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Research article

A downscaled examination of drought vulnerability and self-reported preparedness among livestock farmers in the northeast of Romania

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ABSTRACT

Recent European drought events have highlighted that vulnerability and preparedness play a pivotal role in shaping both the potential impacts of drought and its management. This study aims to take an in-depth look at drought vulnerability and preparedness, their spatial distribution, and the relationships between them, local landforms, and farm settings. The case study focuses on livestock farmers who face challenges related to drought impacts due to significant drought exposure, but whose needs and interests are often overlooked by mitigation strategies and compensation schemes. Examining their vulnerability to drought relied on a downscaled, index-based approach that integrates data collected through an in situ survey, from 141 farmers in the northeast Romania. In the study area, drought vulnerability negatively correlated with self-reported preparedness, and both of them varied across farm sizes. Smaller farms tend to have higher vulnerability and lower preparedness. Cross-correlations indicate that farming educational background, availability of fodder and financial reserves, basic infrastructure, and access to water are key to understanding drought vulnerability and preparedness. To date, there are no studies that compare drought vulnerability estimates with livestock farmers' self-reported preparedness. These findings provide a roadmap for developing drought management plans tailored to food systems focused on livestock farming that can be applied at the European level.

1. Introduction

Over the last decades, climate change taking the form of increased temperatures and more frequent meteorological extremes (Barendrecht et al., 2024) has overshadowed every challenge confronted by society, slowing down the achievement of the Sustainable Development Goals. Since mid-20th century, there has been a notable escalation in global aridity and the extent of drought (Dai, 2011), and drought hazards are expected to increase in frequency and intensity (Calanca, 2007; Sheffield and Wood, 2008; Strzepek et al., 2010; Vicente-Serrano et al., 2014; Hosseinizadeh et al., 2015; Dai et al., 2018; Spinoni et al., 2018; Bouabdelli et al., 2022) especially when considering the anthropogenic influence (Chiang et al., 2021). Since such increases have been already documented in the past decades (Dai, 2011; Spinoni et al., 2014; Vicente-Serrano et al., 2014; Haile et al., 2020), drought management becomes a paramount concern for tomorrow's farming systems, while the concept of anthropogenic drought (AghaKouchak et al., 2021; Chiang et al., 2021) gains prominence.

Drought is a multi-faceted phenomenon that has already covered many definitions by the end of the last century, as shown by Wilhite and Glantz (1985) and Smakhtin and Schipper (2008). It results from the overalpping of lower-than-expected precipitation and high demand for water resources (Wilhite, 2000b), standing out among the other hazards by being caused by scarcity (Hollins and Dodson, 2013) and by not having clear-cut starting and ending points (Maybank et al., 1995). Also, drought is a multiscalar phenomenon that causes multisectoral impacts and pressents a gradual evolution, starting with meteorological drought, progressing to hydrological and hydrogeological drought, pedological drought, and finally to agricultural and socio-economic drought (Wihite and Glantz, 1985; Haile et al., 2019). Other concepts, like groundwater

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drought (Van Lanen and Peters, 2000; Masroor et al., 2021), stream health drought (Esfahanian et al., 2016), ecological drought (Crausbay et al., 2017), technological drought (Mondol et al., 2022), flash drought (Yuan et al., 2015a) are constantly emerging, highlighting the vitality of the research field.

The aforementioned facets of drought have translated into a plethora of research initiatives pertaining to climate change (Dai, 2011; De Boeck and Verbeeck, 2011; Vicente-Serrano, 2016; Cook et al., 2018), food security (Hameed et al., 2020; Kogan et al., 2019, 2020; Stavi et al., 2022), water management (Berbel and Esteban, 2019; Orimoloye et al., 2021; Pokhrel et al., 2021), and natural risks (Wilhite, 2000a, 2000b; Mishra and Singh, 2010; Kreibich et al., 2022). From the last category, drought risk assessments are the most complex, since they include both the drought hazard (which is analysed in terms of frequency, duration, intensity, and spatial extent) and the vulnerability (which supports a broader range of approaches). These two components are most frequently reunited in composite indexes (Elagib, 2014; Han et al., 2016; Luetkemeier and Liehr, 2018; Nasrollahi et al., 2018; Kim et al., 2021; Dunne and Kuleshov, 2023), and Hagenlocher et al. (2019) report that the studies that rely on dynamic simulation methods or qualitative methods represent less than 20 % of the reviewed drought risk assessments.

In the last decade, drought vulnerability has been drawing more and more attention from the UN agencies (e.g., the World Meteorological Organisation, the Food and Agriculture Organisation of the United Nations, the Secretariat of the United Nations Convention to Combat Desertification), the scientific community, and decision-makers (González Tánago et al., 2016) because of its underlying role in determining drought impacts (Brill et al., 2024) and shaping drought management (Savari et al., 2022). Literature reviews on drought vulnerability (González Tánago et al., 2016; Hagenlocher et al., 2019; Dhawale et al., 2024) show a wide range of conceptual and methodological approaches, most of them focusing on the triad of exposure, sensitivity, and adaptive capacity, and on building drought vulnerability indexes (Lindoso et al., 2014; Murthy et al., 2015; Vargas and Paneque, 2017; Ahmadalipour and Moradkhani, 2018; Dumitraşcu et al., 2018; Balaganesh et al., 2020; Engström et al., 2020; Kar et al., 2018; Kalura et al., 2021; Swain et al., 2022; Masroor et al., 2023). Nevertheless, to the best of our knowledge, no studies bring together drought vulnerability and preparedness under an index-based comparative approach or within the context of livestock farming. This parallel requires more scrutiny, enabling the identification of overlaps of high vulnerability and low preparedness. Such knowledge supports decision-making and advances the study of drought from a socio-hydrological perspective (Vanelli et al., 2022).

This study aims to explore the vulnerability of livestock farmers to drought and their self-reported preparedness, selecting the northeast region of Romania as a case study and focusing on agricultural drought. The inquiry was conducted locally, using a survey designed to account for the farming realities of a EU country where grazing still represents a prominent rural livelihood, income source, and cultural heritage. The study area was chosen based on the substantial impact of recent drought events, including the one in 2022 (Rossi et al., 2023), its high-level drought exposure, and the key role of livestock farming in preserving grazing as a traditional, multi-centennial rural activity. In addition to being representative of the study area, livestock farmers were selected based on their exposure to drought throughout the year, indicating a high potential for a wide range of drought impacts spread over time. In this sense, we implemented a downscaled approach that prioritises fine spatial resolution and localised data collection. This methodological choice allows for a granular analysis of farm-level vulnerability and preparedness against drought, moving beyond broad regional assessments to uncover context-specific insights. Moreover, the localised focus facilitates stronger engagement with farming communities, promoting participatory research practices and the co-creation of knowledge.

First, we examine the actual vulnerability level of livestock farms by considering factors such as access to water resources, basic infrastructure, availability of reserves, networking level, farming education background and experience, and diversity of farming activities. The resulting levels of drought vulnerability are then mapped against the level of self-reported preparedness to withstand drought, and analysed in terms of confluences and divergences, outlining prominent implications for drought management.

This is the first study to address the downscaled drought vulnerability of livestock farmers by putting side-by-side estimates of both vulnerability and self-reported preparedness levels. It identifies drought vulnerability and preparedness hotspots and coldspots, as well as related spatial tendencies. Also this study marks the beginning of drought vulnerability and preparedness studies in Romania. Leveraging these results, we also provide tailored recommendations to mitigate drought impacts in the study area, considering a two-tier approach targeting drought vulnerability reduction and improved response to drought impacts.

2. Scene setting: livestock farming in northeast Romania

The farms investigated in this study are located in the Moldavian Plateau, in the northeastern part of Romania (Fig. 1). They are scattered across the Iaşi and Botoşani counties, covering elevations ranging from 40 m to 200 m. The farms are located close to the middle section of the Prut River, which serves as the natural border between Romania and the Republic of Moldavia. The rural areas here possess distinct natural and socio-economic features that make them belong to the so-called „marginal livestock farming" system (Di Vita et al., 2024): a farming-based economic profile, an aged population, a substantial rural exode of young people (Cuciureanu and Iatu, 2016), low transportation connectivity (Muntele et al., 2010), high soil quality (Gerwin et al., 2018), a propensity for soil erosion (Patriche, 2023; Patriche et al., 2023), and at-risk biodiversity (Orgiazzi et al., 2016).

The geological seetings include Neogene sedimentary formations dominated by claystones, siltstones, mudstones, sands, quartz arenites, and oolitic calcarenites that dip southwards. Due to the river homoclinic shifting and the alteration of the mentioned lithologies, a general pattern of cuestas modelled by landslides is almost generalised (Niculiţă et al., 2019). Despite their negative impacts, these landslides have been a significant factor in preserving large areas as pastures throughout the last century (Văculişteanu et al., 2022). The maintenance of landuse as pasture and the conversion of wetlands into pastures is also observable in floodplains. Nowadays each rural administrative unit (NUTS 3) stands out in terms of uniformly distributed, extensive grazing areas (Fig. 1) that are managed mainly by local administration and rented to livestock farmers.

The northeast region is characterised by a dry continental climate according to the Köppen–Geiger classification of the world climate (Kottek et al., 2006), with mean rainfall values varying between 500 and 600 mm/year, mean annual temperatures around 9°C, and mean annual evapotranspiration of 600–700 mm/year (Sandu et al., 2008). In this climatic context, drought is one of the most frequent and impactful climatic hazards affecting the Moldavian Plateau, overlapping significant vulnerability conditions.

Minea and Albulescu (2025) identified 1994, 1989, 2000, 2009, 2010, 2012, 2014, 2015, 2016, 2018, and 2020 as dry years in northeast Romania, based on SPEI values computed using temperature and rainfall data from the meteorological stations at Botoşani and Iaşi. Their data indicate July and August as critical dry months in 1983–2020. Europe also experienced an unusually dry year in 2022 (Rossi et al., 2022). The GDO Analytical Report for July and August (Toreti et al., 2022a, 2022b) shows that the northeast of Romania was among the extremely dry areas based on SPI-6 January–June and February–July 2022 and SPI-3 June–August, among the areas with drier than normal soil moisture at the end of June 2022, and with lower than normal photosynthetic activity at the beginning of August 2022.

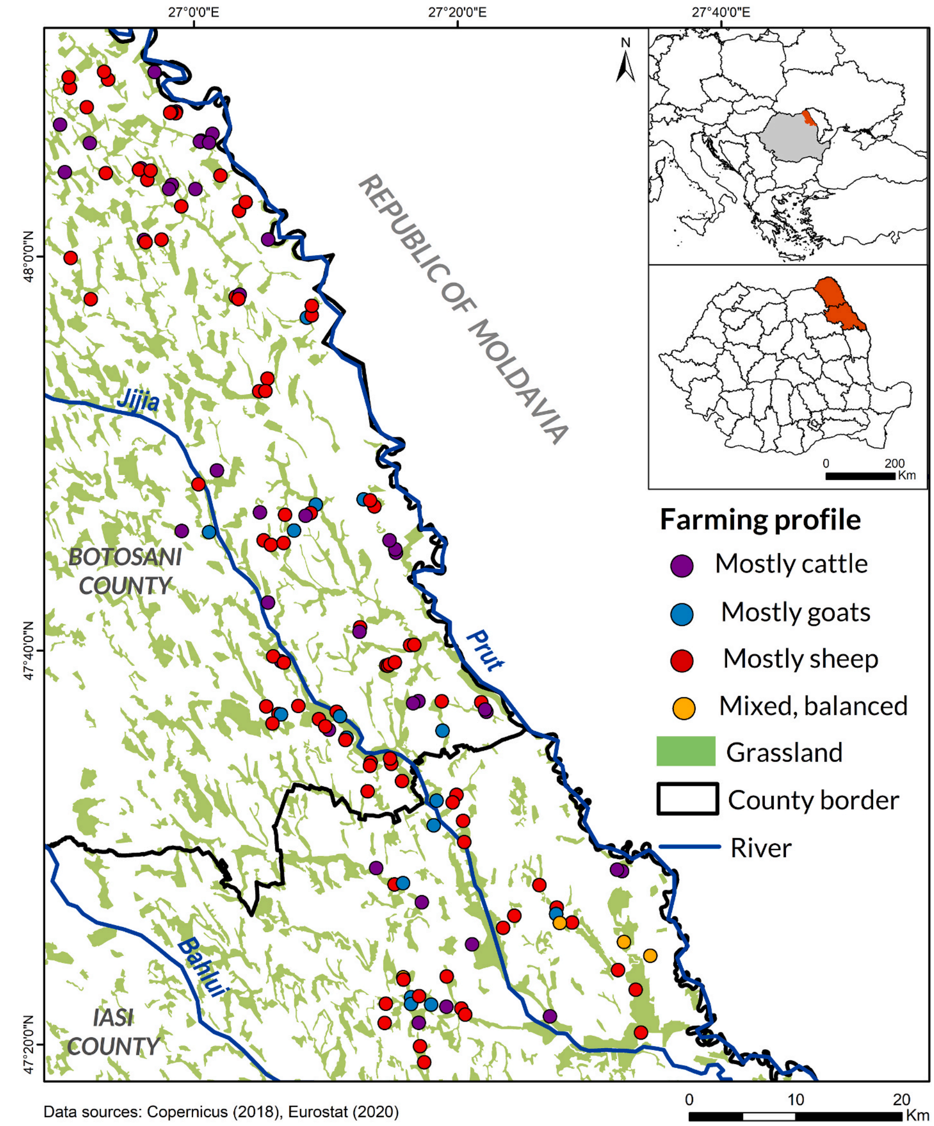

Fig. 1. Location of the study area and the surveyed farms by profile.

Against this climatic and geomorphologic background, access to water resources is a major concern: near the main rivers water is relatively accessible, while along the slopes and in the interfluvial areas water resources are discontinuous, depending on the distribution and temporal variability of the groundwater (Boicu et al., 2020) or the availability of local reservoirs (Mărgărint et al., 2021). This becomes particularly important given the expected drying tendencies in the summer months for the entire Romanian territory, especially in the northeast region (Jaagus et al., 2022). In the eastern part of Romania (including the study area), projected climate change based on the RCP4.5 and RCP8.5 scenarios (Trenberth et al., 2014; IPCC, 2021), is expected to bring higher temperatures (Croitoru et al., 2018), decreased humidity, and reduced runoff. These shifts will likely lead to significant water scarcity, along with fluctuations in groundwater levels and river discharge. Therefore, securing access to water resources represents a primary challenge for livestock farmers. Addressing this issue requires technological resources, which are often disregarded or unaffordable for many farmers.

3. Material and methods

To explore the drought vulnerability and preparedness of the livestock farms in the presented study area, this research was structured around three main research questions:

1) Does drought vulnerability or drought preparedness vary significantly among farm sizes or geomorphological settings?
2) What is the spatial distribution of drought vulnerability and drought preparedness of livestock farms?
3) What is the spatial distribution of hotspots and coldspots of drought vulnerability and preparedness?

The three-step methodological framework (Fig. 2) proposed to answer these research questions relies on a Drought Vulnerability Index (DVI) and a Drought Preparedness Index (DPI), as well as on their mapping. This section details the methodological steps, starting with the conceptual framework developed to suit our investigation.

3.1. Conceptual framework

Drought vulnerability covers a wide range of conceptualisation and operationalisation frameworks, as identified by Hagenlocher et al. (2019). According to the UNDRR's (2017) definition, vulnerability accounts for "the conditions determined by physical, social, economic, and

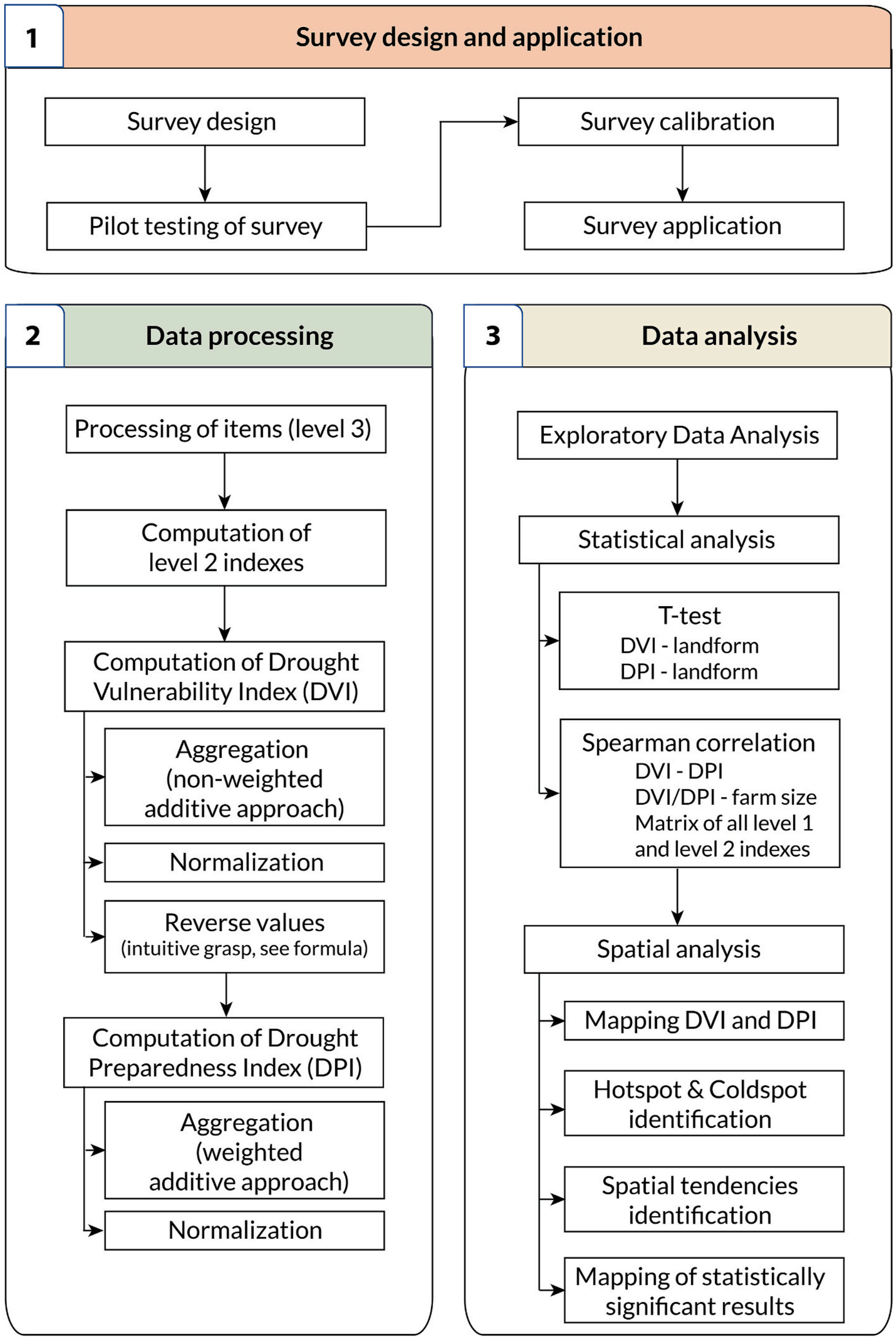

Fig. 2. Methodological workflow.

environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards“. Another set of vulnerability definitions was developed under the Climate Change Adaptation school (IPCC et al., 2007; De Stefano et al., 2015), wherein vulnerability was initially defined as "a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity" () and subsequently as encompassing the sensitivity to be harmed and a lack of capacity to cope and adapt (IPCC, 2014). This means that exposure was excluded from the definition of vulnerability in later IPCC frameworks, while both vulnerability and exposure, alongside hazard were included as components of risk (IPCC, 2014). Nevertheless, state-of-the-art vulnerability approaches account for the multi-dimensionality of vulnerability (González Tánago et al., 2016; Hagenlocher et al., 2019; Armaş and Albulescu, 2025), with drought vulnerability studies pertaining to integrative approaches (Armaş and Albulescu, 2025).

Generally, drought vulnerability is defined through the components introduced by IPCC: exposure, susceptibility, and adaptive or coping capacity, which are integrated into different equations (Lindoso et al., 2014; González Tánago et al., 2016; Murthy et al., 2015; Zarafshani et al., 2016; Vargas and Paneque, 2017; Dumitraşcu et al., 2018; Engström et al., 2020). Hagenlocher et al. (2019) report that "Of the articles reviewed, 34% consider sensitivity and/or susceptibility, 25% consider adaptive capacities and only 14% consider coping capacity as sub-components of vulnerability. Eleven percent of all papers include drought hazard characteristics and 14% include exposure as part of vulnerability". As there is no universal conceptual understanding of vulnerability (Armaş and Albulescu, 2025), nor a consensus on what drought represents, the lack of common ground allows for developing different assessment frameworks but also hinders comparisons across studies (González Tánago et al., 2016; Zarafshani et al., 2016).

Drought vulnerability is largely assessed under index-based approaches (Pandey et al., 2010; Lindoso et al., 2014; Murthy et al., 2015; Vargas and Paneque, 2017; Dumitraşcu et al., 2018; Engström et al., 2020; Wang et al., 2020; Guo et al., 2021; Kalura et al., 2021; Swain et al., 2022; Masroor et al., 2023) that may employ Multi-Criteria Decision-Making methods and GIS (Hoque et al., 2021; Ahmed and Suleimany, 2022), or more complex methodological frameworks (Ahmadalipour and Moradkhani, 2018). Qualitative (Dow, 2010) or mixed-methods approaches (Zarafshani et al., 2012) are also common. A considerable number of vulnerability assessments actually include drought hazard indexes (Pandey et al., 2010; Murthy et al., 2015; Vargas and Paneque, 2017; Engström et al., 2020; Guo et al., 2021; Hoque et al., 2021; Kalura et al., 2021; Swain et al., 2022; Ahmed and Suleimany, 2022; Masroor et al., 2023), aligning with early definitions of the concept provided by IPCC (2001).

In this study, the above-mentioned IPCC (2014) definition of drought vulnerability is held as standard. Drought vulnerability is measured through proxies (here called indexes placed on the second level, computed based on items on the third level of Fig. 3) regarding access to water resources, basic infrastructure, availability of reserves, the networking level, the farming educational background and farming experience of the farm owners, and the diversity of farming activities (Table 1, Fig. 3).

The selection of level 2 indexes used to compute the DVI and DPI was informed by expert knowledge, ensuring alignment with established theoretical frameworks and empirical observations. Drawing from the IPCC's (2014) conceptualisation of vulnerability, we have identified key proxies for the capacity to adapt and cope (e.g., availability of reserves, farming educational background, farming experience of the owners, networking level) and for sensitivity (e.g., access to water resources – exclusively for livestock, access to basic infrastructure, diversity of farming activities). These level 2 indexes and level 3 items were refined through iterative feedback during fieldwork, as the livestock farmers surveyed during the pilot phase, together with local authorities, validated their relevance to drought vulnerability in agricultural contexts in

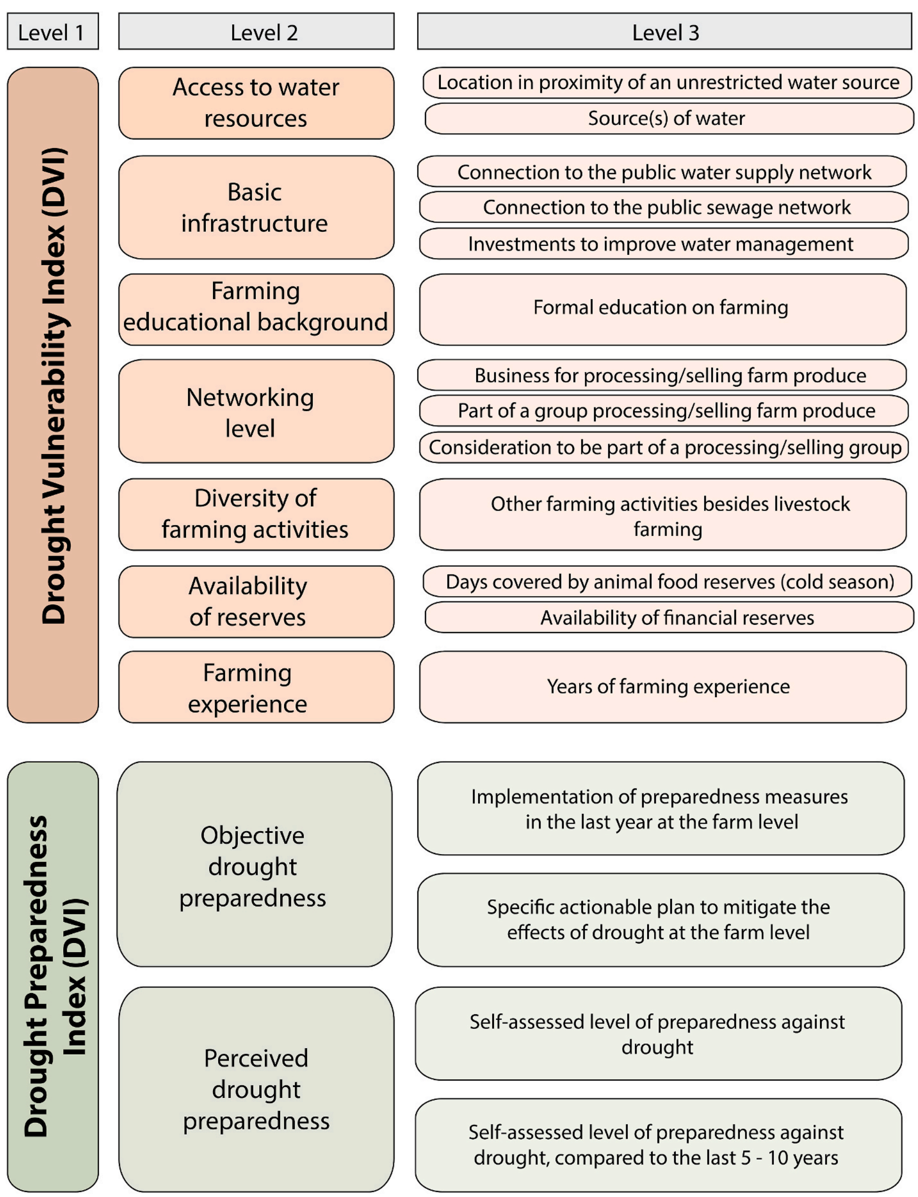

Fig. 3. Composition of the Drought Vulnerability Index (DVI) and Drought Preparedness Index (DPI). Level 1 – Drought vulnerability and preparedness indexes, Level 2 – Indexes included in the computation of level 1 indexes, Level 3 – Items

Table 1
Description of the level 2 indexes integrated into the level 1 indexes (DVI and DPI).

Level 2 index	Description	References
Drought vulnerability level 2 indexes		
Access to water resources (AW)	Access to water resources sets up the premises for drought management, ensuring the survival of livestock. Without access to water resources, farms are more susceptible to being negatively impacted by drought (i.e., livestock number reduction). The index encompasses items related to access to unrestricted water sources and the diversity of these sources (e.g., local springs, ponds, wells, rivers, public water supply system). The higher the access to water resources, the lower the drought vulnerability level.	Zarafshani et al. (2012), Lindoso et al. (2014), Naumann et al. (2014), De Stefano et al. (2015), Yuan et al. (2015b), González Tánago et al. (2016), Urquijo and De Stefano (2016), Vargas and Paneque (2017)
Basic infrastructure (BI)	Basic infrastructure is a pre-requisite for adequate drought management, referring to the connection to the public water and sewage systems, as well as investments in improvements in water management within the farm. Without access to such infrastructure, farms are rendered more susceptible to be negatively impacted by drought. The larger the value of this index is, the lower the drought vulnerability level.	Naumann et al. (2014), De Stefano et al. (2015), Dumitraşcu et al. (2018)
Availability of reserves (AR)	The availability of animal food reserves and financial reserves supports farming activities during dry periods. Large values correspond to low drought vulnerability levels.	Sookhtanlo et al. (2013)
Networking level (NT)	The networking level refers to the social connections of the farmer, measured through proxies like owning a (family) business for processing/selling the produce of the farm and being part of associations or groups with processing or commercial activities. The higher the networking level, the lower the drought vulnerability level.	Zarafshani et al. (2012), Sookhtanlo et al. (2013), Lindoso et al. (2014), Muyambo et al. (2017)
Farming educational background (FED)	A farming-related educational background of the farmer ensures a proper management of the farm in general and improved drought impact management. Farms coordinated by farmers with such a background are more likely to have low drought vulnerability.	–
Farming experience (FE)	Farming experience is an important source of knowledge regarding drought impact management. More experienced farmers are more likely to be in charge of farms with low drought vulnerability.	–
Diversity of farming activities (FD)	During drought events, a wide range of farming activities may secure a source of income, eliminating the disadvantage of depending on a single farming activity and reducing the susceptibility of that farm to drought impacts. More farming activities correspond to lower vulnerability levels.	–
Drought preparedness level 2 indexes		
Objective drought preparedness (OP)	Objective drought preparedness is measured through proxies regarding the existence of a plan of action to mitigate drought impacts and the actual implementation of drought preparedness measures within the farm. The larger its value, the higher the preparedness level.	Engström et al. (2020), Masroor et al. (2023)
Perceived drought preparedness (PP)	Self-estimated drought preparedness represents an important component of the overall preparedness. However, farmers may underestimate or overestimate their own preparedness level. This bias was corrected by assigning 25 % importance to this factor, based on expert knowledge acquired through fieldwork.	–

the northeast of Romania. Expert input also resolved ambiguities in operationalising level 2 indexes, such as quantifying the networking level through membership in agricultural associations or commercial partnerships.

As described in Table 1, all drought vulnerability indexes (level 2) are non-benefit (or cost) indexes, meaning that their high values are associated with lower vulnerability levels. Conversely, drought preparedness indexes (level 2) are benefit indexes, meaning that their higher values correspond to higher drought preparedness. The questions and answers associated with each item (on level 3, Fig. 3) are described in Appendix 1.

Preparedness represents the "knowledge and capacities developed by governments, response and recovery organizations, communities and individuals to effectively anticipate, respond to and recover from the impacts of likely, imminent or current disasters" (UNDRR, 2017). In the context of drought, preparedness is an umbrella term reuniting actions meant to "(a) be better prepared to cope with drought; (b) develop more resilient ecosystems to recover from drought; and (c) mitigate the impacts of droughts" (Solh and van Ginkel, 2014).

Literature abounds with a broad and diverse array of examples of coping strategies: the sowing of drought-resistant crops, diversification of crops, changes in the crop calendar, efficient irrigation practices, increase in groundwater extraction, the use of multiple water sources, water transfers, the sharing of different farming costs between farmers, income diversification or off-farm livelihoods, (temporary) migration, selling of livestock, or cutting down expenditures (Ngaka, 2012; Ashraf and Routary, 2013; Solh and van Ginkel, 2014; Udmale et al., 2014; Urquijo and De Stefano, 2016; Iqbal et al., 2018; Menghistu et al., 2018; Sam et al., 2020; Mkwambisi et al., 2021; Lottering et al., 2023; Masroor et al., 2023).

The survey used in this study does not refer to specific coping strategies but rather to a more general approach that relies on the self-assessment of farmers. Self-reported drought preparedness is conceptualised under a dichotomic approach that integrates proxies of both objective and subjective (i.e., perceived) preparedness (Table 1, Fig. 3). To account for the potential bias associated with the perceived preparedness, the two level 2 indexes were given different weights: 75 % to objective preparedness and 25 % to subjective preparedness. The weighting scheme for preparedness level 2 indexes was derived from repeated expert consultations during the fieldwork. We observed that farmers' self-assessments often over- or underestimated actual preparedness, necessitating a corrective bias adjustment. This approach prioritises measurable actions (e.g., drought plans, implemented measures) over subjective confidence.

3.2. Survey design and application

The multi-level survey focuses on the proxies used to measure drought vulnerability and self-reported preparedness. The questionnaire was administered in person in May–July 2023, upon getting the consent of the respondents, granting them confidentiality and presenting the option to stop the survey at any point without explaining the reasons for their decision. It included 23 questions concerning the demographics of the farmers (i.e., gender, age), the settings of the livestock farms they own or manage (i.e., location, geomorphological setting, farm size, farming profile), and the proxies of drought vulnerability and preparedness (Fig. 3).

Prior to application, we conducted a pilot test on the survey with the help of 48 farmers with different demographics and farm settings. Based on their feedback, we calibrated the questionnaire by deleting 10 questions that were deemed irrelevant and modifying other 15 questions to better capture the local drought-related realities or to clarify their meaning. Upon applying the questionnaire in the field, we obtained 141 complete responses, with a 76% response rate. The respondents were selected based on random sampling, after discussing with local stakeholders (i.e., rural mayors) who manage large areas of pasture that are available to farmers for rent.

3.3. Computation of the Drought Vulnerability Index (DVI) and Drought Preparedness Index (DPI)

Each of the level 2 indexes used to measure drought vulnerability and self-reported preparedness was computed based on answers to at least one question from the survey (Appendix 1). In most cases, the answers to two to three questions (each question corresponding to a specific level 3 item, as listed on level 3 in Fig. 3) were grouped to compute the level 2 indexes; except for the farming educational background, farming experience, and diversity of farming activities, which were all based on the answers related to a single item (i.e., to a single question). To compute the items, the categorical answers specific to each question were converted to points, as explained in Appendix 1. Level 2 indexes based on multiple items had their points aggregated under a simple additive approach, and the resulting value was normalised (i.e., minimum-maximum scaling). These transformations and the computation of the DVI and DPI were coded in R using the tidyverse package (Wickham et al., 2019).

The DVI was computed by aggregating the seven level 2 indexes of drought vulnerability (level 2 in Fig. 3, Table 1) under a simple additive approach. In this case, a weighted approach was excluded due to uncertainties on the exact role of each level 2 index in determining the overall drought vulnerability (level 1 index). The resulting sum was then normalised to ensure comparability. At this point, all seven level 2 indexes used to compute the DVI function as non-benefit (or cost) indexes. This means that higher values were assigned to the answers indicating lower vulnerability (Appendix 1). For instance, increased access to water resources or a high networking level (expressed as values closer to 1) indicate a low level of drought vulnerability. It is important to note that the higher the value of the sum, the lower the vulnerability level, and vice versa. To make the level 1 index easier to interpret, the sum of the level 2 indexes was subtracted from 1 (1). As a result, the DVI ranges from 0 (low vulnerability) to 1 (high vulnerability) – meaning that higher values indicate greater vulnerability and lower values indicate lower vulnerability.

$$\textit{Drought Vulnerability Index} = 1 - (AW + BI + AR + NT + FED + FE + FD) \tag{1}$$

$$\textit{Drought Preparedness Index} = PP^{*}0.25 + OP^{*}0.75 \tag{2}$$

In the case of the DPI, the perceived and objective preparedness function as benefit indexes, meaning that their high values are associated with high preparedness levels, and vice versa. Unlike in the case of the DVI – where all the level 2 indexes weighted the same, the DPI was computed using a weighted approach supported by expert knowledge gained through fieldwork. The perceived preparedness of the farmers, which was computed based on questions that allowed subjectivity, accounted for 25% of the level 1 index, while the rest of it (75%) was determined by objective preparedness (2). By assigning these weights, we aimed to reduce the bias inherently associated with the self-reporting of drought preparedness levels. This weighted sum was then normalised so that the DPI ranges from 0 (low preparedness) to 1 (high preparedness).

3.4. Analysis

Firstly, we conducted exploratory data analysis in R, focusing on descriptive statistics and data visualisation. This overview guided the selection of the statistical tests (Fig. 2) needed to test differences or correlations with statistical significance given that the distributions of the considered level 1 and level 2 indexes were non-normal.

- For the pairs of categorical vs. quantitative variables: a *t*-test was performed on the geomorphologic setting (floodplain or slope) and the Drought Vulnerability and Preparedness Indexes.
- For the quantitative vs. quantitative variables: Spearman correlations were computed for the Drought Vulnerability and Preparedness Indexes, and for these level 1 indexes and the farm size (expressed as livestock units).
- For all the pairs of level 2 indexes (level 2 in Fig. 3) pertaining to drought vulnerability and self-reported preparedness: a correlation matrix was computed using the Spearman correlation.

All the statistical tests were performed in R using the tidyverse package and the corrplot package (Wei and Simko, 2021) for the correlation matrix of the level 2 and level 1 indexes. All of the correlations were tested for statistical significance setting the alpha value at 0.05.

Drought Vulnerability and Preparedness Indexes were mapped into five classes (i.e., very low, low, medium, high, and very high) using equal-interval quantiles. This approach was selected after computing different standard deviation-based thresholds for the DVI values, as well as equal-interval quantiles, and comparing their advantages and disadvantages. Considering the operational goal of the analysis (i.e., to provide authorities with a few key points on which farms need help to manage drought impacts via vulnerability reduction-focused measures, without limiting the help to extreme cases), we selected the equal-interval quantiles approach. In addition, we identified the livestock farms with extreme classes of drought vulnerability and preparedness. Hotspots were designated as farms with very high/high vulnerability and very low/low preparedness levels, while coldspots were designated as farms with very low/low vulnerability and very high/high preparedness. The hotspot and coldspot terminology does not refer to extreme cases (which would have been better highlighted through thresholds set based on standard deviation), but rather to the top 20 % livestock farms in terms of drought vulnerability and preparedness.

4. Results

4.1. Participants

The livestock farmers who participated in the survey were mostly men (88 %) with a median age of 49 years. Both women and young farmers represent minorities in the community of livestock farmers in the northeast of Romania (Fig. 4), which is dominated by experienced adult farmers with ages of 41–60 years. However, the sample presents a broad age range, with a minimum at 24 years old and a maximum at 70 years old.

Most livestock farms were located in the Botoşani County (71%), with slopes being the predominant geomorphological setting (65%). The farming profiles were established based on the dominant livestock breeds (i.e., cattle, sheep, and goats), and the farm size was measured in livestock units. Such units combine the number of all livestock breeds using specific coefficients from the official Romanian guidelines (Ministry of Agriculture and Rural Development, 2013) and scientific papers (Roman et al., 2019). Only 3 % of the farms had mixed breeds (Fig. 5), with sheep (58%) and cattle (28%) being the main species. Farm sizes ranged from 7 to 260 livestock units, with a median of 55 units. The majority (50%) had between 40 and 75 units, but there were notable outliers, with some farms exceeding 240 units (Fig. 5).

4.2. Drought vulnerability and preparedness indexes

The level 2 indexes used to compute the level 1 indexes (Table 1) present non-parametric distributions, as illustrated in Fig. 6A. Half of the farmers display low values when it comes to the availability of reserves, networking level, farming educational background, and diversity of farming activities. Overall medium values correspond to half of the participants in terms of access to water resources, basic infrastructure, farming experience, and perceived drought preparedness.

When it comes to the farming educational background, half of the farmers present low values (0–0.1) of the former factor, with only a few outliers with a strong farming educational background in the form of PhDs or other high-level educational programmes (Fig. 6A). Besides livestock grazing, most farmers perform a narrow range of farming activities, as shown by the 0 to 0.18 values registered by half of the survey participants (Fig. 6A). The same narrow spread of the answers is observed in the case of the networking level, that ranges between 0 and 0.25 for 50% of the participants, and of the availability of reserves, that ranges between 0.04 and 0.29 for half of the participants, with an outlier that disposes of more consistent reserves.

More spread distributions are specific to the basic infrastructure and farming experience level 2 indexes. In the case of basic infrastructure, half of the farmers registered values between 0.33 and 0.66, implying that the overall availability of basic infrastructure is low to medium (Fig. 6A). The farming experience of 50% of the participants ranges between 0.23 and 0.61. Prevailing low to medium levels of access to water resources also correspond to half of the sample, with ranges between 0.28 and 0.57.

The distributions of the values specific to level 2 indexes related to self-reported preparedness show discrepancies between objective and perceived preparedness. The perceived drought preparedness of 50% of

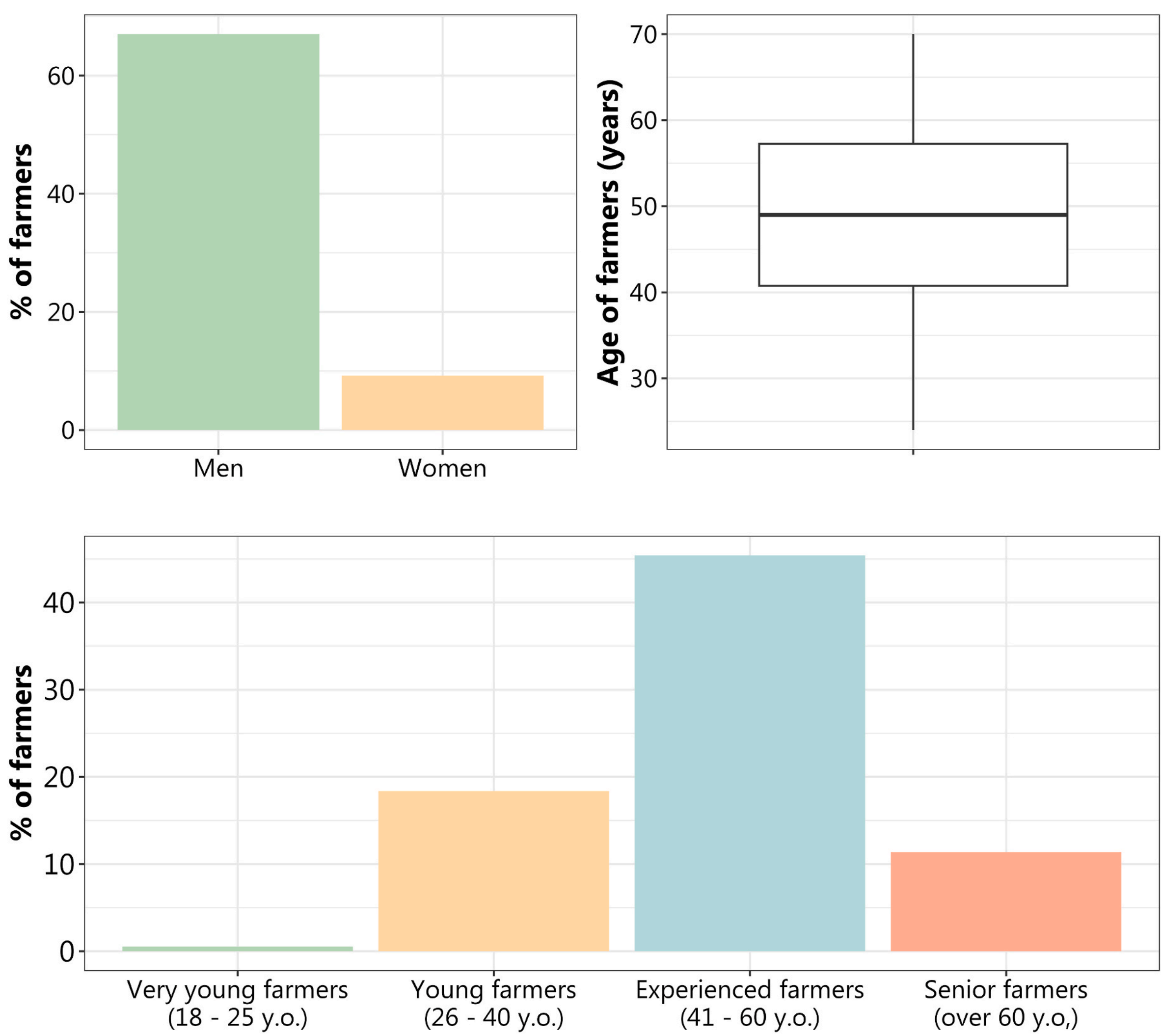

Fig. 4. The demographic characteristics of the livestock farmers.

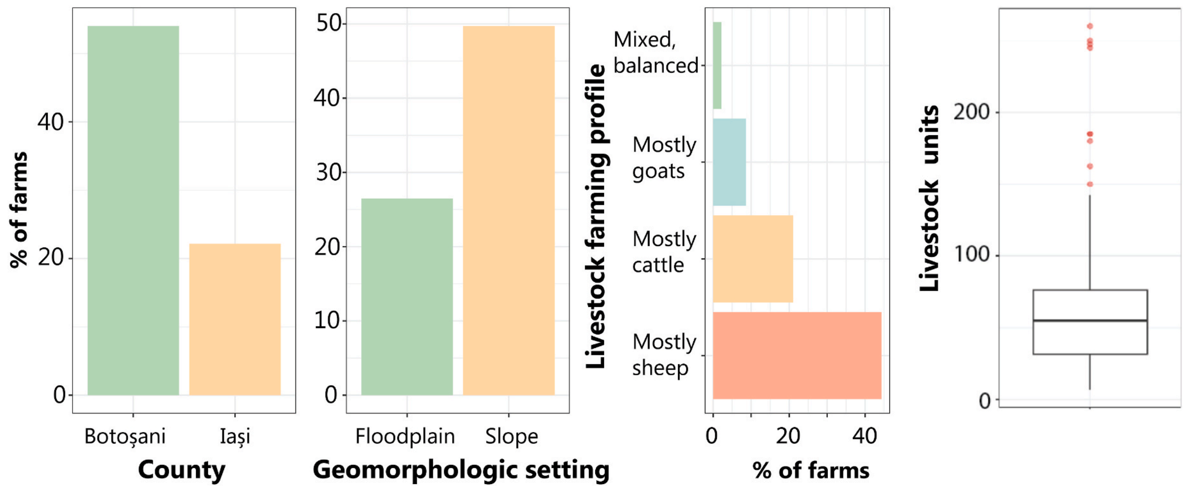

Fig. 5. The farm settings of the livestock farms taken under analysis.

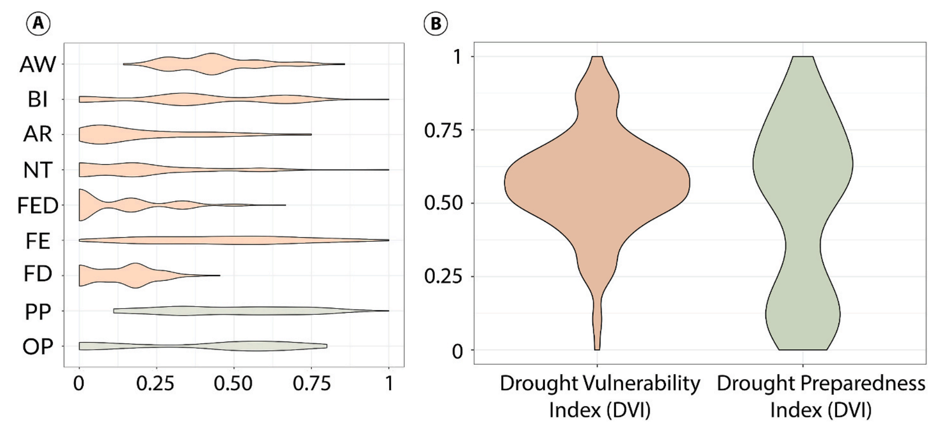

Fig. 6. Distributions of the values of the level 2 indexes (A) integrated into the (B) DVI (orange) and the DPI (green). AW – Access to water resources, BI – Basic Infrastructure, AR – Availability of reserves, NT – Networking level, FED – Farming educational background, FE – Farming experience, FD – Diversity of farming activities, PP – Perceived drought preparedness, OP – Objective drought preparedness.

the surveyed farmers ranges between 0.33–0.66, while the objective preparedness presents a larger spread. In this case, the objective preparedness of half of the participants ranges between 0 and 0.65, with a maximum value of 0.8 (Fig. 6A).

The violin plots of the two indexes (Fig. 6B) show a more spread distribution for the self-reported DPI values compared to the DVI values. All livestock farms (99%) present DPI values ranging from 0 to 1, while the same percentage of participants accounts for values between 0.23 and 0.91 when it comes to DVI. When looking at the 0.25 and 0.75 quantiles, the values indicate a narrower spread and medium-high levels in the case of the DVI (0.48 and 0.66), and a larger spread and low to medium-high levels of DPI (0.17 and 0.68). The medians of the indexes are very close, with 0.57 for the DVI and 0.54 for the DPI. It should be noted that there are few livestock farms with particularly high and particularly low drought vulnerability (Fig. 6B).

4.3. Relationships between DVI/DPI and farm settings

A negative moderate correlation value (−0.41) was found between the DVI and DPI (Fig. 7), which means that higher drought vulnerability levels tend to correspond to lower preparedness levels. Moreover, there is a negative moderate correlation between the DVI and the farm size (−0.43), and a positive moderate correlation (0.43) between the DPI and the farm size. This means that smaller farms tend to have higher drought vulnerability levels and lower drought self-reported preparedness levels.

There are negative correlations of various strengths between the DVI and all of its level 2 indexes, except for farming experience. The strongest correlations are reported between the DVI and basic infrastructure (−0.67), availability of reserves (−0.59), access to water resources (−0.57), and farming educational background (−0.55) (Fig. 7). Furthermore, the DVI is negatively correlated with objective and perceived preparedness, but to a lesser extent (−0.39, respectively −0.18).

On the other hand, the DPI presents a very strong correlation with objective preparedness (0.97), and a weaker correlation with perceived preparedness (0.43); which is explained by the set 75:25 relative importance of the two level 2 indexes. Other notable correlations result between the DPI and the availability of reserves (0.49) and farming educational background (0.42) (Fig. 7).

Among the integrated level 2 indexes, there are only 3 negative correlations, all of weak strength: between farming experience and perceived (−0.18) and objective (−0.25) preparedness, and farming education background (−0.22). This means that more experienced farmers tend to display lower levels of both perceived and objective preparedness and are less likely to have followed formal farming-related educational programmes. These negative correlations are explained by the fact that the most experienced farmers are also the oldest ones, having low levels of farming education and potentially lacking financial means to prepare against drought.

Positive moderate correlations are recorded between the availability

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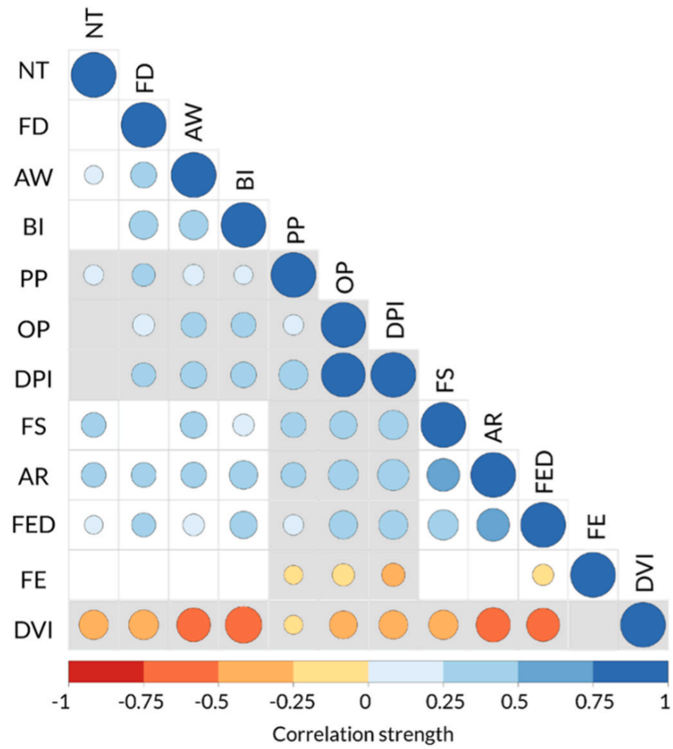

Fig. 7. The correlation matrix of the level 1 and 2 indexes. NT – Networking level, FD – Diversity of farming activities, AW – Access to water resources, BI – Basic Infrastructure, PP – Perceived drought preparedness, OP – Objective drought preparedness, FS – Farm size, AR – Availability of reserves, FED – Farming educational background, FE – Farming experience. The DPI and DVI are highlighted in grey. All of the values are statistically significant, with a p-value lower than the 0.05.

of reserves and farming education (0.53), between the availability of reserves and objective preparedness (0.45), followed by the one between access to water and basic infrastructure (0.42), the one between basic infrastructure and farming diversity (0.40), and the one between farming education and objective preparedness (0.40). All of these show that objective drought preparedness is associated with the availability of reserves and formal education regarding farming and that livestock farmers who perform other farming activities are more likely to benefit from basic infrastructure (Fig. 7). Another aspect to consider is that the farmers who benefited from farming-oriented education tend to be wealthier and dispose of more consistent fodder reserves.

There are also positive correlations of medium strength between the access to basic infrastructure and availability of reserves (0.40), objective preparedness (0.31), and farming education (0.37) on the one hand, and between access to water and objective preparedness (0.32), farming diversity (0.33), and availability of reserves (0.32) on the other hand.

A correlation that is noteworthy due to its implications is the one between perceived and objective preparedness (Fig. 7). The two factors are positively correlated, but only to a low degree (0.21). Still, this means that the prepared livestock farmers have a relatively fair appreciation of their drought preparedness level. Other insightful but weak correlations are the ones showing that educated farmers are also part of farming networks or that they tend to perform other farming activities besides livestock grazing.

On the other hand, the *t*-test performed to identify if there is any statistically significant difference between the means of the DVI or the DPI and the landform (i.e., slope or floodplain) specific to the livestock farms did not confirm the existence of such differences, as all the p-values were larger than the set significance level of 0.05.

4.4. Spatial distribution of drought vulnerability and preparedness

The spatial tendencies presented in this section have to be interpreted with caution, as their identification is based on mapping livestock farms' locations against their computed DVI and DPI. In this case, the spatial autocorrelation (Moran I) for the DVI and DPI did not provide statistically significant results. We attribute this result to the insufficient size of the livestock farm sample. Hence, we intentionally steer clear of the word "pattern" and substitute it with "tendency."

Dividing the values of the indexes into five equal-interval classes (e.g., 0–0.2, 0.21–0.4, 0.41–0.6, 0.61–0.8, 0.81–1), it can be observed that most livestock farms have medium drought vulnerability levels (34.1%). In the case of self-reported preparedness, the most prominent class is the one of high preparedness (24.9%) (Fig. 8A and B). Under 10% of the surveyed farms present very low and low vulnerability levels, and the classes at the other end of the spectrum (i.e., very high and high vulnerability) correspond to more than a third of them (32.41%). In the case of drought self-reported preparedness, more than a quarter (26.91%) of the farms present very low and low preparedness levels, while 37.3% of them display very high and high preparedness levels.

The spatial distribution of the DVI shows a group ("cluster" is avoided on purpose, as the spatial autocorrelation did not provide statistically significant results) of medium and low levels of vulnerability in the south of the study area (i.e., the northeast of Iași County) (Fig. 9A). Vulnerability tends to increase following a South-North direction, with most of the livestock farms with very high and high vulnerability levels located in the central and northern area of Botoşani County. Analysing the map specific to drought preparedness (Fig. 9B), one can observe that livestock farms with very high and high preparedness levels are spread across the entire study area, with no particular tendency. The farms that are least prepared tend to group in the northernmost area of Botoşani County and in the proximity of the border between the Iasi and Botoşani counties.

The farms identified as hotpots present very high/high vulnerability levels and very low/low preparedness levels, accounting for 16.3% of the total sample (Fig. 8C). The coldspots are defined by very low/low vulnerability levels and very high/high preparedness levels, representing 10.6% of the total analysed farms. Other notable combinations of drought vulnerability and preparedness levels are represented by the very low/low vulnerability and very low/low preparedness (2.11%), and the very high/high vulnerability and very high/high preparedness (18.41%).

To study the relationships between drought vulnerability and preparedness, and farm size, we performed a *t*-test on the farms designated as hotspots or coldspots and the farm sizes. The size of the hotspot farms is lower (with a mean of 0.12 livestock units) than the size of coldspot farms (0.4 livestock units), holding statistical significance. This result is in accordance with the negative correlation between the DVI and the farm size, as well as the positive correlation between the DPI and the farm size (Fig. 7).

Fig. 9C shows that coldspot farms are typically positioned close to large water sources (e.g., rivers or large ponds). In contrast, hotspot farms are located on slopes or interfluves, but some of them are close to water sources. This finding was validated during the fieldwork. Hotspots are widespread across the study area, displaying a higher density on both sides of the boundary between the Iaşi and Botoşani counties.

The spatial distribution of the drought vulnerability and preparedness levels against the farm size (Fig. 10) is also evocative of the relationships between these elements. All of the larger farms have very low to medium vulnerability levels, followed by medium to (mostly) very high preparedness levels. Such farms are primarily located close to water sources. Conversely, the smallest of farms present very high or high drought vulnerability levels, as well as very low or low preparedness levels. While larger farms tend to form groups along the eastern border of Romania (marked by the Prut River), as well as near the boundary between the Iaşi and Botoşani counties, livestock farms with fewer

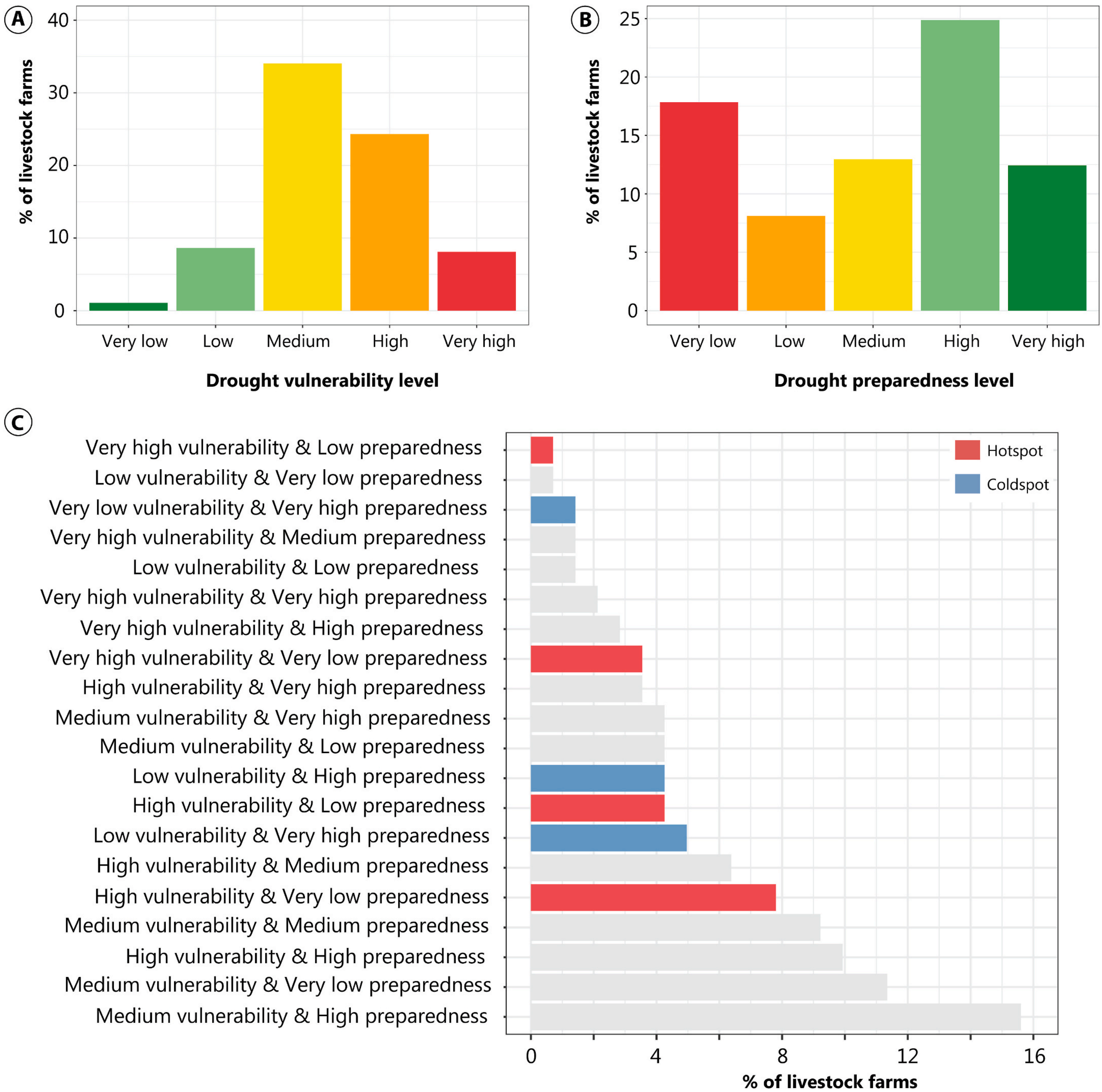

Fig. 8. The proportions of drought (A) vulnerability levels and (B) preparedness levels, and (C) their combinations. The terms "hotspot" and "coldspot" do not denote extreme cases, which could have been more effectively identified using standard deviation-based thresholds. Instead, they refer to the top 20% of livestock farms ranked by their level of drought vulnerability and preparedness.

livestock units group along the small or medium-length rivers in the study area (e.g., along the Jijia River) (Fig. 10).

5. Discussion

5.1. Downscaling drought vulnerability and preparedness

This study puts forward a downscaled approach to drought vulnerability and preparedness, tailored to the realities of the food system in northeast Romania (Fig. 2). This allows for an in-depth understanding of vulnerability at the local level, potentially highlighting the pitfalls of drought impact management in an area that lacks a cohesive mitigation strategy. Additionally, mapping drought vulnerability and preparedness levels enables the identification of spatial tendencies that may require corrective actions in order to build drought-resilient farming systems and communities. This section highlights key findings that inform actionable recommendations for enhancing drought impact mitigation.

In the northeast of Romania, drought vulnerability and preparedness vary significantly among farm sizes (Fig. 10), but not among geomorphological settings. There is a weak negative correlation between farm size and the DVI (−0.43) and a slightly stronger positive correlation between farm size and the Drought Preparedness Index (0.43). In other words, smaller farms tend to be more vulnerable to drought despite their lower exposure determined by lower numbers of livestock, compared to

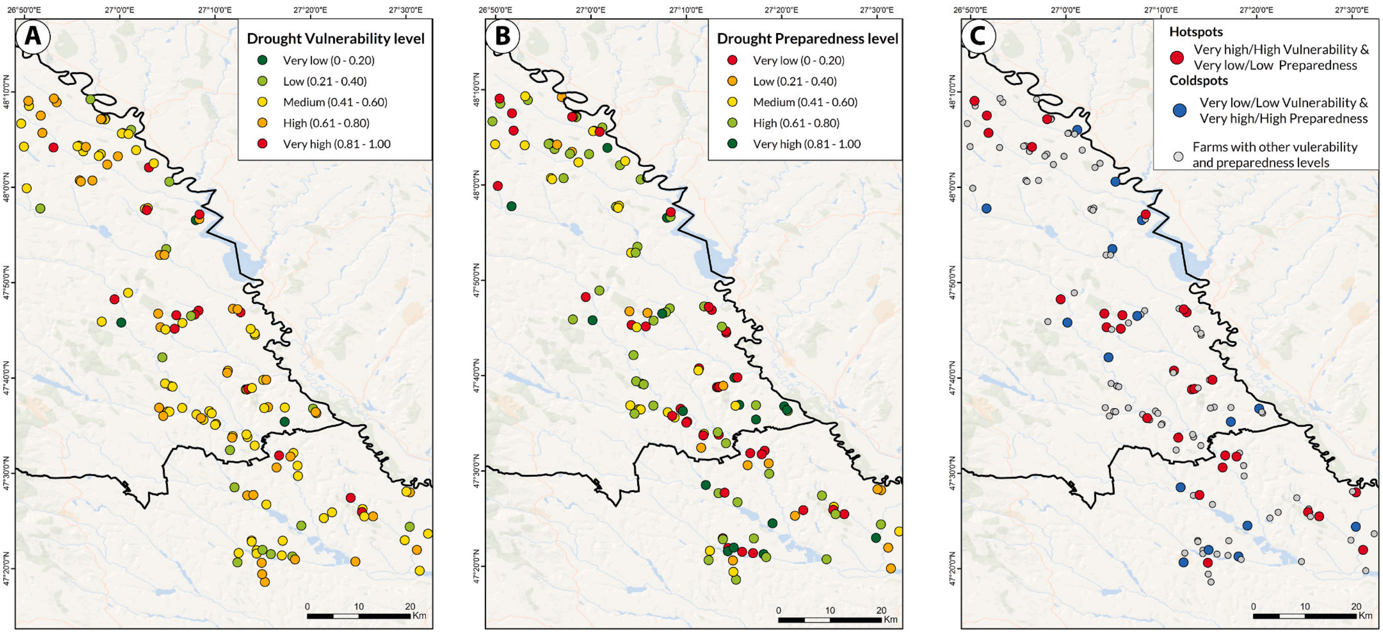

Fig. 9. The spatial distribution of (A) drought vulnerability levels, (B) drought preparedness levels, and of (C) the identified hotspots and coldspots. The terms "hotspot" and "coldspot" do not denote extreme cases, which could have been more effectively identified using standard deviation-based thresholds. Instead, they refer to the top 20% of livestock farms ranked by their level of drought vulnerability and preparedness.

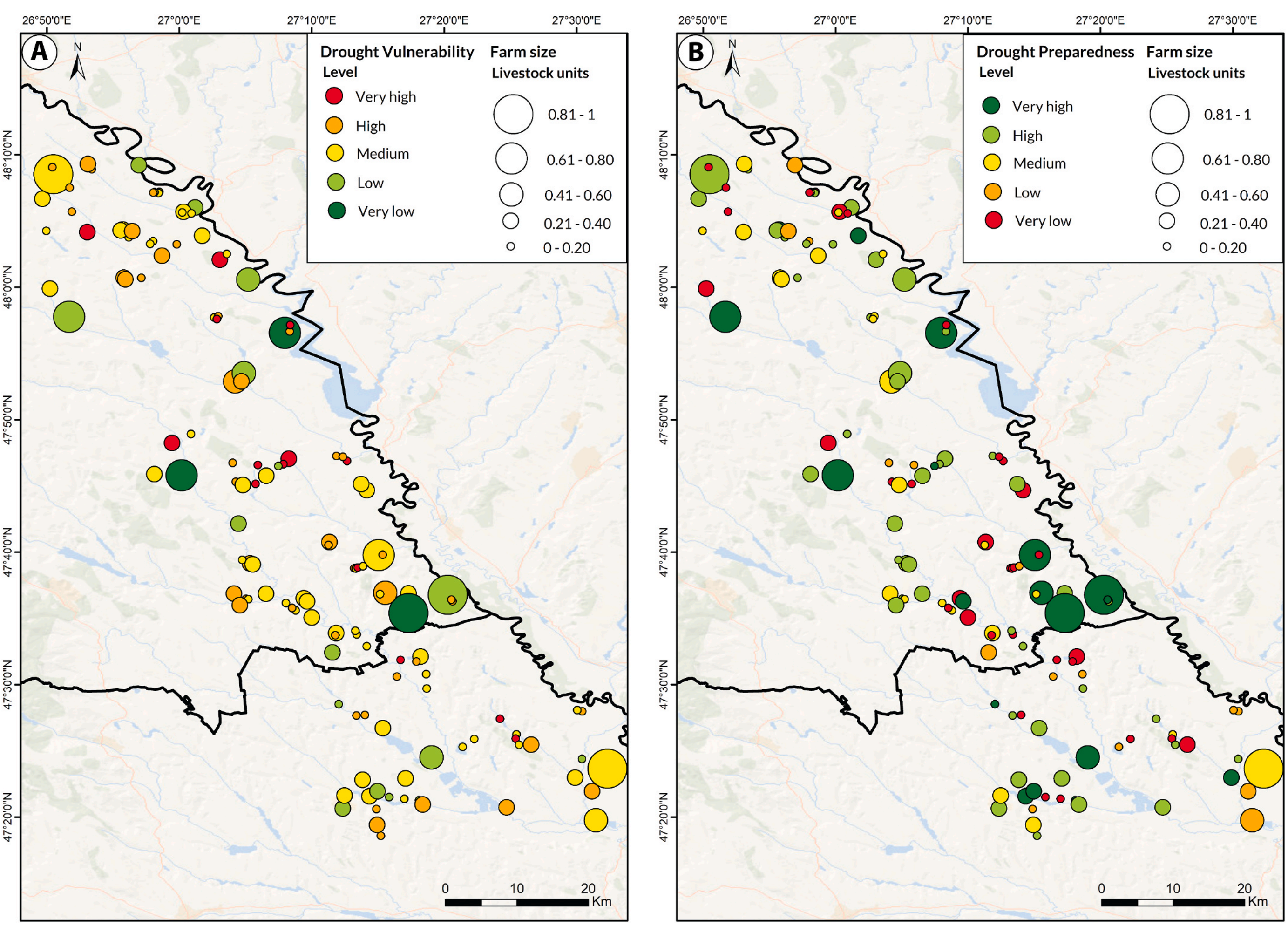

Fig. 10. The levels of drought (A) vulnerability and (B) preparedness mapped against farm sizes.

livestock farms with higher livestock unit values. On the other hand, smaller farms tend to be less prepared to face drought (Fig. 10), which may be explained by a lack of financial resources or even an absent or weak willingness to prepare. These findings are complemented by the statistically significant differences registered between the mean size of coldspot and hotspot farms, where coldspots have larger mean livestock unit values (0.4) than hotspots (0.12). Other important correlations between farm size and the level 2 indexes integrated into the DVI were also identified (Fig. 7). Larger farms tend to have more consistent fodder and financial reserves (0.53), to be managed by formally trained farmers (0.45), and to have increased access to water resources (0.35).

The close values of the medians of the DVI and DPI suggest an overall balance between drought vulnerability and preparedness in the study area, but a closer look at the distribution of these values by classes (Fig. 8A and B) indicates that most of the livestock farms present medium (34.1 % of the total) and high (24 %) vulnerability levels, as well as high (24.9 %) or very low (17.8 %) preparedness levels. The disparities become visually noticeable when examining the spatial distribution of vulnerability and preparedness levels: vulnerability to drought increases from South to North (Fig. 9A), while self-reported preparedness against drought shows no clear spatial tenedncy (Fig. 9B). Nevertheless, spatial autocorrelation of drought vulnerability or preparedness did not provide statitically significant results. This means that livestock farms with high vulnerability/preparedness are not necessarily located close to farms with the same vulnerability/preparedness levels.

Although there are more hotspot farms (16.3 % of the total farms) than coldspot ones (10.6 % of the total farms) (Fig. 8C), the small proportion of hotspots indicates that there are just a few livestock farms in need of support for drought impact mitigation. Hotspots are scattered across the study area, with grouping tendencies at the boundary between the Iaşi and Botoşani counties – potentially because of the long distance to the main cities which implies a certain degree of isolation and less infrastructure investments (Fig. 9C), while coldspots tend to be located close to water sources (e.g., main rivers, ponds).

5.2. Tailored recommendations for mitigating drought impacts

The findings regarding drought vulnerability and preparedness of livestock farms in the northeast of Romania can inform targeted interventions and adaptive strategies aiming to mitigate drought impacts. This goal requires a two-tier approach that should also be replicated in policymaking: vulnerability reduction and rapid response. While the first aims to reduce the severity of drought impacts before they happen, the latter reduces the severity of the impacts that already occurred.

Access to water resources that are vital to livestock farming varies in the study area. While some farms have reliable and sufficient water supplies (especially the coldspot farms, Fig. 9C), others face significant challenges in securing water supply during dry periods. Moreover, the availability of fodder and financial resources needed to withstand drought impacts varies across farms. Such disparities need to be specifically addressed by vulnerability reduction plans, aiming for equitable access to resources and also factoring in the particularities of the continental temperate climate. This can be achieved by.

- Developing cooperative networks to pool resources (e.g., fodder reserves, equipment) and reduce individual costs, particularly under bottom-up approaches;
- Setting up drought funds to help small farms prepare against drought impacts (e.g., by improving the infrastructure of their farm), especially in the rural, remote areas in the north of the study area;
- Ecouraging livestock farmers to secure customised insurance policies against drought;
- Encouraging diversified income streams to reduce reliance on livestock, especially among small farmers.

Particularly, access to water resources proves to be key in reducing vulnerability to droughts, given the high water demand for livestock herds and also the foreseen drying tendencies associated with climate change (Trenberth et al., 2014; Croitoru et al., 2018; IPCC, 2021). Water scarcity can lead to severe consequences, such as livestock dehydration, poor weight gain, reduced milk production, and even livestock deaths. As previously detailed, certain hotspot farms need targeted interventions to improve their access to water resources. Potential adaptive actions include.

- Developing shared water management systems in areas marked by water scarcity (such as the northernmost part of the study area), including water storage infrastructure;
- Building small-scale reservoirs or restoring/extending existing ponds (particularly at the border between the two counties of the study area);
- Setting up water-saving technologies, especially within remote or small farms across the study area;
- Improving the monitoring infrastructure of water supply and its quality (including river discharge and groundwater monitoring), doubled by an enhanced communication of the results to local communities;
- Dedicating special attention to research and monitoring of groundwater recharge trends, especially in the south of the study area, where recent studies found that the strength of the correlations among meteorological drought and its impacts on surfce and underground water resources decrease following a North-South direction (Minea and Albulescu, 2025)();
- Improving inter-institutional communication at the local scale;
- Improving communication between local authorities and water supply providers, especially during droughts;
- Educating farmers on efficient water management, including water rationing, reducing water consumption per livestock, acquiring funding for water-saving technologies;
- Increasing the share of drought-resistant fodder crops (especially in the southern part of the study area) which may be more suitable for this type of crops.

The absence of community-based initiatives to address drought challenges collectively leaves small farmers to face drought impacts alone, often with limited resources. In the absence of a cohesive drought impact management approach, stories of successfully addressing such impacts are scarce and also hard to replicate, given the variability of financial resources, farming-related educational background, access to basic infrastructure, etc. This isolation holds the potential to perpetuate vulnerability (in positive feedback loops, described by Albulescu and Armaş, 2024 related to other hazards but also potentially to drought) to the point where reinforced drought impacts threaten livestock farming livelihoods. A lack of community support also prevents the sharing of knowledge, resources, and best practices that could improve resilience at a collective level. This lack of community cohesion (that is itself a vulnerability) can be corrected by.

- Creating a regional or county-level drought task force involving farmers, local decision-makers, and scientists to coordinate policy design and implementation, monitor progress, and share best practices of drought impact management;
- Stimulating communication and collaboration among small and large farms by jointly applying for funding to extend water infrastructure, as part of bottom-up initiatives;
- Educating local communities on drought impact management and broadening the school curriculum to include subjects on (multi-)hazards, (multi-)risk, and their management (Mărgărint et al., 2023);
- Partnering with local universities or NGOs from the Iaşi or Suceava cities, to deliver workshops on climate-smart agriculture and drought early-warning systems (Adedeji et al., 2020) to the benefit of all farmers;

- Collectively negotiating loans and insurance with the support of authorities from the Iaşi and Botoşani counties;
- Establishing community-based communication platforms and knowledge-sharing platforms using social media.

All of these measures aim to reduce vulnerability, also promoting sustainable land and water management. Complementarily, effective response measures play a critical role in mitigating the immediate effects of drought once they occur. Such measures include.

- Providing rapid assistance (e.g., water deliveries, provision of emergency fodder) to affected farms by leveraging reserves established at the community level;
- Strengthening recommendations regarding the rational consumption of water during dry periods;
- Setting up financial support mechanisms, such as grants or subsidies in partnership with local authorities;
- Establishing drought response networks where farmers can share information and resources under downscaled approaches;
- Addressing livestock health concerns and protecting animal welfare with the help of subsidised veterinary assistance.

These recommendations may serve as entry points for elaborating future policies on drought impact management relevant for the study area and similar agro-pastoral areas across Europe (particularly where small-scale farming dominates). The proposed two-tier approach (i.e., vulnerability reduction and rapid drought response) can be transferred into national and even EU-wide drought policies by prioritising context-specific adaptation measures tailored to distinct farming systems. Given the disparities in water access and financial resources observed in this study, national drought strategies should emphasise targeted support for small farmers, including microgrants for water-saving technologies, regional fodder reserves, and customised drought insurance policies. These measures align with the EU's Farm to Fork Strategy (European Commission, 2020) and Common Agricultural Policy 2023–2027 (European Commission, 2022) by promoting climate-smart agriculture and equitable resource distribution.

To bridge insights gained at the local level with broader policy frameworks, we recommend establishing multi-level governance mechanisms that target the impacts and vulnerabilities identified at local scales. Such an approach should integrate vertical coordination (from EU/national to regional/local levels) with horizontal collaboration among stakeholders (e.g., local authorities, farmer associations, and water management agencies). This collaborative model improves both policy legitimacy and community engagement in implementation, thereby supporting compliance. Another aspect worthy of consideration is that decentralised decision-making structures can also enhance the agility of drought response mechanisms, allowing for more timely and context-specific interventions that are also accepted by the targetedc communities.

A final recommendation concerns the creation of a regional repository of drought hazard, vulnerability, and impact data. Such a resource would significantly enhance the capacity to conduct comprehensive risk assessments, which will serve as scientific grounding for the development of informed drought impact management policies. At present, the limited availability of reliable and accessible drought-related data constrains rigorous risk and vulnerability assessments. In the absence of comprehensive datasets, researchers are often compelled to collect drought data through surveys and similar methods; approaches that, while valuable, are time-intensive, context-dependent, and often lack the spatial and temporal consistency needed for broader-scale analysis and policy development.

5.3. Strengths

This study opens the way to addressing the research gap concerning the lack of investigations that comparatively analyse drought vulnerability and preparedness of livestock farmers in areas prone to drought and that are also marked by the technological divide between large and small farmers. This approach also reduces the gap between the numerous socio-hydrological studies that focus on floods and the ones that target drought (Vanelli et al., 2022). Furthermore, this study escapes certain shortcomings of other drought vulnerability studies signalled by Hagenlocher et al. (2019) by specifying elements that are usually left out: the type of drought hazard it refers to (i.e., agricultural drought), a clear definition of the main concepts (i.e., vulnerability and preparedness), and the weighting methods of the level 2 indexes.

Most drought vulnerability studies published between 2002 and 2014 focus on Asian regions (especially India and China) (González Tánago et al., 2016), while the larger part of research works on drought perception focus on regions from Africa (Slegers, 2008; Bahta et al., 2016; Tora et al., 2021a, 2021b; Lottering et al., 2023) or South Asia (Ashraf and Routray, 2013; Sam et al., 2020; Masroor et al., 2023). At the moment, drought vulnerability is not sufficiently studied in Europe, as there are few studies with this focus (De Stefano et al., 2015; González Tánago et al., 2016; Dumitraşcu et al., 2018). Also, there is only one study that addresses drought vulnerability in Romania, targeting only its socio-economic dimension (Dumitraşcu et al., 2018). Therefore, this paper extends our understanding of drought vulnerability, holding significant relevance for future drought risk analysis and management and water management. The significance of the findings is highlighted by forecasted increases in both drought frequency and intensity (Spinoni et al., 2015, 2018), alongside the powerful impact of this hazard on agriculture (Stahl et al., 2016).

The practical achievements of this research work refer to the actionable points that can be derived from analysing the spatial distribution of drought vulnerability alongside self-reported preparedness across livestock farms in the study area. Small farms, generally presenting higher vulnerability and lower preparedness to drought, would benefit from investments in water infrastructure and technology aimed at improving water accessibility and management, and from the diversification of water sources. Considering that deficient financial support partially explains the unavailability of water resources in the study area and not only, implementing such solutions at the individual level is challenging, leading to a vicious circle of underfunding and inconsistent development. This means that authorities should provide substantial support to livestock farms in the northeast of Romania, initiating a top-down development of water infrastructure, as relying solely on grassroots efforts proves impractical, especially due to the scarcity of community initiatives targeting drought impact mitigation.

Another development avenue regards the setting aside of (financial) resources (both at the individual and collective levels) to be used in times of crises induced by drought. This proactive approach is key to the construction of a safety net for livestock farmers, also having the benefit of fostering sustainability. To support livestock farmers, local and regional authorities can set up financial assistance initiatives, which can take the form of loans, customised insurance, or other types of financial aid. Furthermore, beneficial programmes should focus on providing climate-smart agriculture training to farmers with weak formal farming education, in the endeavour to increase their preparedness, productivity, and autonomy, bridge the digital gap between small and large farms, and educate people about sustainable farming practices.

These examples highlight the benefits of downscaled approaches to drought vulnerability and preparedness, which offer nuanced insights that can support decision-making at various spatial scales. This granular perspective on vulnerability enables more targeted interventions, while the programmes aimed at increasing preparedness against drought should be implemented following a top-down approach. Going even further, drought vulnerability research would greatly benefit from studies on the vulnerabilities acknowledged and addressed by relevant stakeholders, as such studies are scarce in Romania (Armaş et al., 2025).

5.4. Limitations and constraints

A proper interpretation of the presented scientific findings is only possible by acknowledging and explaining the limitations of this study. At the conceptual level, the limitation of estimating drought preparedness in a broad sense leaves room for more focused analyses of the specific adaptive strategies implemented by livestock farmers. Nevertheless, by encompassing both the objective and subjective dimensions of drought preparedness, the DPI addresses various facets of preparedness. The ratio of 75:25 favouring objective preparedness over perceived preparedness was derived from repeated expert consultations conducted during fieldwork, though potential biases in the weighting process may persist.

The reliance on a non-standardised questionnaire (missing psychometric validation) represents a major limitation. Also, the questionnaire does not consider temporal variability, which imprints the research with a static temporal scope that does not allow for inferences regarding long-term drought vulnerability and preparedness patterns or tendencies. The survey does not refer to a specific drought event (but to drought and its impacts perceived in the last 5 years, meaning 2018-2023) and it also consideres drought as a single event - missing the opportunity of analaysing drought vulnerability dynamics (Albulescu and Armaş, 2024) or compounded impacts (Albulescu, 2023) in relation to co-occurrent or sequential hazards.

The relatively small size of the sample stands out as an inherent constraint specific to most scientific undertakings, implying that the findings are only generalisable to some livestock farmers in the local food system. This was compensated by selecting the surveyed farmers with the help of local authorities, who pointed out the most representative individuals in charge of livestock farms.

The non-representativeness (and small size) of the sample precludes the implementation of more advanced methodologies, such as multivariate regression or structural equations to identify the relative influence of different factors considered in the computation of the DVI and DPI. These sample limitations similarly constrain spatial analytical approaches. While basic geospatial techniques can be implemented, more advanced methodologies cannot be reliably performed. This restriction potentially masks important place-based variations in vulnerability and preparedness tendencies. This limits the credibility of the identified spatial tendencies presented in section 4.4 and partially explains why pattern identification using spatial autocorrelation (Moran I) was not viable. Future research agenda includes expanding both the scope and scale of sampling to permit the implementation of more robust analytical approaches.

Another methodological limitation refers to the normalisation biases, as the min-max scaling approach assumes linearity in the relationship between level 1 and level 2 index values and their normalised scores. While normalisation ensures comparability across level 1 and level 2 indexes, it can blur extreme values or dilute contextual differences in how individual level 2 indexes contribute to overall vulnerability (level 1). For instance, the equal weighting of normalised level 2 indexes (composing the DVI) may overlook the disproportionate influence of certain indexes (e.g., water access vs. farming diversity) in specific geographic settings. Additionally, normalisation relies on the observed range of values within the sample, making results sensitive to outliers. Although expert judgement helped refine the level 2 indexes selection, the aggregation of normalised scores can still introduce biases by flattening variability that is worthy of consideration when designing downscaled drought mitigation measures.

These limitations introduce several inherent uncertainties. First, the reliance on downscaled, self-reported survey data introduces measurement uncertainty, as farmers' perceptions of drought vulnerability and preparedness may not fully align with objective conditions. Second, the selection and aggregation of level 2 indexes, though informed by expert knowledge, involve inherent subjectivity, particularly in assigning equal weights to DVI components despite potential variations in their actual influence. Third, the normalisation and additive aggregation of level 2 indexes may oversimplify the complex interactions among environmental and socio-economic factors in the study area. While fieldwork and expert input addressed (to a certain extent) part of these biases, the mentioned uncertainties highlight the need for caution in interpreting and generalising the results.

The transferability of this methodology to other EU regions presents both opportunities and conceptual challenges. The survey items and level 2 indexes integrated into the DVI and DPI (Appendix 1) are tailored to the livestock farming system, which is also encountered in other regions in Europe and around the world. While the index-based framework is structurally portable, the questions and indices should be adapted to other agricultural systems. Therefore, this study reveals an often-overlooked aspect: vulnerability assessment methods themselves must demonstrate adaptive capacity when transfered across EU farming contexts. For instance, scientific investigations of drought vulnerability and preparedness related to crop farming can include level 2 indexes related to irrigation extent and efficiency, crop diversification, and the use of drought-resistant seeds. For other systems, such as Mediterranean olive farming systems, potential drought vulnerability level 2 indexes may refer to traditional water harvesting infrastructure (e.g., cisterns), transgenerational knowledge transfer, and the functional status of communal water channels. This flexibility underscores the framework's potential for broader application, provided future studies validate and refine level 2 indexes for distinct farming systems and climatic regions.

6. Conclusions

Drought recurrently affects both natural and social systems, positioning the study of drought risk adn vulnerability among global priorities for climate adaptation, especially considering drought impact management in farming and food sectors and its transformative power over landscapes and livelihoods. While Europe's drought research has long focused on arable systems, this study is a noteworthy addition to the existing knowledge on drought vulnerability as it addresses livestock farming, a sector that remains relatively underexplored in both scientific literature and public discourse. The impact of drought on livestock farms, alongside their vulnerability and preparedness, has received little attention in the literature or the media, being overshadowed by the more prominent crop farming sector. To shed light on this topic, we selected the northeast of Romania as one of the most representative study areas for livestock farming in Europe.

The study employed spatial and statistical analyses based on context-specific data collected through a questionnaire, which is adaptable to other agricultural contexts. This approach allows for a nuanced estimation of farm-level drought vulnerability and preparedness, revealing aspects with broader implications for drought impact management. The main findings of this exploratory study were:

- A notable disparity in drought vulnerability and preparedness between farm sizes, with small farms presenting higher drought vulnerability due to constrained access to water, infrastructure, and financial reserves.
- Cross-correlations point out that the farming educational background, availability of fodder and financial reserves, access to basic infrastructure and water play prominent roles in shaping both drought vulnerability and preparedness. This underscores the important role of farmers' education in reducing vulnerability, complementing the traditional focus on physical resources.
- Drought vulnerability negativelly correlates with self-reported preparedness, warranting further investigation.
- There were no statistically significant spatial clusters of drought vulnerability or preparedness in the study area. Therefore, these represent just preliminary results that will inform further research and the collection of larger samples to support a more robust analystical approach.

These findings carry important implications for drought impact management policy in Romania and across the EU. Current strategies, largely designed around crop-based systems, should be expanded to integrate livestock-specific measures. They can inform contextually relevant drought impact management plans under a two-tier approach that include measures aiming to reduce drought vulnerability and also to strenghten drought response. The variation of drought vulnerability and preparedness across farm sizes imposes challenges to drought impact mitigation, requiring supplementary efforts to close diverse gaps between small and large livestock farms. Such inequalities are not unique to Romania but can be observed in other European countries severely impacted by drought in recent times (e.g., Italy, Greece, Spain, France, etc.).

Further research should aim to explore how livestock farmers perceive drought risk and how traditional or education-derived knowledge informs specific adaptive practices. Such insights will complement the preliminary findings put forward in this study, providing a more solid foundation for building drought resilience in the northeast Romania and other food systems centred on livestock farming across the EU.

CRediT authorship contribution statement

Andra-Cosmina Albulescu: Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software. **Mihai-Ciprian Mărgărint:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Investigation, Funding acquisition, Data curation, Conceptualization. **Mihai Niculiță:** Validation, Resources, Investigation, Data curation. **Jianshuang Wu:** Validation, Investigation, Data curation. **Daniela Larion:** Writing – review & editing, Investigation. **Paolo Tarolli:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

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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This manuscript reflects only the authors' views and opinions; neither the European Union nor the European Commission can be considered responsible for them.

Appendix 1. Details on the computation of the level 2 indexes included in the *Drought* Vulnerability and Preparedness Indexes (level 1)

Index (Level 1)	Index (Level 2)	Item (Level 3)	Questions used to construct the items or level 2 indexes	Answers	Points	Type of answer selection
Drought Vulnerability Index	Access to water resources (AW)	Location in proximity of an unrestricted water source	Is your farm located in the proximity of an unrestricted water source?	Yes	1	Single answer
				No	0	
		Source(s) of water	Where does the water utilised in your farm come from?	Local springs	1	Multiple answers
				Ponds	1	
				Wells	1	
				Rivers	1	
				Public water network	1	
				Other	1	
	Basic infrastructure (BI)	Connection to the public water supply network	Is your farm connected to the public water network?	Permanently	1	Single answer
				During the warm season	0.6	
				During the cold season	0.3	
				No	0	
		Connection to the public sewage network	Is your farm connected to the public sewage network?	Permanently	1	Single answer
				During the warm season	0.6	
				During the cold season	0.3	
				No	0	
		Investments to improve water management	Did your farm benefited from investments in improvements in water management during the last 10 years?	Yes	1	Single answer
				No	0	
	Availability of reserves (AR)	Days covered by animal food reserves (cold season)	How many days are covered in terms of animal food reserves during the hot season (including drought periods)?	Open answer	Normalisation	Single answer
		Availability of financial reserves	Do you dispose of financial reserves to be used during potential droughts?	Yes	1	Single answer
				Partially	0.5	
				No	0	
	Networking level (N)	Business for processing/selling farm produce	Do you have your own (family) business for processing/selling the produce obtained within your farm?	Yes	1	Single answer
				In an incipient form	0.5	
				No	0	

(continued on next page)

(*continued*)

Index (Level 1)	Index (Level 2)	Item (Level 3)	Questions used to construct the items or level 2 indexes	Answers	Points	Type of answer selection
		Part of a group processing/selling farm produce	Are you involved in a group for processing/selling the produce obtained within your farm?	Yes In an incipient form No	1 0.5 0	Single answer
		Consideration to be part of a processing/selling group	Do you consider to get involved in a group for processing/selling the produce obtained within your farm?	I already am Yes No I don't know	1 0.75 0 Not included	Single answer
	Farming educational background (FB)	Formal education on farming	Were you enrolled in the following educational programmes?	Farming-specialised highschool Farming-specialised vocational education Farming-specialised faculty Faculty of Veterinary Medicine Faculty of Agriculture and Economics Farming-related grad school	1 1 1 1 1 1	Multiple answers
	Farming experience (FE)	Years of farming experience	How many years of farming experience do you have?	Open answer	Normalisation	Single answer
	Diversity of farming activities (FD)	Other farming activities besides livestock farming	Does your livestock farm also include farming activities like the following?	Regular crops Fodder crops Technical crops Poultry farming Swine farming Vegetable farming Orchard farming Vineyard farming Fish farming Beekeeping Other	1 1 1 1 1 1 1 1 1 1 1	Multiple answers
Drought Preparedness Index	Objective drought preparedness (OP)	Implementation of preparedness measures in the last year at the farm level	In the last year, have you implemented drought preparedness measures within your farm?	Yes No I don't know	1 0 Not included	Single answer
		Specific actionable plan to mitigate the effects of drought at the farm level	Do you have a concrete plan of action to mitigate the effects of drought within your farm?	Yes, in detail Yes Partially No	1 0.6 0.3 0	Single answer
	Perceived drought preparedness (PP)	Self-assessed level of preparedness against drought	How well prepared do you consider your farm to be when it comes to droughts?	Likert scale	1 to 5	Single answer
		Self-assessed level of preparedness against drought, compared to the last 5–10 years	How well prepared do you consider your farm to be when it comes to droughts, compared to 5–10 years ago?	Likert scale	1 to 5	Single answer

Data availability

Data will be made available on request.

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