Agricultural Systems 208 (2023) 103647

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Climate change-induced aridity is affecting agriculture in Northeast Italy

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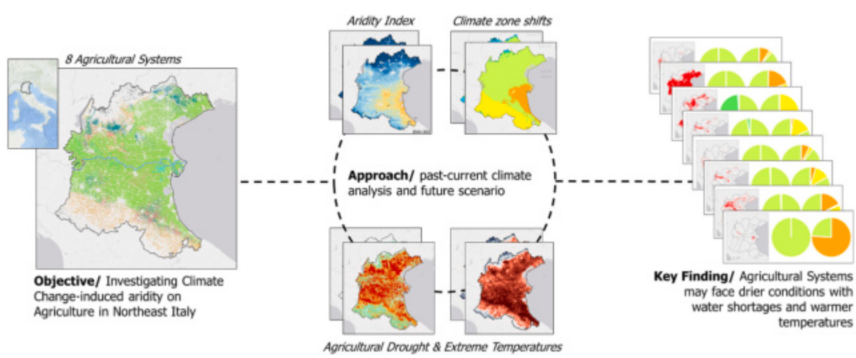
HIGHLIGHTS

- Northeast Italy is a key agricultural area for food production threatened by climate change.
- Drought and high temperatures are major hazards to agriculture in the area (significant was the summer 2022)
- Climate projections indicate Arid zones in the future, consistent with trends observed in recent decades
- Rice fields and irrigated arable land (70% of the surface) will be the most affected systems by the climate shift
- Mapping of areas/systems at risk of climate change is useful for planning resilient agricultural management

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Guillaume Martin

Keywords:
Climate change
Italy
Agriculture
Aridity
Remote sensing

ABSTRACT

CONTEXT*:* The Mediterranean basin and specifically Northeast Italy are recognised as climate change hotspots. The latter is a key socio-economic area in Europe among the most agriculturally productive. However, increasingly frequent drought periods (typical of drier climates) are threatening agriculture. An extreme event occurred in the summer of 2022. It dramatically affected northern Italy, through high temperatures, water shortages and indirect processes (such as saltwater intrusion in the Po River Delta).
OBJECTIVE: The objective is to map and quantify the agricultural areas in Northeast Italy at risk of climate zone shift due to human-induced climate change, providing a comprehensive overview of the main threatened agricultural systems and supporting the use of projections through historical data analysis.
METHODS: We compared the distribution of current (1980 > 2016) and future (2071 > 2100; RCP8.5 scenario) climate zones for 8 main agricultural systems in 14 key provinces in Northeast Italy. Further analyses were performed on historical data to support future climate projections and to analyse agricultural drought during extreme events: (1) a multi-temporal Aridity Index (AI) to investigate aridification dynamics; (2) a focus on the 2022 event (drought and temperature extremes, a situation that is likely to occur more often in the future), combining a Vegetation Health Index (VHI) with a zonal investigation of high Land Surface Temperature (LST); (3) a climate focus for the Po River Delta cultural landscape.
RESULTS AND CONCLUSIONS*:* The results show that the climate in Northeast Italy is evolving towards drier conditions, posing a challenge to agriculture. The Adriatic coast could become an Arid zone, a finding in line with historical observations. Rice fields will be most at risk (76% of their surface could become Arid in the future), as well as the irrigated lands that are essential for food security (around 20% expected in the Arid zone). Worthy is

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https://doi.org/10.1016/j.agsy.2023.103647
Received 7 December 2022; Received in revised form 23 March 2023; Accepted 27 March 2023
Available online 5 April 2023

what is foreseen for crops on slopes (often not irrigated), which may experience drier summers (60% of the surface).

SIGNIFICANCE: We identified the areas at risk of climate change at the farm scale in Northeast Italy, mapping where the threatened fields are located, what their extent is, and which agricultural systems are currently implemented. Such information would facilitate early action, guiding large-scale planning towards more resilient agriculture. Findings could promote sustainable water management plans, open the debate on which crops are worth growing based on future climate, and inspire more localised studies in the design of mitigation measures.

1. Introduction

The world is experiencing climate change in recent decades (Abbass et al., 2022). Remarkable is the role of CO_2 emissions into the atmosphere (IPCC, 2021; Al-Ghussain, 2019). The increase in global mean surface temperature (GMST) and global surface air temperature (GSAT) is alarming. Looking at the anomaly trends, studies show that the temperature is tending to rise on Earth, from land to ocean (Sánchez-Lugo et al., 2021), with effects on water cycle (Milly et al., 2002; Vermeer and Rahmstorf, 2009; Allan et al., 2020). Global warming alters atmospheric circulation patterns and exacerbates the severity of droughts (IPCC, 2021), with more frequent events with combined dry and hot conditions (Feng et al., 2020). It is a major climate change-related natural hazard (Stagge et al., 2015). Several intense episodes were recently recorded. Examples occurred in East Africa (OCHA - UN Office for the Coordination of Humanitarian Affairs, 2011), Chile (Muñoz et al., 2020), North America (Mann and Gleick, 2015), and Europe (JRC Global Drought Observatory, 2022a; 2022b). Drought impacts the environment, such as ecosystems (van der Molen et al., 2011; Ahmed et al., 2020), forests (Doughty et al., 2015; Klos et al., 2009) and wetlands/peatlands (Stirling et al., 2020). Serious influences also occur on societies. It is among the main causes of migration (Hermans and McLeman, 2021). It affects many sectors, such as energy (Wan et al., 2021), tourism (Wilhite et al., 2007) and navigation (Nouasse et al., 2015). However, agriculture is among the most at risk (Cammalleri et al., 2020). When drought makes water resources in the soil insufficient to meet crop needs, it is referred to as 'agricultural drought'. This can occur due to a lack of precipitation and high temperatures that accelerate evapotranspiration (Wilhelmi and Wilhite, 2002). High Land Surface Temperatures (LST) often indicate deficient soil moisture and high heat stress (Karnieli et al., 2010). The consequences of the combined phenomena are serious for rural regions, which may experience decreases in production with consequences for food security. Furthermore, it can compromise the identity of cultural landscapes, especially when agriculture is practised according to traditional knowledge.

The impacts of climate change are often amplified at the local scale (Lehner and Stocker, 2015; Seneviratne et al., 2016). The increasing frequency of droughts is expanding drylands in the world (Cherlet et al., 2018), and the Mediterranean basin is a related hotspot. Giorgi (2006) shows a progressive decrease in mean precipitation for the region and an increase in rainfall variability during the dry season. Summer climate variations are the main contributors to aridification, a worrying phenomenon that is occurring more here than anywhere else on the planet (Allen and Ingram, 2002; Seager et al., 2014). This is also confirmed by Tuel and Eltahir (2020). Climatic variations towards arid conditions lead to considerable environmental imbalances, altering a delicate balance that puts territorial uniqueness at risk (Tomozeiu et al., 2014). Severe effects of aridification are often observed along the seacoast. Examples are in Spain (Miró et al., 2006), Greece (Morianou et al., 2018), and Israel (Yosef et al., 2019). Aridity could be compounded by other effects of climate change, such as sea level rise (Cazenave and Llovel, 2010), increased frequency of flooding (Schiermeier, 2018), salinisation of water resources (Colombani et al., 2016), alteration of river flows (Vineis et al., 2011) and erosion (Toimil et al., 2020). The direct and indirect consequences of aridity are reflected in plant germination, as shown by studies conducted in Spain and Italy in the Po Delta (Estrelles et al., 2015), with potential consequences on crops.

Northeast Italy is among the most industrialised and agriculturally productive regions in Europe (European Union, 2021). In recent years, it was one of the Italian areas mainly affected by drought (Caloiero et al., 2021). In 2022, particularly during the summer season, an extreme event took place in Italy, characterised by record-high temperatures and several months of insufficient rainfall. The Po River basin, its Delta, and much of Northern Italy were deeply affected (Toreti et al., 2022). Po River suffered a drastic reduction in its flow rate (which reached a discharge lower than the threshold of 450 m^3s^{-1} indicated for guaranteeing its ecological function; Autorità di Bacino Distrettuale del Fiume Po, 2022), with the occurrence of an extreme process of saltwater intrusion inland for >40 km (Tarolli et al., 2023). Drought caused severe damage to agriculture, which in some areas resulted in the total loss of production (e.g. rice yield dropped by >30%; Coldiretti, 2022). The period assumed a strong symbolic value on the issue of climate change, drawing the attention of society and the international media. Therefore, the scientific community has the responsibility to enrich the debate on what is happening in the region, assess local implications and lay the groundwork for sustainable mitigation strategies.

Past-current-future climate analyses are essential to identify climate change traces towards drier conditions and to assess impacts on agriculture. Interesting is the application of an aridity index (AI). It provides a quantification of the gap between rainfall and water demand (Salvati et al., 2013). For example, FAO proposes a version of the index at a global scale useful for desertification dynamics investigation (FAO, 2022). Other authors applied it at different spatial scales, such as in China (Liu et al., 2013), Greece (Nastos et al., 2013) and Iran (Bannayan et al., 2010). Drought indexes and their evolution over time are also commonly used for large-scale studies. For example, meteorological (such as the NOAA Drought Index - NDI) or remote sensing-indexes (such as the Vegetation Health Index; VHI) can be used to assess agricultural drought (WMO, 2016). At a more detailed scale, climate change traces can be identified using weather station data. Examples at the regional level could be found in Spain (Moral et al., 2016), Romania (Prăvălie and Bandoc, 2015) and Italy (CMCC, 2022a; 2022b). Climate projections could be used for future climate zone analysis. Related algorithms often work at a global level and are then scaled on specific locations. In Europe, a widely used climate model is the COSMO-CLM (Rockel and Geyer, 2008). It was successfully applied for Italy over the period 1971–2100 using the IPCC RCP4.5 and RCP8.5 scenarios (Bucchignani et al., 2016). Other authors propose a combination of different models. Among the most high-resolution product is the one proposed by Beck et al. (2018), which assembles 32 climate models to assess the distribution of future climate zones according to RCP8.5 (or without the adoption of climate mitigation policies). Future climate maps, although characterised by inherent errors, offer valuable information for defining the areas most affected by climate change, assessing potential impacts, and anticipating protective measures.

Previous research investigated climate change impacts on agriculture in Northern Italy. For instance, some studies compare current and future climatic conditions to evaluate the water balance in a small catchment on the Adriatic Sea (Mollema et al., 2012). Other studies focus on more agronomic aspects, such as the variation of specific crop yields and related water footprint (Bocchiola et al., 2013). However, to the best of our knowledge, there is no high-resolution quantification of the agricultural areas affected by shifting climate zones in Northeast Italy. Therefore, our research aims to bridge this gap by comparing current agricultural systems with present and future climate maps for the area of interest. To do this, the 1-km resolution Köppen-Geiger climate zone maps proposed by Beck et al. (2018) are used, supported by further analyses based on historical climate data. Specifically, (1) to assess potential evolution towards arid conditions by the application of a multi-temporal aridity index over time; (2) to investigate the agricultural drought that occurred in the summer of 2022 by combining the VHI index and the LST; (3) to provide a local-scale analysis of temperature/precipitation trends recorded by the network of regional meteorological stations for the Po River Delta cultural landscape. The results could help to map and quantify agriculture at risk due to climate change by detailing the main agricultural systems currently present in the area. The shift towards drier and warmer climate zones could challenge agriculture in the area, largely characterised by irrigated arable land and essential for national food security.

2. Material and methods

2.1. Study area

The investigated area is in Northern Italy (see Fig. 1). It is centred on the Po River Delta, stretches 260 km along the Adriatic coastline, and covers a surface of 33,534 km^2. A large part is lowlands (around 70%), while the remainder is hilly and mountainous (such as the Pre-Alps in the north and the Apennine chain in the south). The area matches 14 Italian provinces (Venice, Treviso, Padua, Rovigo, Vicenza, Verona, Ferrara, Ravenna, Forlì-Cesena, Rimini, Bologna, Modena, Reggio Emilia, and Mantua) covering three regions (Veneto, Emilia-Romagna and Lombardy). According to ISTAT (2022), in January 2022 around 8,750,000 people lived in this zone (15% of Italian residents). The Po Valley occupies a significant part of the study area. Its flat morphology and direct access to the sea have guaranteed these regions an important anthropic development for millennia. The landscape has been profoundly shaped by agriculture, a core activity in the region (Pijl and Tarolli, 2022). The area is rich in history and home to some important cities of art (e.g. Venice or Bologna), as well as protected sites. For instance, sites along the Adriatic coast are shown in Fig. 1 (c,d,e), that host at least two UNESCO locations ('Venice and its Lagoon' and 'Ferrara, City of the Renaissance, and its Po Delta'), regional parks (such as the Po Delta Park in Veneto and Emilia-Romagna) and Natura 2000 sites (Parco Delta del Po Emilia Romagna, 2022; UNESCO, 2022a; 2022b). The Po River Delta is one of Europe's main wetlands and a key water source for agriculture (Gaglio et al., 2017). It is also a cultural landscape with a strong traditional rural character. Cultivation has been practised for centuries thanks to important hydraulic works (primarily the so-called "Taglio di Porto Viro" carried out in 1604 by the Republic of Venice) and land reclamation. Today, agriculture and fishing are among the main economic activities. The territory analysed is therefore characterised by a delicate man-nature balance, where the pressure of climate change could have irreparable consequences on its very identity.

2.2. Agriculture

Data about agriculture was obtained from the up-to-date open-access data of the Veneto (Regione Veneto, 2020), Emilia-Romagna (Regione Emilia-Romagna, 2020) and Lombardy (Regione Lombardia, 2018) regions. They were homogenised into a single information layer related to 'Agriculture' (Fig. 2). It consists of 186,350 polygons covering a total surface of 18,727 km^2 (about 56% of the entire area). For the convenience of the reader, each analysis in this paper was expressed in percentage. Eight main agricultural classes were defined. "Irrigated arable lands" is the most common (70%) and is mainly distributed in the flat portion of the Po Valley. It consists of irrigated fields delimited by drainage ditches, regularly ploughed and under crop rotation. They are

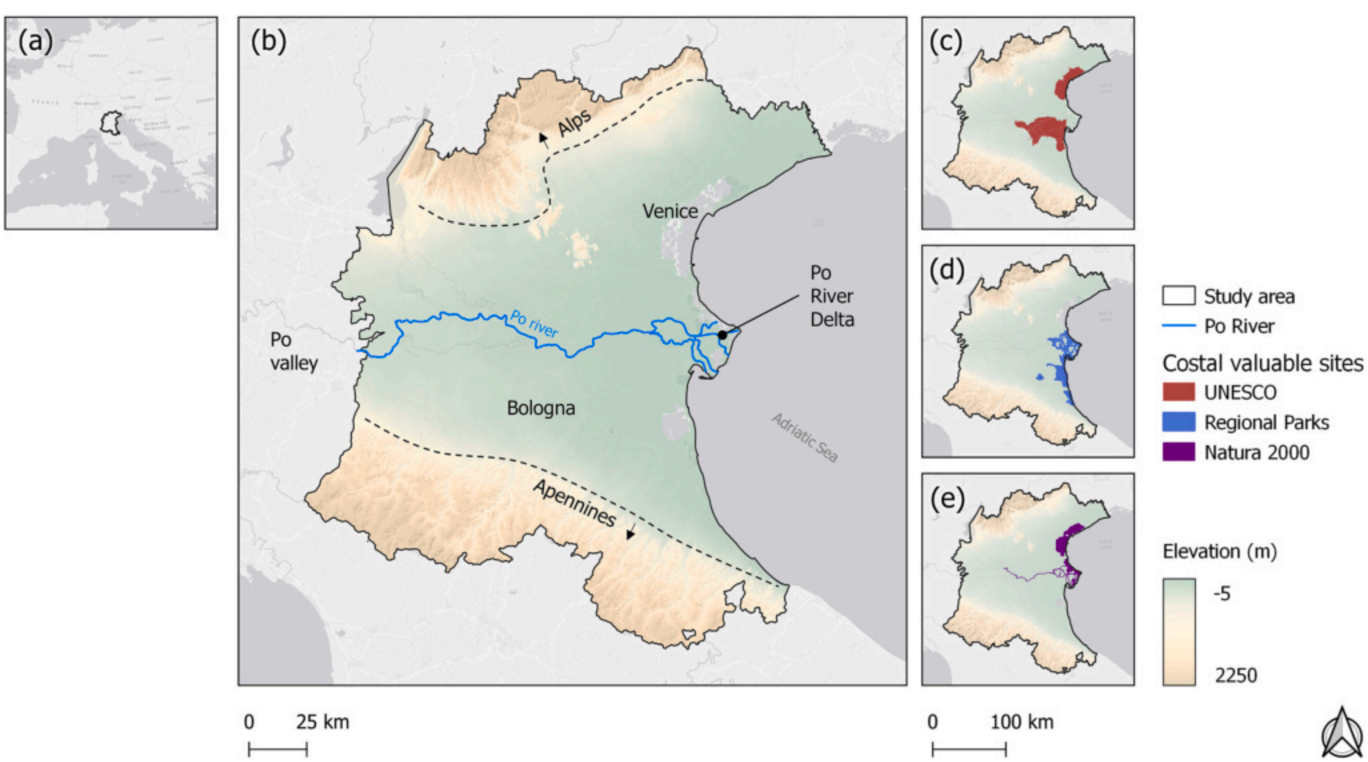


Fig. 1. (a) The study area covers 14 provinces in northern Italy. It is crossed by the Po River, which flows eastwards into the Adriatic Sea, where its Delta is located. (b) Elevation ranges from −5 m asl (in reclaimed coastal areas) to over 2200 m asl in the Alps. The central part is occupied by the Po Valley, to the north are the Alps and to the south the Apennines. (c), (d) and (e) illustrate the location of some sites of particular natural and social importance (UNESCO site, Regional parks and Natura 2000 sites, respectively). [color].

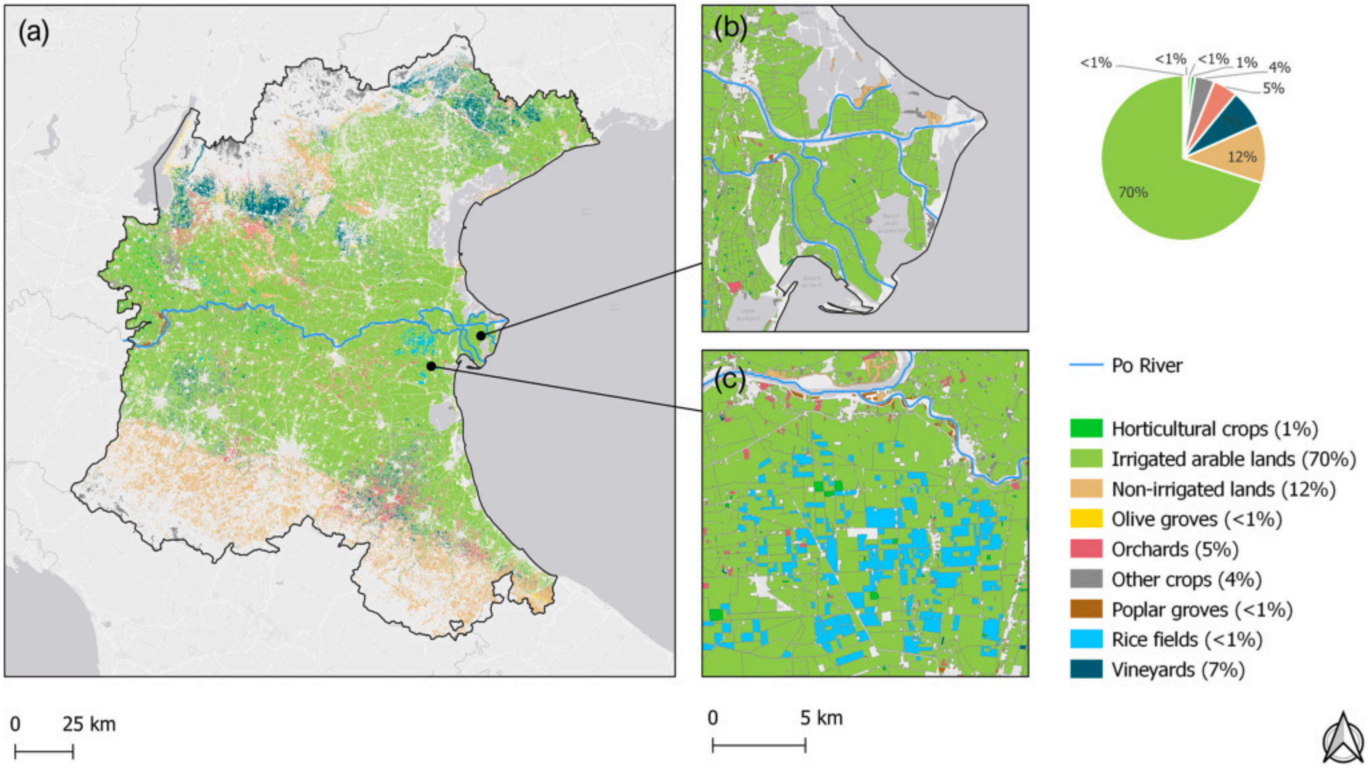


Fig. 2. (a) The distribution of agricultural fields. A large part of the surface is occupied by irrigated arable land (mainly in lowlands); (b) Enlargement in the Po River Delta; (c) Enlargement on rice fields along the Adriatic coast. [color].

mainly devoted to the herbaceous cultivation of cereals and legumes, such as soybean, sugar beet, wheat, and alfalfa. The second class includes fields cultivated with similar crops but on non-irrigated land ("Non-irrigated arable lands"). They are mainly concentrated on slopes, such as the hilly regions to the north and the Apennine belt to the south. Most vineyards are also located in such areas ("Vineyard"). Valuable wine-growing territories are for example the Globally Important Agricultural Heritage Systems (FAO-GIAHS) site of Soave (Verona province), the UNESCO World Heritage site of the Conegliano Valdobbiadene hills (Treviso province) or the hilly regions between Bologna and Rimini. Other classes analysed are "orchards", i.e. tree plantations for fruit production, distributed fairly homogeneously throughout the study area; "poplar groves", mainly located along the Po river; "horticultural crops", mainly distributed in the plain; "Rice fields", primarily in the Po River Delta and in the Mantuan province. An additional class called "Other crops" was then reported in Fig. 2 but not investigated. It includes some non-homogeneous minority crops in terms of occupied surface (together does not exceed 4%). The availability of fresh water is crucial for the survival of the sector. Possible aridification of the climate is consequently a primary threat to the entire human-nature system.

2.3. Climate

2.3.1. Aridity Index (AI)

A multi-temporal aridity index (AI) was applied to identify possible evolutions of aridity-like climate patterns. Two periods were considered (2010>2021 and 2001>2009, depending on the availability of historical data). We select the aridity index ($AI_{FAO\text{-}UNEP}$) proposed by the FAO in the United Nations Environment Programme (UNEP). It is considered an effective scientific tool for investigating the evolution of drylands worldwide (Salvati et al., 2013). It measures aridity by comparing the long-term average of water supply (precipitation, P) with the long-term average of climatic water demand (potential evapotranspiration, PET). Its formulation is reported in the next Eq. 1 (EU Joint Research Center, 2022).

$$AI_{FAO-UNEP} = \frac{\sum_{i-1}^{n}\left(\frac{P_i}{PET_i}\right)}{n} \tag{1}$$

Where n is the time interval used to calculate long-term averages, i denotes the i-th year, P is the annual precipitation (mm), and PET is the annual potential evapotranspiration (mm). Middleton and Thomas (1997) indicate "Dryland subtypes" index values below 0.65, and "Non-Drylands subtypes" index values >0.65. P data was obtained from the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) project. It is a quasi-global rainfall dataset (0.05° resolution from 1981 to the present) already tested in northern Italy by comparison with a rain gauge network and indicated as one of the most accurate gridded precipitation datasets available for this area (Moccia et al., 2021). It incorporates satellite and weather station data (https://chc.ucsb.edu/data/chirps). PET is derived from the MODIS satellite distributed at 500 m resolution from 2001 (https://lpdaac.usgs.gov/products/mod16a2v006/). The algorithm is based on the Penman-Monteith equation (Running et al., 2019). The combination of these products is widely used for regional-scale research, e.g. to investigate drylands evolutions and drought impacts on agriculture (Dutta, 2018; Sandeep et al., 2021). AI calculation was performed using the Google Earth Engine (see Appendix A). The statistical differences between the two indices were tested using the *t*-test in the R environment and may indicate evidence of climate change. The result can be used to confirm the reliability of climate projections describing the area as at risk of aridity.

2.3.2. Summer 2022: Agricultural drought and extreme temperatures

We propose the application of the VHI (Rhee et al., 2010) to investigate the exceptional agricultural drought that affected northern Italy during the summer of 2022. It is a tool recommended by the United Nation Office for Outer Space Affairs (2022) as it considers both climatic variables and vegetative response. For the calculation of VHI (Eq. 2), MODIS satellite data was implemented to classify 4 drought classes (extreme, severe, moderate, and mild) for June, July, and August (2020,2021,2022).

$$VHI = 0.5 \times VCI + 0.5 \times TCI \quad (2)$$

VHI combines two indicators. The first is the Vegetation Condition Index (VCI), which uses the difference between the maximum and minimum NDVI to assess vegetation stress (Eq. 3).

$$VCI = \frac{(NDVI_j - NDVI_{min})}{(NDVI_{max} - NDVI_{min})} \times 100 \quad (3)$$

Where $NDVI_{max}$ and $NDVI_{min}$ are calculated for a multi-year dataset and $NDVI_j$ refers to the average value of a single month analysed. The second is the Temperature Condition Index (TCI). It is similar to VCI in its formulation (Eq. 4), but it implements the LST as a measure of the energy balance of the Earth's surface.

$$TCI = \frac{(LST_j - LST_{min})}{(LST_{max} - LST_{min})} \times 100 \quad (4)$$

We also separately mapped the LST for summer 2022 to detect extreme temperature hotspots. MODIS satellite data processed in Google Earth Engine were used (Appendix B). The satellite product provides an average LST of 8 days, which was used to estimate the mean monthly value for the entire study area (June, July, and August 2022). We mapped areas with high LST values as they can be responsible for significant crop stress (>35 °C such as Abdullah-Al-Faisal et al., 2021; other authors described "high temperature" from >32 °C; Imran et al., 2021). These areas were paired with those classified as extreme agricultural drought by the VHI, thus delimiting the critical zones. Data were finally compared with the agriculture information in Northeast Italy, resulting in an assessment of the extent of the most involved agricultural systems.

2.3.3. Hotspot in the Hotspot: The Po River Delta

Po River Delta is a climate change hotspot. Drought can lead to saltwater intrusion, with a severe impact on agriculture (such as in the summer of 2022). We propose a dedicated climate analysis investigating precipitation and air temperature trends recorded over the last years. These measures were chosen as they are among the most widely used for climate classification for geographical purposes (Belda et al., 2014). Data are provided by the Veneto Agency for Environmental Prevention and Protection (ARPAV). It distributes in open-access format validated data from 1994 recorded by a network of meteorological stations. In this analysis, daily precipitation/temperature values from 1994 to 2021 related to the summer period (June > August) were investigated (ARPAV, 2022a; 2022b). Precipitation analysis was performed by studying the cumulative rainfall for the three months (mm) and the number of rainy days (n). For temperature, the average of mean/maximum temperatures (°C) were used. An analysis of precipitation/temperature for 2022 is also proposed (one of the hottest periods ever recorded in Europe; Copernicus Climate Change Service, 2022). It is useful to confirm trends observed in the past and to highlight the symbolic impact that 2022 is having on society concerning climate change. The 2022 cumulative monthly rainfall value (January to the end of August) was compared with the long-term monthly average. The same procedure was performed for the mean monthly temperature. In both cases, an investigation of anomalies is proposed (difference from the long-term average). Finally, the reference period was divided into two parts (1994 > 2009 and 2010 > 2021) and compared using the statistical *t*-test. Significantly different values (p-value <0.05) indicate changed conditions between the two periods. Evidence could be useful to support future climate projections that are often calculated globally and then scaled in a specific area and therefore prone to bias.

2.4. Agriculture under current and future climate scenario

After understanding the climatic evolution of the study area in recent decades, it is important to know which areas will be at risk in the future. Climate shifts could have impacts on agriculture. For example, irrigated rural landscapes are currently located in temperate zones with non-dry summers. Some of them will likely become drier in the future with an increased likelihood of water scarcity. The risk of compromising food security is serious. It is therefore essential to map where such fields are, quantify them and know what is currently cultivated. This section describes the climate zone maps used and their relationship to the agriculture map.

2.4.1. Present vs future climate maps

We utilized the present and future climate maps proposed by Beck et al. (2018) to explore the projected climate change. Both maps have a resolution of 1 km and are based on the Köppen-Geiger climate classification (Köppen, 1936), today among the most widely used internationally for geographical purposes. Climate zones are classified using threshold values and seasonality of air temperature and monthly precipitation (following the criteria adapted from Peel et al., 2007). The scheme is organised into five main classes (A: Tropical; B: Arid; C: Temperate; D: Continental; E: Polar) and several sub-classes. The current climate map was designed for the 1980 > 2016 period. It was created by combining three climate datasets for air temperature (WorldClim V1 and V2, and CHELSA V1.2) and four datasets for rainfall (WorldClim V1 and V2, CHELSA V1.2, and CHPclim V1). The map was validated by the authors by calculating its accuracy by comparison with a series of weather stations as a reference. The future climate map (2071 > 2100) is based on the IPCC scenario RCP8.5, where emissions continue to rise during the 21st century (Riahi et al., 2011). The algorithm combined 32 CMIP5 climate models using the anomaly method proposed by Teutschbein and Seibert (2012). We chose these maps for several reasons. Firstly, it is widely used in the literature and recognised as reliable; secondly, it simulates the worst-case climate scenario and is therefore useful for quantifying maximum potential impacts.

2.4.2. Climates in rural landscapes

The objective is to relate the extent of existing agricultural lands distributed over the analysed territory to their (1) current and (2) future climate zone. The climatic characterisation was performed using a zonal statistics approach through a Geographical Information System (GIS). For each polygon representing the agricultural fields, the climate class occupying the largest area was assigned. During the calculation, we operated in terms of surface area, but for better readability of the results we express the outcomes in percentages. For each agricultural field, we identified the agricultural system (e.g. irrigated land, rice paddies, etc.; see section 2.2) and the current future climate zone. Table 1 shows the climatic classification adopted.

3. Results

3.1. Towards drier climates

3.1.1. Aridity index (AI) mapping

Fig. 3 shows the results of the multi-temporal AI. The Adriatic coast is the area characterised by the lowest values. In the first time frame, this region mainly extends about 25 km inland south of the Po River Delta. Low values are also in the surroundings of Ferrara, a historic city in a predominantly rural landscape and a UNESCO site. In contrast, the index describes wetter areas along the mountains. This condition is mainly because of higher rainfall on the slopes. The area characterised by more arid conditions has undergone a spatial expansion in the last decade compared to the previous one. The regions with AI<0.65 have increased by 58%. The statistical comparison of the two indices indicates a significant difference within the study area (p-value <0.05) and supports the hypothesis of ongoing climate change. The values distribution is represented by the boxplot in Fig. 3 and shows a decrease in the median values of roughly 10%. The main direction of aridification is from the

Table 1
Overview of Köppen-Geiger climate classes. Modified by Beck et al. (2018).

Main class	Sub-class	Description
		Tropical
	f	Rainforest
A	m	Monsoon
	w	Savannah
		Arid
	W	Desert
B	S	Steppe
	h	Hot
	k	Cold
		Temperate
	s	Dry summer
	w	Dry winter
C	f	Without dry season
	a	Hot summer
	b	Warm summer
	c	Cold summer
		Cold
	s	Dry summer
	w	Dry winter
	f	Without dry season
D	a	Hot summer
	b	Warm summer
	c	Cold summer
	d	Very cold winter
		Polar
E	T	Tundra
	F	Frost

Adriatic coast towards the hinterland. The driest area around the city of Ferrara also increased in size. It tends to expand southwards and affect the flat zone around Bologna. Less marked but still important values reductions are noted in the mountains, more in the Apennines than in the Alps.

3.1.2. VHI and LST mapping

The VHI allows the exploration of agricultural drought through remote sensing. It was applied for June, July, and August (2020, 2021, 2022; Fig. 4). The drought of 2022 severely challenged agriculture and ecosystems. Already in June, the index indicates the presence of extreme agricultural drought, especially in the central plain. The critical zone increased dramatically when compared to the previous two years. In July 2022, the phenomenon was even worse. A large part of the site was characterised by extreme drought, with spatial expansion mainly to the north (i.e. towards the Alps, even at higher altitudes) and inland to the west. In the previous two years, some critical areas were recorded to the south but with lower severities. In August 2022, rainfall finally occurred in Europe. In the week 11–17 August 2022, >40 mm of rain (cumulative) was reported in the eastern part of the investigated region (JRC Global Drought Observatory, 2022b). This led to a reduction in extreme drought areas, but with persistent critical spots on the northeast coast.

Further analyses involved the mapping of monthly average LST processed by MODIS. Areas with higher values can potentially be problematic for crops. July was the most critical month. High surface temperatures affected a large part of the lowlands, posing a significant hazard for thousands of hectares of farmlands. Particularly severe were the temperatures recorded along the Adriatic coast. Hot areas extended north and south affecting portions of the Alps and Apennines.

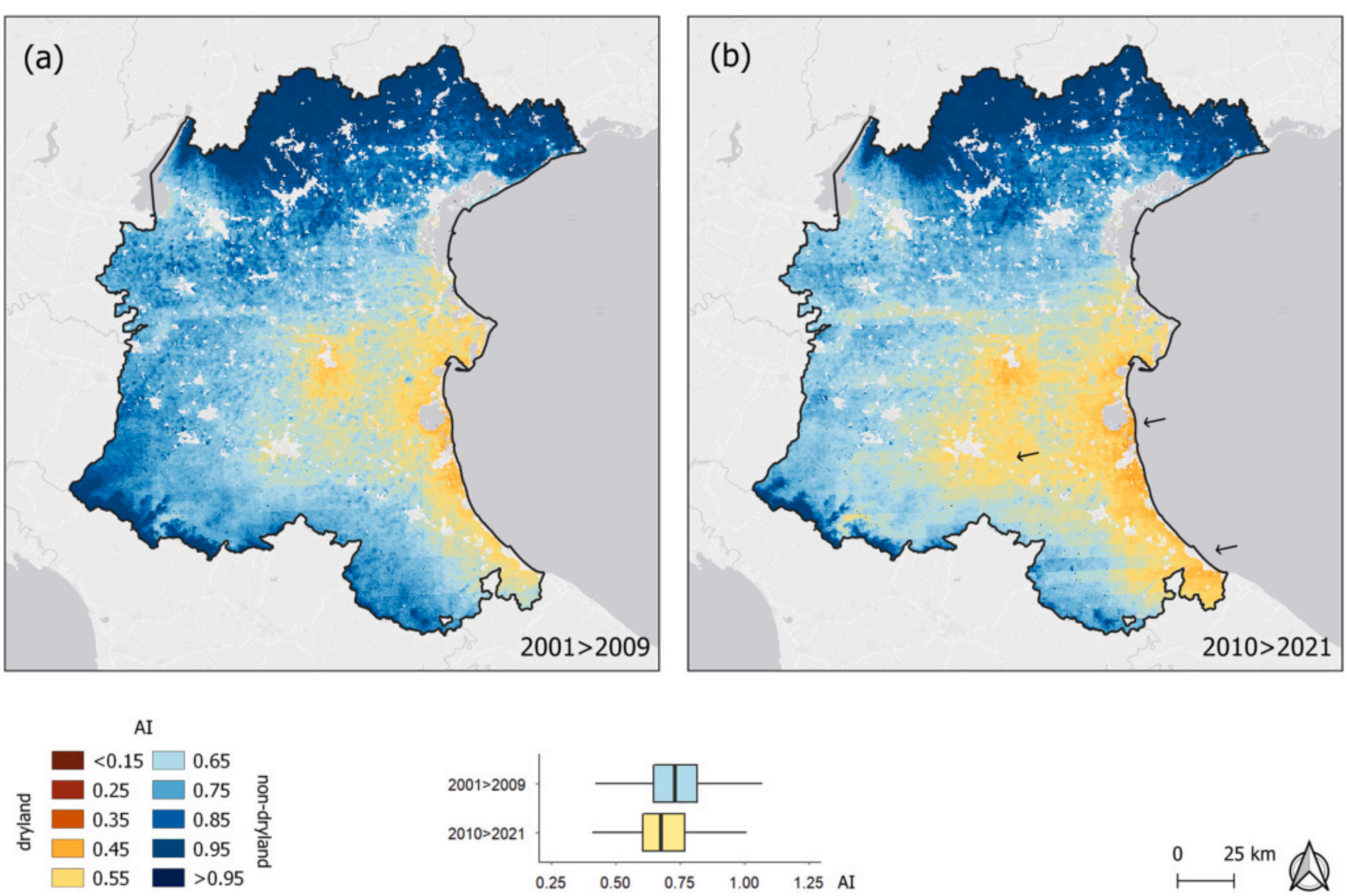


Fig. 3. Application of the aridity index ($AI_{FAO-UNEP}$). (a) refers to the period 2001 > 2009; (b) to 2010 > 2021. Classification according to Middleton and Thomas (1997). Warmer color indicate progressively drier conditions. Black arrows indicate some illustrative areas of worsening of the index towards drier states. Below, are two boxplots with index-value distributions (p-value <0.05). [color].

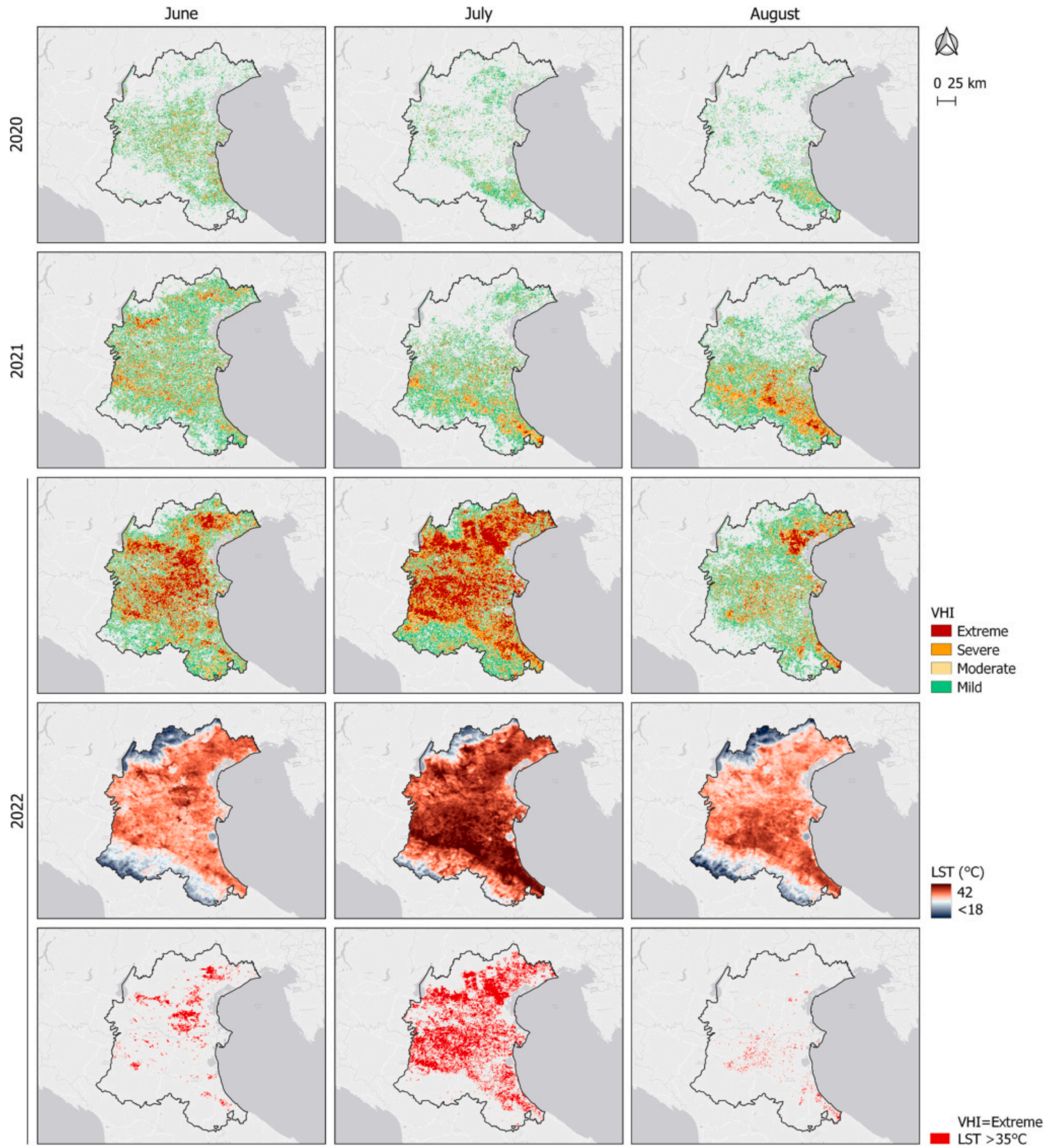


Fig. 4. Application of the drought index based on the VHI for the study area in June, July and August (2020, 2021, 2022). The summer of 2022 was characterised by large areas of extreme agricultural drought, which led to a severe impact on agriculture. For this year, average LST and areas characterised by the combination of extreme agricultural drought and LST >35 °C were also mapped. The delineation of these critical areas could have implications for the development of more climate change-resilient agricultural systems. [color].

Furthermore, we studied the regions affected by the combination of agricultural drought and high temperature. We identified the areas classified as 'extreme' by the VHI index and which recorded LST values above 35 °C (Fig. 4, bottom). The results indicate that 38% of the agricultural area in Northeast Italy was affected by the phenomena combination. Specifically, 41% of irrigated arable land (typical of the lowlands) and 20% of non-irrigated arable land (a smaller fraction as they are mainly located on slopes). Vineyards were severely involved, with 43% of the total. The most concerned wine-growing areas were the Veneto region, in particular the cultural landscapes that produce the wines of Soave (FAO-GIAHS site) and Prosecco (UNESCO site), and the zone of Valpolicella (home of notable wines such as Amarone).

3.1.3. Climate in the Po River Delta

We conducted a rainfall/temperature analysis in the Po River Delta, the main parameters for evaluating aridity. The average annual precipitation over the period 1994 > 2021 was 710 mm/year (152 mm/year standard deviation), distributed over 75 rainy days (13 days of standard deviation), and is trending downwards (ARPAV, 2022a; 2022b). On a seasonal level, a stable rainfall trend was observed during the winter and spring. In summer, the average rainfall for the period 2009 > 2021 decreased by 31% compared to 1994 > 2008 (*p*-value <0.05), highlighting traces of climate change towards more dry conditions. Fig. 5(a) depicts the cumulative precipitation over the June–July-August period. Both the rainfall value and the number of rainy days (i.e. with at least 0.1 mm of rain) are decreasing. The year 2022 confirms the worsening of the drought conditions observed in the past. Fig. 5(b) describes the average monthly rainfall trend and compares it with what was recorded in 2022. There was a strong lack of rain in February and March (anomalies of 88% and 55%, respectively) and during summer 2022, especially in July (anomaly of 65%), a situation observed for a large part of the European continent (Toreti et al., 2022). The autumn experienced a strong fluctuation in rainfall.

The average annual temperature was 14.0 °C and the average maximum was 18.8 °C. Both series are gradually increasing (ARPAV, 2022a; 2022b). Comparing the periods 1994 > 2008 and 2009 > 2021, there is a significant temperature rise in recent years (p-value <0.05), quantifiable as +0.7 °C for both mean and maximum temperatures. Similar values were obtained for 1982 > 2004 (Toreti and Desiato,

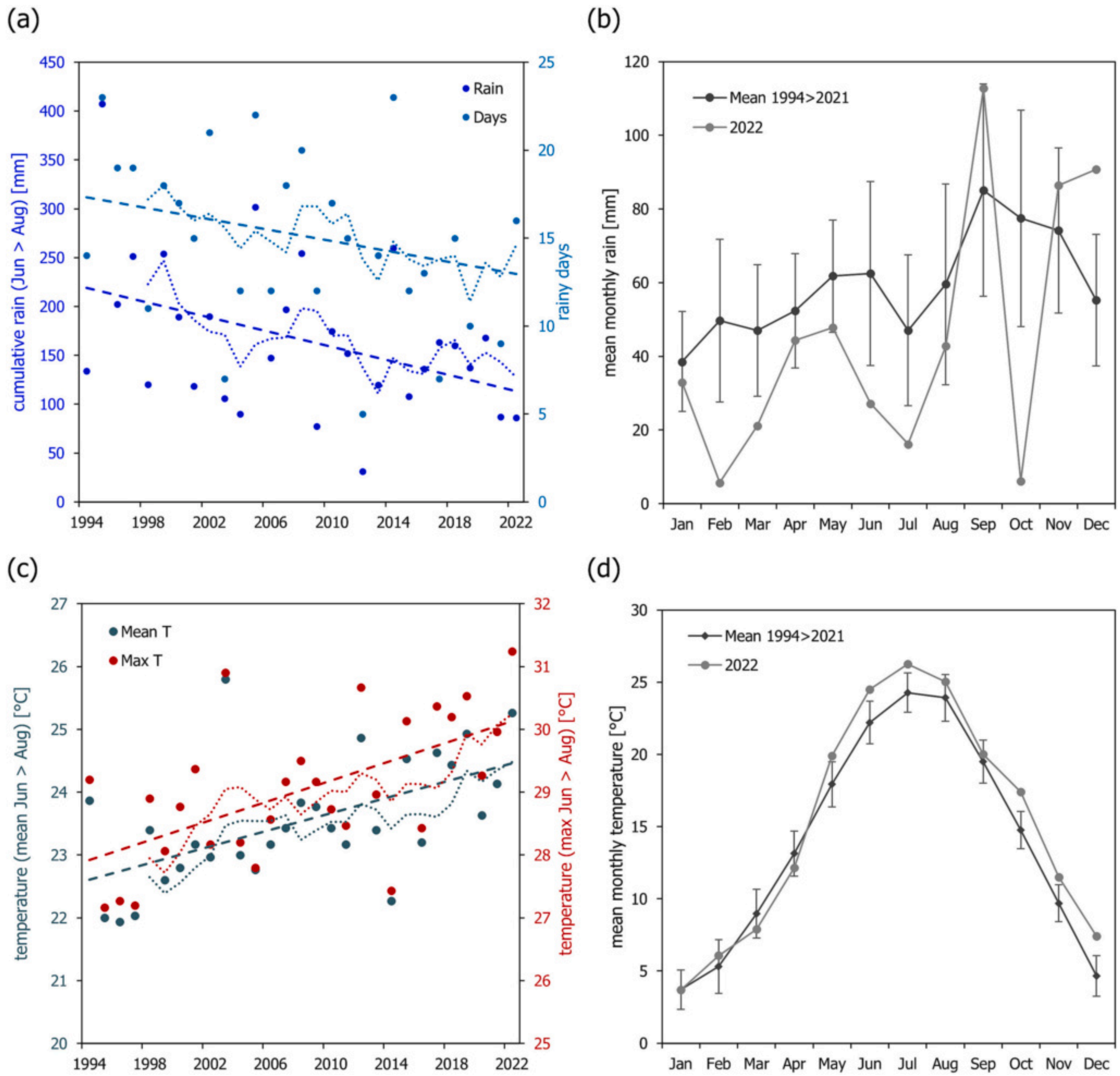


Fig. 5. Climatic analysis of the Po River Delta cultural landscape. (a) cumulative rainfall trend during the June–August period (left axis) and the relative number of rainy days. Both series have a negative trend (linear trend line and 5-year moving average are reported). (b) average monthly rainfall during 1994 > 2021 in comparison with the year 2022. (c), similar to (a), but with trends in average (left axis) and maximum temperatures (right axis). Both series have positive trends. (d), similar to (b), but with monthly mean temperatures. [color].

2008) and 1952 > 2002 (Bozzola and Swanson, 2014). No significant temperature increases were recorded for the winter months, while a weakly significant increase was observed for the spring (p-value = 0.05) and a significant increase for the summer months (p-value <0.05). This condition is in line with other studies in the Mediterranean coastal areas (Miró et al., 2006). Summer temperatures are reported in Fig. 5(c), and the comparison of mean monthly temperatures with those recorded in the year 2022 in Fig. 5(d).

3.2. Climate shifts is threatening agriculture in Northern-Italy

The current Köppen-Geiger climate zone distribution is proposed in Fig. 6(a). The map, as well as the future scenario, was elaborated from the data offered by Beck et al. (2018) at a 1 km resolution. A large part of the area is currently characterised by a Temperate climate (91%), specifically Cfa (no dry season and hot summers, 82%) and Cfb (no dry season, warm summer; 9%). These climatic conditions are distributed throughout the central plain, then towards the north-south directions to the entrance of the mountains. At altitude, Cold climates are observed (8%), mainly Dfb (cold, no dry seasons, warm summers; 7%) and to a limited extent of Dfc (cold, no dry seasons, cold summers; 1%).

The projected future climate map (2070 > 2100; PRC8.5) is displayed in Fig. 6(b). Warmer and drier conditions are predicted for the future. Two main-class climate variations can be observed in Fig. 6(c). The Temperate zone decreases from 92% to 85%. Of particular concern is an area classified as Arid (22% of the total) located along the Adriatic coast inland (south of the Po River Delta). Main-class climate variations also occur in the mountains. There, the area classified as Cold will disappear in the future to be replaced mainly by Temperate climates with hot summers (Csa). The latter will expand from 9% to 22%. Intra-class variations (i.e. within climates of the same main class) could also be observed in Fig. 6(d). On lower altitudes (roughly the region described by Fratianni and Acquaotta (2017), a major variation from Cfa to Csa could be observed. The climate is still classified as Temperate, but with hotter and drier summers. Similarly, on the highest peaks in Alps, summers will be characterised by wormers temperatures (Dfc to Dfb).

The climate shift could severely affect agricultural systems, which will be challenged to adapt to ensure food security. To provide useful support for resilient planning, Fig. 7 compares the distribution of various crops in the current climate and future scenarios. For each scenario, it shows the agricultural area divided by the agricultural system (sorted alphabetically) expressed as a percentage. Rice fields will be the most affected by the worsening climate. They are mainly located in the coastal area around the Po River Delta and are currently under a Temperate climate with no dry season that may become Arid in the future (76% of the total area). Horticultural crops are also at risk. They are mainly spread in the flat region (Temperate climate and no dry seasons) from the Adriatic coast to the western borders. In the future, 10% of them will be under Arid conditions (9% arid-hot, 1% arid-cold) and 2% in Temperate climate but with hot and dry summers. A similar situation is predicted for irrigated arable land. The actual Temperate climate without dry seasons and hot summers could evolve towards drier summers (4% of the surface) and Arid climate (19% arid-hot, 1% arid-cold). The non-irrigated lands are mainly located in the hilly and mountainous areas to the north and south. At present, 78% are in Temperate climate with hot summers and 21% with colder summers. A smaller portion (1%) is in a Cold zone. A similar situation is expected for vineyards. They are mainly located in the north. Their climatic zones will shift from Temperate without dry season to more dry summer (12% of the surface) and the Arid condition (4%). Along the Po River are concentrated most

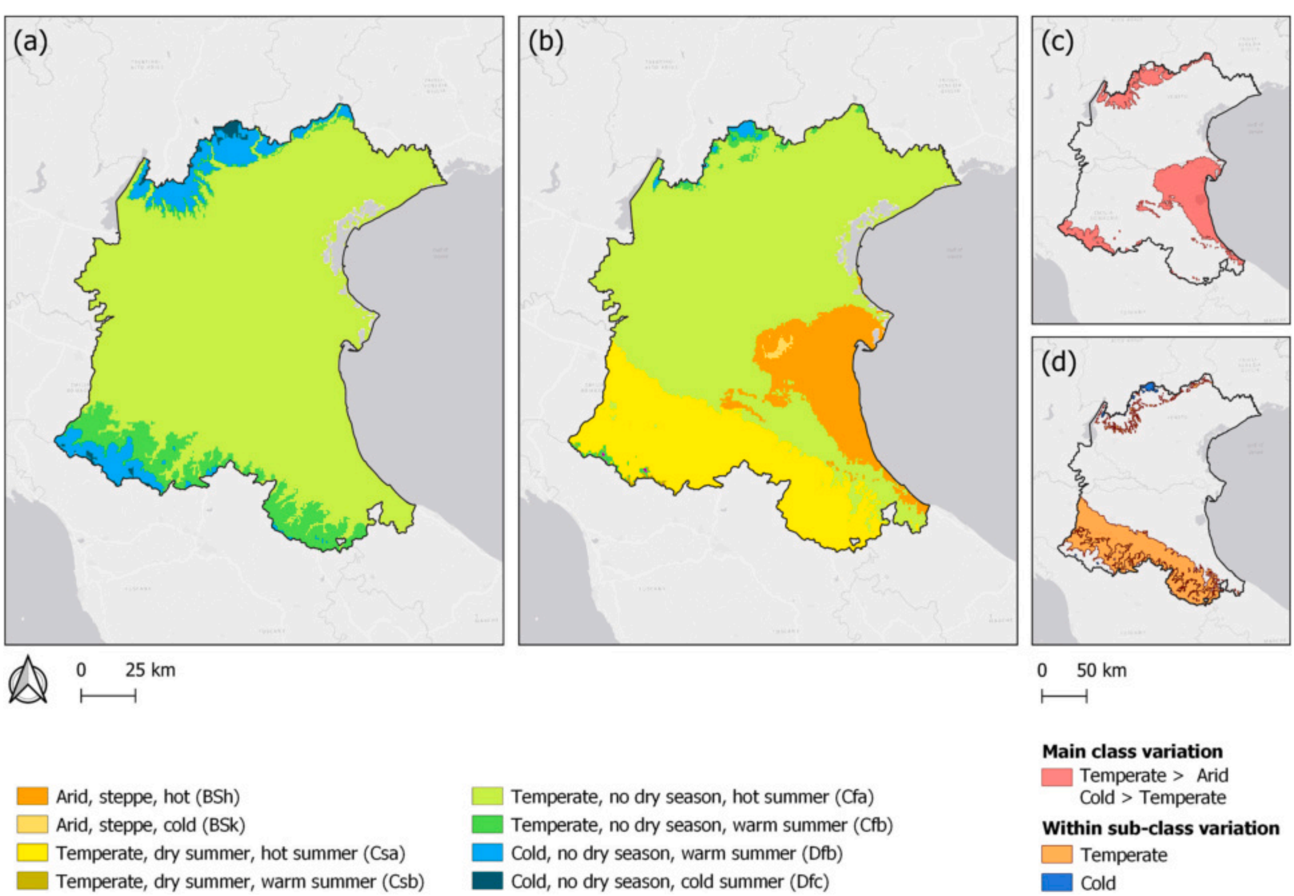
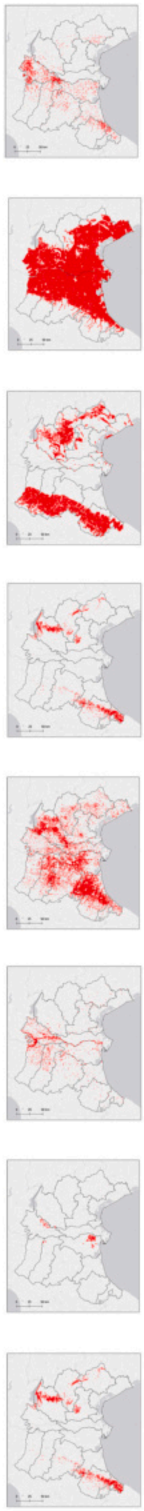


Fig. 6. Climate maps modified from Beck et al. (2018) for the study area. (a) Present climate zones. (b) Future climate zones (2071 > 2100; RCP8.5 scenario). (c) Areas subject to main climate class change. (d) Areas subject to sub-climate class variation. [color].



Horticultural crops (1%)	Present	Future	Δ
Arid, steppe, hot (BSh)	0%	9%	9%
Arid, steppe, cold (BSk)	0%	1%	1%
Temperate, dry summer, hot summer (Csa)	0%	2%	2%
Temperate, no dry season, hot summer (Cfa)	100%	88%	-2%

Irrigated arable land (70%)	Present	Future	Δ
Arid, steppe, cold (BSk)	0%	1%	1%
Arid, steppe, hot (BSh)	0%	19%	19%
Temperate, dry summer, hot summer (Csa)	0%	4%	4%
Temperate, no dry season, hot summer (Cfa)	100%	76%	-24%

Non-irrigated arable land (12%)	Present	Future	Δ
Arid, steppe, hot (BSh)	0%	1%	1%
Temperate, dry summer, hot summer (Csa)	0%	60%	60%
Temperate, no dry season, hot summer (Cfa)	78%	39%	-40%
Temperate, no dry season, warm summer (Cfb)	21%	0%	-21%
Cold, no dry season, warm summer (Dfb)	1%	0%	-1%

Olive groves (1%)	Present	Future	Δ
Arid, steppe, hot (BSh)	0%	2%	2%
Temperate, dry summer, hot summer (Csa)	0%	16%	16%
Temperate, no dry season, hot summer (Cfa)	98%	82%	-16%
Temperate, no dry season, warm summer (Cfb)	2%	0%	-2%

Orchards (5%)	Present	Future	Δ
Arid, steppe, hot (BSh)	0%	18%	18%
Arid, steppe, cold (BSk)	0%	1%	1%
Temperate, dry summer, hot summer (Csa)	0%	17%	17%
Temperate, no dry season, hot summer (Cfa)	99%	64%	-35%
Temperate, no dry season, warm summer (Cfb)	1%	0%	-1%

Poplar groves (1%)	Present	Future	Δ
Arid, steppe, hot (BSh)	0%	7%	7%
Temperate, dry summer, hot summer (Csa)	0%	3%	3%
Temperate, no dry season, hot summer (Cfa)	100%	90%	-10%

Rice fields (<1%)	Present	Future	Δ
Arid, steppe, hot (BSh)	0%	76%	76%
Temperate, no dry season, hot summer (Cfa)	100%	24%	-76%

Vineyards (7%)	Present	Future	Δ
Arid, steppe, hot (BSh)	0%	4%	4%
Temperate, dry summer, hot summer (Csa)	0%	12%	12%
Temperate, no dry season, hot summer (Cfa)	99%	84%	-16%
Temperate, no dry season, warm summer (Cfb)	1%	0%	-1%

Fig. 7. On the left, is the geographical location of the individual agricultural system. In the centre, tables summarise the area (in terms of percentage) classified as present and future climate and its variation. On the right, are pie charts summarising the results. [color].

of the poplar cultivations. They are currently located in a Temperate climate zone, which in the future could become Arid (7%, especially along the coast) or Temperate with dry seasons (1%). The condition of orchards is similar. They are fairly distributed throughout the study area, with a greater concentration in the northwest (towards the Alps) and southeast (in the Apennines). The climate is currently Temperate with no dry seasons but could become Arid (18% arid-hot, 1% arid cold) or Temperate with dry summers (17%). The same can be observed for olive groves, which shift from a purely temperate regime to more arid conditions.

4. Discussion

4.1. Aridification, drought and high temperatures in Northeast Italy

Multi-temporal AI shows an expansion of climatically drier areas and can indicate potential traces of climate change. The result is alarming, as the pattern of drier areas is consistent with future Arid zones (see Section 4.2.1). Hotspots are along the Adriatic coast. This is confirmed by studies which observed a negative trend in rainy days and an increase in hot days (1989 > 2020), predicting worsening future scenarios (CMCC, 2022a; 2022b). AI results are in line with Salvati et al. (2013), which report a reduction in the index for Northern Italy (−17.2% for Veneto and − 15.3% for Emilia-Romagna). Their work is based on gridded data of 30 km side interpolated with the Kriging method, thus presenting limitations in considering the effects of land morphology, among the main variables in the climate study (Minder et al., 2008). Our findings are also consistent with Domínguez-Castro et al. (2020), which analysed climate indicators at a European scale and less representative of local conditions. Through remote sensing, we propose an increase in resolution compared to previous work, offering more detailed results. We deepen the spatial dynamics of drylands and map specific hotspots to foster the development of resilient agricultural systems.

Drought events combined with extreme temperatures could occur more often due to climate change. Scientific research is showing interest in the 2022 extreme event. Bonaldo et al. (2023) illustrate the persistent negative rainfall anomalies for the Po River basin, also focusing on 2022. Our findings are in line with what they observed. However, we enriched the discussion by mapping the severity of the agricultural drought during the event. The application of the VHI index offered interesting results, a novelty compared to other drought reports (JRC Global Drought Observatory, 2022a; 2022b). It allowed mapping the extreme severity areas, as already successfully applied in other locations (Yu and Guo, 2022). We validated the results by considering the data published by NOAA STAR (2022) at a lower spatial resolution. Droughts generally coincide with heat stress and more extreme con-current events are expected in the future (Lesk et al., 2022). We analysed the LST for summer 2022, a period of record temperatures. In July, the Copernicus Climate Change Service recorded air temperature anomalies >3 °C within the study area (https://www.copernicus.eu/it/node/11780). For example, 30.7 °C in Venice, 33.8 °C in Verona, 33.4 °C in Rovigo and 32.9 °C in Bologna (open-access data from the regional environmental agencies of Veneto - ARPAV - and Emilia Romagna - ARPAE). LST is a widely used measure for analyzing heat stress in agriculture. It has a direct influence on the thermoregulatory effect of crops and influences plant growth and crop yields (Heinemann et al., 2020). MODIS is broadly used for its measurement. Recent applications in agriculture were performed in Taiwan island (Chen, 2021) and around Tokyo (O'Malley and Kikumoto, 2021). The combination of drought and extreme LST allowed the mapping of critical spots during July 2022. This result was cross-referenced with agriculture information. Therefore, we determined which crops potentially suffered the most, a novelty offered by this work.

We proposed an in-depth investigation of the Po River Delta. Summer 2022 was particularly emblematic of what future summers might look like. Colombo et al. (2007) showed that summer temperatures are tending to increase along the Italian coastline, associated with a decrease in precipitation. We confirm this direction by proposing an update for the Po River Delta. Outcomes also show that summer-like climatic conditions are propagating during autumn (significantly warmer and less rainy than in the past). Potential signs of aridification are already evident, a condition observed in other coastal regions of Europe (Seager et al., 2014) but still missing in our study area. Although not directly analysed in this paper, it is worth mentioning other climate-related potential impacts. The first is the Po River discharge. Other authors report that it is progressively assuming more torrential behaviour, i. e. greater fluctuations in flow rates (Simeoni and Corbau, 2009). At low river flows, saltwater intrusion can be observed. During the summer of 2022, the process took on extreme magnitudes, moving up the river for >40 km and causing extensive damage to agricultural systems (Tarolli et al., 2023). The rising sea level and temperature are also worsening the situation (Raicich and Colucci, 2019; Vilibić et al., 2017).

4.2. Climate shifts and agriculture in Northeast Italy

A worrying novelty for Northeast Italy is the emergence of arid areas in the future, a development indicated by different models (Bucchignani et al., 2016). This is alarming and in line with other findings (Appiotti et al., 2014; Brunetti et al., 2000; Nistor, 2021; Zomer et al., 2022). Such critical circumstances could impact societies having major implications on agricultural systems. Some studies already used climate projections to investigate climate change in agriculture in the region. However, they are mainly focused on the analysis of production yields related to individual crops (Mereu et al., 2021; Zagaria et al., 2021), the application of specific agricultural policies and/or decision-making models to promote adaptation measures (Bojovic et al., 2015; Lugato and Berti, 2008), and hydrological research to improve water management (Teegavarapu et al., 2020). Therefore, to the best of our knowledge, there is still no mapping and quantification of agricultural areas at risk of climate change for this strategic territory, based on climate scenarios internationally recognised by the scientific community. This work aims at bridging this gap, a novelty that could stimulate mitigation strategies in agriculture.

We assumed that current cropping systems would remain unchanged over time. This offers insights into the risks that crops might face because of future scenarios. The results show that rice fields will be the most affected crops by aridity. Such new conditions could have a considerable impact on the production chain, which usually requires large amounts of water (Tuong and Bouman, 2003). This concern is confirmed by other studies (Bocchiola, 2015; Bregaglio et al., 2017). It is therefore recommended to act urgently in the development of sustainable crop and water management (Arcieri and Ghinassi, 2020). Due to the extreme drought observed in the summer of 2022, around 60% of rice production in the Po Delta was compromised (Henley, 2022). Heat stress and droughts can also directly impact the physiology of some horticultural crops, accelerating stress conditions and causing mortality (Sangiorgio et al., 2020). In irrigated arable land, water availability is a key element that may be more complex to obtain in the future. This is a serious concern because they occupy about 70% of the rural lands. There is an urgent need to adopt sustainable and efficient water management and to favour crops that require less specific amounts of water. Cereals are widespread crops that could suffer greater reductions in production rates due to climate change (Mereu et al., 2021). For example, for soybean, high temperatures and lack of water can severely limit pod development (Onat et al., 2017). Regarding non-irrigated arable lands, current rainfall is normally sufficient to ensure production. However, these areas will be characterised by climates with hotter and drier summers. While conditions will not be as extreme as along the Adriatic coast, the climate shift could result in an increased frequency of droughts and heat stress, with consequences due to the lack of widespread irrigation systems. Crops are often located on steep slopes. Here, it is advisable to introduce sustainable water management derived from traditional knowledge, such as water storage (Wang et al., 2022a;

2022b). This can also be valid for vineyards. High-efficiency drip irrigation is recommended, selecting drought-resistant varieties, and carefully evaluating the vineyard structure (Ortuani et al., 2019; Gutiérrez-Gamboa et al., 2021). Particular attention must be paid to heat stress. Indeed, vineyards were among the most affected agricultural systems during the 2022 event and similar conditions could occur more frequently. Aridification is a significant concern since the socio-economic importance of viticulture is combined with cultural values expressed in an FAO-GIAHS site (Vigna Tradizionale di Soave) and a UNESCO cultural landscape (Colline del Prosecco di Conegliano e Valdobbiadene). Although not analysed directly in this study, it is important to mention that climate change is also posing challenges due to heavy rainfall, which causes soil erosion and slope instability (Straffelini et al., 2022). Regarding the cultivation of poplars, they generally do not require irrigation. However, it can be used to improve the quantity and quality of the product, especially in the case of drought (Allegro et al., 2022). Finally, we analysed the situation of olive trees. They are Mediterranean plants that are physiologically resistant to lack of water, making them resilient crops to the climate projected for the study area. However, the reasoning for olive and oil production is different, as drought could compromise production rates. Drip irrigation could be a smart solution to ensure production and increase the efficiency of water resources in such conditions (Greven et al., 2009).

4.3. Limitations and future perspective

A research limitation concerns the calculation of AI and the type of input data used. For annual precipitation, potential evapotranspiration and air temperature data were only partly measured in the study area and mainly estimated from satellite observations. This could limit the accuracy of the measurement. However, given the extent of the study area and the type of result sought, this approach is consistent with the purpose of the research. Another limitation may arise from the use of future climate maps. They are constructed using simulation algorithms inherently subject to bias. The data proposed by Beck et al. (2018) are, to the best of the authors' knowledge, among the most up-to-date and widely used global open-access Köppen-Geiger climate zone maps. These are based on the CMIP5 model. Data from the new phase of the project, called CMIP6, have recently been published. Thanks to technological advances and improved computational capabilities, the latter promises better performance than previous models, mainly by offering a wider range of future scenarios included in the new socioeconomic pathways (SSPs) (Stouffer et al., 2017). CMIP5 and CMIP6 comparison is a topic discussed in the literature and numerous studies have questioned their differences in different parts of the world, such as in North America (Thorarinsdottir et al., 2020), Canada (Bourdeau-Goulet and Hassanzadeh, 2021) and South Asia (Kamruzzaman et al., 2021). For example, CMIP6 has recently been used in agriculture for analyzing the global productivity of some major crops (Jägermeyr et al., 2021). The authors show that using the latter, the average global production of maize (among the most important crops in terms of food security) is reduced by up to about 20% compared to analyses using CMIP5. Despite improvements in the latest model, which often result in different ranges of values, several times CMIP5 and CMIP6 offer aligned results, especially concerning precipitation and temperature (Bourdeau-Goulet and Hassanzadeh, 2021). A recent publication compared CMIP5 and CMIP6 climate projections for the study of climate change in the Mediterranean area, i.e. the macro-area that includes the zone investigated in this paper (Cos et al., 2022). Regarding temperatures, CMIP6 tends to warm more than CMIP5 but with a good spatial agreement between the two models; in contrast, both models estimate a similar reduction in precipitation. Another limitation concerns the use of current agricultural areas concerning future climate zones. We are aware that agricultural systems can evolve. However, we have chosen to use current rural areas (1) to send a clear message to stakeholders and policymakers about what the future climate conditions of current rural landscapes will potentially be; and (2) to identify which of the current systems are most at risk, recognising critical areas to support resilient future agricultural planning.

Despite limits, this study opens new opportunities for future research to support future agricultural cultivations under arid scenarios. This might include (1) the need to develop a system for monitoring drought impacts in these areas, e.g. by exploiting remote sensors (satellite + UAV) coupled with in-field systems; (2) the investigation of planting crops that require less water in the production cycle; (3) the implementation of precision irrigation technologies to improve efficiency; (4) the development of specific sustainable water management plans for the 'new arid areas', that integrates food security and rural cultural landscapes protection; (5) the design of measures to preserve ecosystems, especially along the coast. (6) An in-depth exploration of the impacts of saltwater intrusion on agriculture in the Po River Delta. Finally, we would like to stress that the future climate scenario could also directly affect people. Comparing population data (for 2022) with the extent of potentially arid areas in the future, it is reasonable to estimate about 1.2 million citizens (out of a total of about 9 million in the area) at risk (approximate value not considering future developments). Immediate actions are needed to manage the associated risk.

5. Conclusion

This paper addressed the issue of human-induced climate change in agricultural systems in Northeast Italy. The great challenge for agriculture will be to adapt to the new and more arid conditions while guaranteeing food security. Our contribution is the high-resolution mapping and quantification of 8 major agricultural systems at risk of climate zone shift in 14 key provinces. In addition to their rural heritage, they are important for several Community Interest Areas (such as cultural landscapes and protected sites). The results show that rice fields are the most endangered system among those analysed. We estimate that 76% will be in dry areas in the future, as well as 20% of irrigated arable land. Currently, the latter occupy 70% of the total agricultural area. Securing water resources in arid areas may be more difficult. This is a key point. We recommend the development of targeted management plans to address this issue, encouraging policymakers and stakeholders to be aware of the risk related to climate aridification. Therefore, we encourage more efficient use of water resources and the selection of crops suitable for the new scenario. Similar considerations can be made for steep slope agriculture of the Alps and Apennines. We estimate that about 60% will experience drier summers. These areas are also home to vineyards, which are important from a socio-economic and cultural point of view (some are FAO-GIAHS or UNESCO sites). 12% of their current surface will be in a Temperate climate but with dry summers, and 4% in an Arid zone. The introduction of efficient water harvesting and irrigation systems is recommended. The implementation of future scenarios was combined with an analysis of historical data. The application of a multi-temporal aridity index (AI) indicated the advancement of arid conditions, showing a significant reduction in AI values in recent decades (p-value <0.05). The most critical region is along the Adriatic coast towards the plains, a pattern similar to the arid zone predicted for the future. We studied the dynamics of the severe drought and high temperatures during the summer of 2022. In addition to severe direct damage to crops, the event caused severe indirect processes such as saltwater intrusion. The VHI index indicated large areas of severe agricultural drought, while the LST measure showed large spots of high temperature. The combination of phenomena affected 38% of the rural landscape. The most affected agricultural systems were irrigated arable land on the plains and vineyards on the slopes. Finally, we observed traces of climate change in the Po River Delta, with a decrease in summer precipitation associated with an increase in mean/maximum temperature and the number of very hot days.

In conclusion, we stress that climate aridification could be one of the most significant challenges for agriculture in northeastern Italy, from water shortages to serious saline water intrusion issues along the

Adriatic coast. The analyses conducted enrich the discussion on the impacts of climate change in the area. The results can be used to guide the planning of targeted solutions (such as the development of sustainable water management strategies and the selection of suitable crops) and support the development of mitigation policies.

CRediT authorship contribution statement

Eugenio Straffelini: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft. **Paolo Tarolli:** Conceptualization, Writing – review & editing, Funding acquisition, Project administration, Supervision.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgements

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Appendix A. Aridity Index (AI) Calculation in Google Earth Engine (GGE) over a time period in a study area

```
// Aridity Index (AI) Calculation in Google Earth Engine (GGE) over a time period in a study area
// AI is based on Mean Annual (1) Precipitation and (2) Potential Evapotranspiration (PET)

// Step 0 – Prepare Datasets, Study Area polygon & Visualisation parameters
var chirps = ee.ImageCollection("UCSB-CHG/CHIRPS/PENTAD") //precipitation data
var mod16 = ee.ImageCollection("MODIS/006/MOD16A2") // Modis satellite data
var StudyArea = ee.Geometry.Rectangle([10.5, 43.5 , 13.5, 46.5]); // coordinates of the Study Area
var rain_palette = ['#eff3ff','#bdd7e7','#6baed6','#3182bd','#08519c'] // colour palette for precipitation
var pet_palette = ['#d7191c','#fdae61','#ffffbf','#abdda4','#2b83ba'] // colour palette for PET
var ai_palette = ['#d7191c','#fdae61','#ffffbf','#abdda4','#2b83ba'] // colour palette for PET
var visRain = {min:400, max: 1400, palette: rain_palette} // visualisation parameters for precipitation
var visPET = {min:400, max: 1400, palette: pet_palette} // visualisation parameters for PET
var visAI = {min:0.3, max: 1.1, palette: ai_palette} // visualisation parameters for PET
Map.setCenter(11.3, 44.9, 8);

// Step 1 – Define the investigation period
// 1.a) define starting & ending year (example: 2001>2009)
var startYear = 2001;
var endYear = 2009;
// 1.b) create a list of years
var startDate = ee.Date.fromYMD(startYear,1, 1);
var endDate = ee.Date.fromYMD(endYear + 1, 1, 1);
var years = ee.List.sequence(startYear, endYear);

// Step 2 – Calculation of the Mean Annual Precipitation
// 2.a) aggregate the Chirps' data to get the mean annual precipitation for each year investigated
var annualPrec = ee.ImageCollection.fromImages(
  years.map(function (year) {
    var annual_Prec = chirps // imageCollection that contains rainfall data
        .filter(ee.Filter.calendarRange(year, year, 'year')) // filter data in the year
        .sum(); // get annual cumulative data
    return annual_Prec
        .set('year', year)
        .set('system:time_start', ee.Date.fromYMD(year, 1, 1));
}));

// 2.b) apply a reducer to get the mean annual precipitation over the period and display data on the map
var MeanAnnualPrec = annualPrec.mean().clip(StudyArea); // mean annual prec. over the period in the Study Area
Map.addLayer(MeanAnnualPrec, visRain, 'MeanAnnualPrec'); // display data

// Step 3 – Calculation of the Mean Annual PET
// 3.a) select the band "PET" from the MODIS imageCollection
var PET = mod16.select("PET")

// 3.b) calculate the mean annual PET
var annualPET = ee.ImageCollection.fromImages(
  years.map(function (year) {
    var annual_PET = PET
        .filter(ee.Filter.calendarRange(year, year, 'year')) // filter data in the year
        .sum() // get annual cumulative data
        .multiply(0.1); // multiply by the scale factor
    return annual_PET
        .set('year', year)
        .set('system:time_start', ee.Date.fromYMD(year, 1, 1));
}));

// 3.c) apply a reducer to get the mean annual PET over the period and display data on the map
var annualMean_PET = annualPET.mean().clip(StudyArea); // mean annual PET over the period in the Study Area
Map.addLayer(annualMean_PET, visPET, 'annualMean_PET'); // display data

// Step 4 – Calculation of the Aridity Index
// 4.a) apply AI equation and display it on map
var AI = MeanAnnualPrec.divide(annualMean_PET) // apply AI equation
Map.addLayer(AI, visAI, 'AI');
```

Appendix B. Calculation of Land Surface Temperature (LST) for Northeast Italy

```
// Calculation of Land Surface Temperature (LST) for Northeast Italy

// Step 0 – Prepare Datasets, Study Area polygon & Visualisation parameters
var modis = ee.ImageCollection("MODIS/061/MOD11A2") // Modis satellite data
var StudyArea = ee.Geometry.Rectangle([10.5, 43.5 , 13.5, 46.5]); // coordinates of the Study Area
var vis_temp = {"min":20,"max":40,"palette":["#033270","#4091c9", "#9dcee2","#f29479","#ef3c2d", "65010c" ]};
Map.setCenter(11.3, 44.9, 8);

// Step 1 – Define the investigation period
var start = ee.Date('2022-07-01'); // start period: set the first day of the month to be analyzed (here it is July 2022)
var dateRange = ee.DateRange(start, start.advance(1, 'month')); // addition of one month

// Step 2 - Filter the LST whithin the date range
var modis_06_22 = modis.filterDate(dateRange);

// Step 3 - Select the 1km LST data
var modis_LST = modis_06_22.select('LST_Day_1km');

// Step 4 - Convert to Celsius
var modis_LST_celsius = modis_LST.map(function(image) {
  return image
    .multiply(0.02) //scale
    .subtract(273.15) //convert
    .copyProperties(image, ['system:time_start']); //acquisition time
});

// Step 5 - Calculate mean LST temperature in the data range
var LST_celsius_StudyArea = modis_LST_celsius.mean().clip(StudyArea);

// Add image to the map
Map.addLayer(LST_celsius_StudyArea, vis_temp, "LST_celsius_StudyArea")
```

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