in Figure 6). At the same time, they do not appear to produce significant externalities, as evidenced by the fact that 16 were classified as having low or very low co-benefits and 24 as having low or very low dis-benefits (I and J in Figure 6). However, measures on the adaptive side of the spectrum were perceived to have higher frequency of having high or very high co-benefits and low or very low dis-benefits. In contrast, on the coping side, measures were considered to have only low or very low co-benefits, and their disbenefits range from very low to very high.

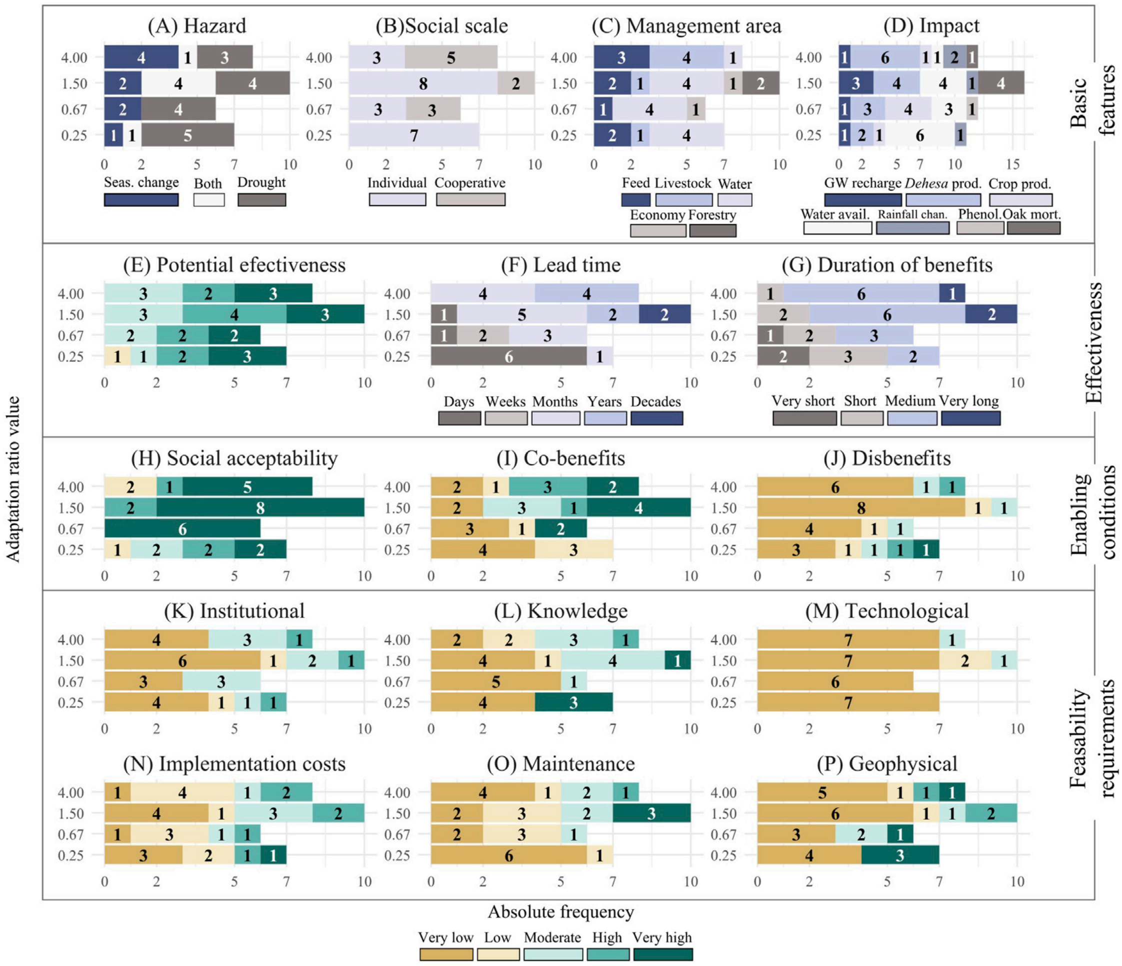

FIGURE 6
Absolute frequency of the values of the attributes by adaptation ratio group from coping (0.25) to adaptation (4.00).

Most of the measures have very high social acceptability (H in Figure 6), regardless of which side they fall along the coping-adaptation spectrum. Technological requirements are generally very low except for some adaptive measures (M in Figure 6). Institutional, geophysical requirements and implementation costs are generally very low, although they can take higher values in the case of adaptive measures (K, P and N in Figure 6).

3.2 Adaptation ratio value groups and attribute correlation

We carried out a correlation analysis (chi-square test, Fisher's exact test and analysis of Pearsons' residuals) to identify the main attributes that statistically determine the differences between the four adaptive ratio value groups. This analysis revealed that the lead time to full effectiveness is the most relevant attribute for assigning measures to each adaptation ratio group (Table 3). Other attributes that showed a significant correlation were the social scale at which measures are implemented (individual or cooperative), the co-benefits to the measure's main goal, its social acceptability, and the knowledge requirements for implementation.

When looking at the relationships between the adaptation ratio groups and the value of BEFEc attributes, we found that coping-oriented measures were primarily defined by short lead times to full effectiveness (days). They are also strongly correlated with very low maintenance requirements, as well as very high knowledge and geophysical requirements. These measures were typically implemented at the farm level (individual scale), as evidenced by their strong negative correlation with the cooperative social scale. They are characterized by very low or low co-benefit values and show a negative correlation with high social acceptability. It is important to note that this does not imply that they are rejected socially but, rather, that measures in other adaptation ratio groups are generally better received than coping measures.

Measures with high adaptation ratio values are primarily related to livestock management. They are defined by a lead time to effectiveness of years, high co-benefits and implementation by the cooperative. This is confirmed by the negative correlation of these measures with individual farm-level action, short time to achieve full effectiveness and the water management area (Table 3).

Measures grouped in the intermediate adaptation ratio group closer to coping (ratio values = 0.67), are correlated to lead times of

TABLE 3 Results of the chi-square analysis and Pearson's residuals determine the value of the correlation between the ratio value groups and the attributes that describe it. Statistical significance was indicated by the p-value (t = p < 0.1, * = p < 0.05, ** = p < 0.01, *** = p < 0.001) and the type of relationship by the v value of the Pearson residuals.

Ratio index value group	Variable	Category	P-value		v.Value
Coping (0.25)	Lead time	Days	0.0003	***	3.66
	Maintenance	Very low	0.02	*	2.29
	Knowledge	Very high	0.03	*	2.18
	Social scale	Individual	0.03	*	2.18
	Social acceptability	Moderate	0.05	*	2.00
	Geophysical	Very high	0.07	t	1.83
	Cobenefits	Low	0.07	t	1.83
	Knowledge	Moderate	0.09	t	−1.68
	Cobenefits	Very high	0.09	t	−1.68
	Social scale	Cooperative	0.03	*	−2.18
	Social acceptability	Very high	0.02	*	−2.26
Coping-oriented (0.67)	Lead time	Weeks	0.03	*	2.14
	Social acceptability	Very high	0.07	t	1.79
	Knowledge	Very low	0.08	t	1.76
	Geophysical	Moderate	0.09	t	1.68
Adaptation-oriented (1.50)	Maintenance	Very high	0.03	*	2.22
	Cobenefits	Moderate	0.03	*	2.22
	Management area	Forest	0.09	t	1.66
	Lead time	Decades	0.10	t	1,66
	Technological	Very low	0.09	t	−1.67
	Implementation cost	Low	0.08	t	−1.74
	Maintenance	Very low	0.07	t	−1.68
Adaptation (4.00)	Management area	Livestock	0.03	*	2.20
	Lead time	Years	0.03	*	2.20
	Cobenefits	High	0.05	*	2.00
	Social scale	Cooperative	0.09	t	1.69
	Social scale	Individual	0.09	t	−1.69
	Management area	Water	0.06	t	−1.86
	Lead time	Days	0.06	t	−1.87

weeks, very high social acceptability, very low knowledge needs, and moderate geophysical requirements. On the other hand, measures grouped in the higher intermediate adaptation ratio group (ratio values = 1.50) are correlated to very high maintenance requirements and lead times of decades, address forest management area, and have moderate co-benefits. They are also negatively correlated to low or very low implementation costs and technological and maintenance requirements.

The Multiple Correspondence Analysis (MCA) confirmed these statistical relationships. The results of the MCA are summarized in Figure 3 of Supplementary Material S1 and are not presented here for space limitations.

4 Discussion

4.1 Contributions of the methodological framework

The *dehesa* socioecological system is vulnerable to the impacts of climate change, including heat waves, prolonged droughts and decreases in water availability and groundwater levels (Field and Barros, 2014). In this paper we studied the response of *dehesa* extensive livestock farmers in Los Pedroches region in Spain to a prolonged drought (2013-2024) through a mixed-methods approach that builds on the work of Fischer, 2019; Fischer and

10.3389/fenvs.2025.1540818

Denny, 2024; Magnan et al., 2020. The methodological framework applied in this paper contributes to the existing field of adaptation studies in several ways.

First, it allows for the characterization of climate risk management measures taking into consideration farmer input and local context. Placing the measures along the coping-adaptation spectrum and characterizing their context-specific attributes help systematize qualitative information about measures implemented in a specific region. This, in turn, contributes to identifying existing barriers and ways to address them, and identify and support strategies that can improve preparedness in the face of future climate-driven impacts. At times, coping actions, such as building new wells, may facilitate adaptation by reducing climate impacts in the short term and thus giving space and time for more adaptive long-term action (Schipper, 2020). However, it is essential to ensure that they do not lead to postponing or dismissing long-term risk reduction strategies, or to affecting the viability and effectiveness of present and future adaptation measures. Methodological approaches such as the one applied in this study, that identify contextual conditions under which adaptation and coping occur, can contribute to reducing the potential for long-term maladaptation.

Second, the quantitative statistical analysis used in this framework facilitates the identification of patterns in adaptation action, helping structure the narrative that can be derived from the qualitative data. It also contributes to corroborating relationships that may otherwise be attributed to chance. For instance, the correlation analysis evidenced the statistically negative relationship between high adaptation ratio values and the water management area, and that fully coping (mostly water-related) responses were implemented at a farm level. These results suggest the pressing need to strengthen water management for livestock farming in Los Pedroches, seeking the implementation of adaptive measures with longer-term effects on water demand and supply and a greater involvement of the local guild cooperative.

Third, our methodological framework helps shed light into the spatio-temporal complexity of adaptation. We observed that a given measure is not adaptive or coping *per se*, but rather its adaptation ratio value is dependent on how, when and where it is implemented. For instance, the growth of on-farm herbaceous plants (hay and others) to ensure availability of forage for livestock in the summer months emerged as a coping-oriented response (0.67), given that in Los Pedroches it was mostly implemented by farmers in an autonomous and reactive way. In a different context or at a different moment, and driven by a collective, long-term vision triggered by a recognized need to address increasingly longer and more severe droughts, such a measure could be placed closer to adaptation on the spectrum. Thus, sharing the results of this study with local actors could inspire reflections on what the livestock sector can learn from the 2013–2024 drought episode and what strategies to implement to progress toward adaptation.

4.2 Placing drought management measures along a coping-adaptation continuum

During the 2013–24 drought, extensive *dehesa* livestock farmers in Los Pedroches focused primarily on ensuring food and water availability for livestock while striving to maintain the economic viability of the farming activity. Our study found that half of the measures (16/31) implemented had intermediate adaptation values, confirming that responses to climate related impacts rarely fit into a dichotomy between adaptive and non-adaptive actions (Fischer, 2019; Fischer and Denny, 2024; Magnan et al., 2020). This could be explained by the compound nature of risk management processes, where agents need to combine different responses depending on complex and changing circumstances (Schlüter et al., 2017). This meant for instance that some measures, such as the collective purchase of feed supplies, although planned, were reactive or non-transformative, obtaining intermediate scores in the ratio index. In a dichotomous analytical approach, those measures would have been classified as non-adaptive, thus failing to capture the planning efforts of local actors.

By focusing on the characteristics that place each measure in one of the four adaptation value ratio groups – purposefulness, timing and scope –, it is possible to identify what aspects of adaptation are already present and need to be maintained or enhanced, and which require to be boosted by targeted actions and public policies. For instance, during the 2013–2024 drought, the cooperative requested a temporary permit from the river basin authority to exceptionally use one of the public reservoirs for watering livestock. The measure was reactive, responding to the critical water scarcity in the last period of the drought. While water in the reservoir was not originally intended for livestock use, the experience of the drought could lead to proactively including this water supply option in the drought management plan developed by the river basin authority for the region, thus reducing future vulnerability to droughts and enhancing water resource management.

The prevalence of planned measures (as opposed to autonomous) in the region (23/31) reflects the relevance of farming cooperatives influencing farmer decision-making processes and on-farm interventions by coordinating individual efforts. This clearly emerges in the areas of agricultural and livestock management, where the technical personnel of the cooperative play an important advisory role. Beyond the support of individuals in coping with emergencies triggered by extreme drought, the cooperative led numerous adaptive measures in Los Pedroches. For instance, in 2015 the local cooperative promoted proactive measures through the development of a long-term strategic plan for *dehesa* livestock farmers that proposed the reduction of the livestock load to adapt it to changing conditions. It also promoted the diversification of feed crops cultivated in the *dehesa*. These actions seek to ensure the long-term viability of the socioecological *dehesa* system and the associated economic activities, and the technical know-how and resources required for their design and implementation require the leadership of a collective body such as a guild cooperative. These results are in line with those of other authors that highlight how cooperatives can play a critical role in supporting their members' adaptation action (see for instance Bijman and Höhler, 2023) by providing technical or financial support and influencing farmer decision-making on climate adaptation (Suazo Muñoz and Sandoval-Díaz, 2023). Other authors emphasize how community based resource management enhances adaptive capacity by strengthening social networks (Tompkins and Adger, 2004). Facilitating collaboration among individuals strengthens the effectiveness of climate governance (IPCC, 2022) and has the potential to enable planned and transformative adaptation (Gillard et al., 2016) by connecting real-context needs with policy or/and research development (Njuguna et al., 2024) and involving stakeholders in the process of policy and research development (Parra-López et al., 2023). This emphasizes the value of considering multiple perspectives in the development and implementation of adaptation strategies as we can see in other case studies (e.g., Aldunce et al., 2016; Barton et al., 2015).

Our analysis revealed a slight predominance of reactive over proactive measures (18 vs. 13), especially in the water management area, possibly because of the unprecedented duration of the drought episode. As water management is not a traditional sphere of action for the local livestock cooperative, farmers adopted most water-related measures autonomously. However, when the drought reached a critical phase in 2023, the cooperative intervened to support farmers by promoting collective measures such as building shared water storage tanks or coordinating the use of reservoirs for watering livestock. In relation to food availability, the intensification of the drought over time eventually triggered reactive and incremental measures by the cooperative, such as the collective purchase of feed. This suggests that coordinated responses are no guarantee of adaptation-oriented actions but can provide agile means to respond to extreme events by reducing individual transaction costs. This, in turn, is key to minimize short-term impacts and ensure the ongoing viability of activities affected by adverse climate events (Tompkins and Adger, 2004; Zamani et al., 2006). Changes in individual behaviors and in public policies often occur in response to shocks or disruptions (Bennett and Howlett, 1992; Howlett and Cashore, 2009). Extremes events can act as a catalyst of transformative change if there is an explicit and detailed ex-post assessment of what occurred, its causes and possible paths toward better preparedness. In this context, the proposed characterization and analysis of the adopted measures can be used as such ex-post assessment and therefore contribute to trigger debate about how to learn from past experience and build local capacity to adapt to increasing climate variability.

The limited number of transformative measures found in our case study (only nine out of 31) could be related to the fact that transformation at times implies local communities to partially or completely give up their livelihood strategy, and thus also their culture and way of life (Zant et al., 2024). In Los Pedroches region, the conservation of the *dehesa* ecosystem is a primary objective of livestock farmers and other local actors, thus constraining the space of possible adaptation options. For example, reforestation could be carried out with other species, such as carob or cork oak, with potentially higher long-term survival rates under the new climatic conditions (LIFE BioDehesa, 2018). However, this measure has not been considered given the key role of holm oaks to ensure high quality Iberian meat products (Delgado-Serrano et al., 2024). This highlights the influence of cultural and traditional values on behaviors and adaptation decisions (Fischer and Denny, 2024) and the importance of carefully considering the implications of transformative actions on land use practices (Engbersen et al., 2024; Zant et al., 2024). Transformational measures should therefore not always be the goal of adaptation strategies. Rather, adaptive strategies must consider local values, goals and preferences to maximize acceptability and potential success. An understanding of the interplays between cultural and natural values is necessary to inform adaptation action.

4.3 Characterizing the BEFEc attributes of drought management measures

Adaptive measures often need years or even decades to be fully effective (Schipper, 2020). This was found also in our study, with measures such as the reduction of stocking rate or actions to improve soil quality and structure. Moreover, adaptation measures often have higher maintenance and knowledge requirements. Sometimes adaptive measures cannot be implemented in contexts with limited resources and capacity, despite the potential co-benefits they may have for other sectors and for the ecosystem (Hidalgo-Galvez et al., 2022). In our case study, coping measures, such as the purchase of water in tanker trucks or the purchase of additional feed, are characterized by their immediate effectiveness (within days or weeks) and are useful to swiftly address an unexpected critical situation. The purchase of supplementary feed always involves an extra cost for the farmers in the summer months, even in years with normal precipitation. A severe drought can result in additional costs to purchase feed in spring and autumn (Iglesias et al., 2016), leading to increased operational costs and farm vulnerability to other external climatic and non-climatic factors (Moreno et al., 2018).

In Los Pedroches region, the viability of the livestock production system depends on the health of the *dehesa* ecosystem. This requires actions perceived as a priority for climate change adaptation, such as the reforestation of holm oaks or the improvement of soil quality and structure (Escribano et al., 2024). These measures take several decades to achieve their full effectiveness and intensive maintenance in the early stages (Carbonero and Fernández-Rebollo, 2014). Coping measures have shorter lead time to full effectiveness, such as adapting stocking rates, depending on acorn, pasture and water availability. These three factors are climate dependent and vulnerable to changing conditions and longer and more intense droughts (Field and Barros, 2014). In this context, farmers must make strategic decisions and investments to adapt to a changing climate based on information that is not only uncertain but also rarely tailored to their specific needs. The provision of improved climatic and hydrological information downscaled and adjusted to the local context and capacity is therefore key to assess ex-ante the viability of potential adaptation measures and, ultimately, to improve decision making (Boon et al., 2021).

Although global and national climate-related datasets are improving data availability, the information they provide often lacks sufficient spatial or temporal resolution and, to be useful, must be transformed into user-tailored information. Scientists and researchers can play an important role in reducing this gap by developing services that meet the needs of end users by using co-creation approaches (Brandsen et al., 2018; Manez Costa et al., 2022). This also points to the importance of outreach activities to transfer scientific advancements to local contexts. For instance, in Los Pedroches, farmers and cooperative staff highlighted the value of having improved seasonal and sub-seasonal rainfall forecasts at specific times of the year to support the planning of annual livestock feeding, which is particularly critical in the case of drought. Incorporating forecasts in decision-making, however, requires building capacity of farmers on the use of such information, for instance, including concepts such as probabilistic forecasts and uncertainty assessments.

In our case study, social acceptability is not a determining attribute of fully adaptive measures. While measures in the intermediate adaptation value groups (0.67 and 1.50; see Figure 1 in Supplementary Material) such as rotational grazing, on-farm forage production or design of efficient livestock water troughs, have high social acceptability, some fully adaptive measures do not. For example, on-farm forage production, understood as an aggregate measure for the whole region, is associated with a negative impact on water quality, which is a major concern in the area (ADROCHES, 2021). Another measure with a high adaptation ratio index, the damming of small streams to favor water infiltration, is also perceived negatively because of its potential impact on downstream farms. In contrast, some fully coping measures such as the construction of new wells or boreholes, are perceived positively. A close analysis of the groundwater use measures shows that they have high knowledge requirement values, which is not the case for other coping measures. Los Pedroches aquifer system is poorly understood. The aquifer was only officially acknowledged as such by the water authorities and incorporated into river basin management plans in 2011 (CHG, 2011) and 2015 (CHG, 2015). Currently there are only two official groundwater monitoring points for an aquifer of 2,600 km^2 and a third one is under construction. Farmers often describe the aquifer as 'pockets of underground water' with scarce spatial interconnections. The positive social perception of new wells and boreholes may be due to the limited understanding of the potential impacts of increased groundwater pumping. Moreover, the unmet knowledge requirements of this measure affect its effectiveness, as new boreholes are often not productive or have dried up after a short time because they were drilled in suboptimal locations.

4.4 Study limitations and future research

This study has several limitations that should be considered. First, the number of livestock farmers involved in the study is limited and they worked with the cooperative. The information collected describes overall trends and common practices rather than nuances in individual practices and decision-making processes. We worked with a specific cooperative, but other exist in the region. The workshops, focus groups and interviews with actors that are not directly devoted to livestock farming, however, enriched and complemented the perspectives collected directly from farmers. Future work could look at the experience of farmers that work with different cooperatives or that operate individually, to identify potential differences and contrast adaptation strategies. A broader survey targeting a larger number of individual farmers, focusing on specific aspects of the assessments such as the perception of risk or the requirements for implementing measures likely to enhance adaptation could help identify additional barriers and leverage points and inform policies and decision-making processes.

Second, our methodological approach requires intensive interaction with and active engagement of local actors, which may not always be feasible due to resource constraints or limited access to willing participants. In this study, fieldwork was conducted during a severe drought, which provided a particularly favorable context for capturing real-time responses, as local actors were actively engaged in addressing the situation. Applying this approach to past events would require some adjustments to account for the effect of memory on how past actions are recalled and described.

Third, coding the data, applying the adaptive ratio index and valuing the BEFEc attributes is necessarily subject to interpretation by the coder. To ensure consistency of the results we conducted individual assessments of the values for each characteristic and attribute. The high homogeneity in the outcome of the individual assessments indicated that no further inter-rater reliability tests (Cole, 2024) were necessary, and minor discrepancies were discussed and resolved based on coded data and validation with participants. Beyond the interpretation of the researchers, the description of the characteristics of the measures is also influenced by the personal and collective perspective of farmers and organizations participating in the study (Suazo Muñoz and Sandoval-Díaz, 2023).

This study analyzed how the extensive *dehesa* livestock sector in Los Pedroches responded to the 2013–2024 drought. The resulting insights that can inform future preparedness efforts. Given the evolving nature of climatic conditions and of the decision-making context, it would be useful to apply this methodological approach at different points in time, for example, after each prolonged drought, to support learning and inform future actions. For this assessment to have a meaningful impact in the region, its results should be shared and discussed with local stakeholders, for instance, through targeted outreach workshops involving organizations such as cooperatives, rural development organizations and agricultural extension agents, capable of transferring lessons to individual farmers and catalyzing collective actions.

5 Conclusion

This study contributes to the literature on adaptation studies by developing a methodological framework to characterize responses to drought risk, building on existing scholarly work (Fischer, 2019; Fischer and Denny, 2024; Magnan et al., 2020) and taking into consideration farmer input and local context. It also offers a detailed case study of how the livestock farming sector in a Spanish *dehesa* agroforestry system responded to such risks in a recent, severe drought (2013-2024).

Livestock farmers in rainfed systems with high natural value such as the *dehesa* in Los Pedroches region confront the interconnected impacts of climate change and severe drought with a broad range of measures across different management areas (water, feed production, economy, forest, livestock). Extensive field work and interactions with local actors during an ongoing severe drought - guided by the proposed methodological framework–enabled us to characterize these responses in a way that goes beyond the dichotomy between non-adaptive *versus* adaptive efforts. This approach allowed us to identify the adaptive components of each measure as well as those aspects that may lead to maladaptation. The analysis can help develop policies that reinforce the former and address and adjust the latter.

The methodological framework applied in this study positions responses along the coping-adaptation spectrum while capturing nuances in their design and implementation by assessing their basic features, effectiveness, enabling conditions and feasibility requirements. This, in turn, sheds light on the strengths of the implemented measures and potential barriers in their pathway toward adaptation. For instance, a local guild cooperative was found to promote coordinated actions to effectively respond to emergency situations, and to influence the long-term decisions of individual members in favor of more adaptive responses. Thus, reinforcing established social networks, such as farming cooperatives, or fostering the establishment of new forms of collective action could enhance implementation of adaptation-oriented interventions.

In terms of constraints, we found that the natural and cultural value of an agroforestry system such as the *dehesa* is an asset worth being protected, but, at the same time, the priority of maintaining it conditions the range of possible transformational options that may lead to a more resilient but less traditional system. Thus, to be socioeconomically viable, the quest for adaptation must always start with a deep knowledge of the local socioecological system. Any cross-pollination across case studies requires a careful adjustment of adaptation "success stories" documented in other regions to the multifaceted local reality.

In dryland socio-hydrological systems such as Los Pedroches, livestock farmers use blue water for watering their animals and for operating farms and the associated processing facilities (dairy, meat processing, *etc.*). An unprecedentedly prolonged drought revealed the high vulnerability of the livestock sector, prompting mostly reactive, short-term coping measures, especially in the water management area. This highlighted critical gaps in local knowledge about groundwater dynamics, which limit farmers' ability to respond effectively. Improving understanding of the groundwater system and the influence of climate variability on this resource could enhance decision-making capacities for both individual farmers and the cooperative. Moreover, the prolonged drought underscored that the lack of climate predictions with adequate spatiotemporal resolution and prediction skill limited farmers' ability to make proactive decisions that could help minimize climate impacts. Improved forecast information could assist climate-sensitive decision making, such as adjusting livestock stocking rates or crop calendars. These examples point to the need for improved site-specific climate and hydrological information that fills identified knowledge gaps and supports the design of measures to address climate risk.

Our study found that adaptive responses often need years or decades to achieve full effectiveness and have high maintenance and knowledge requirements. Meanwhile, coping measures have more immediate effectiveness and are useful to swiftly address unexpected critical situations. However, their benefits are often short-lived, so they must be sustained over time, leading to higher operational costs and farm vulnerability. Coping measures can also facilitate long-term adaptation as they can enable the survival of socioeconomic activities in extreme events and allow for planning transformational changes in the aftermath of the emergency. Nevertheless, efforts must be made to track and analyze their implementation through methodological frameworks suited to the dynamic nature of the decision-making context to avoid long-term maladaptation.

Data availability statement

Data will be made available on request.

Author contributions

NR: Conceptualization, Data curation, Investigation, Methodology, Software, Writing – original draft, Writing – review and editing. NH-M: Conceptualization, Investigation, Methodology, Supervision, Writing – review and editing, Visualization, Writing – original draft. LD: Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review and editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This study was funded by the EU Horizon 2020 project I-CISK (Innovating climate services through integrating scientific and local knowledge) under Grant Agreement 101037293.

Acknowledgments

The authors also thank the members of the rest of the CREAF team, Lluis Pesquer, Ester Prat, Annelies Broekman and Amanda Battle, who co-led the Andalucía-Los Pedroches Living Laboratory for their collaboration. Thanks are due to the reviewers who have enriched this work with their comments. The authors are thankful to the local stakeholders that have generously contributed to this study with their knowledge, time, and perspective.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1540818/full#supplementary-material

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