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Cultural Landscapes under Global Environmental Change: Monitoring and Assessment through Remote Sensing and GIS

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Paesaggi Culturali e Cambiamenti Ambientali Globali: Monitoraggio e Valutazione attraverso Telerilevamento e GIS

Tesi redatta con il contributo finanziario della Fondazione CARIPARO

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Contents

Abstract

Cultural Landscapes embody a profound connection between humans and nature in a rapidly changing world. Climate change and intensified human activity threaten the delicate balance necessary for their survival. This is especially true for sites with strong rural identities, where traditional agricultural and water management techniques are at risk.

Enriched by nine articles published in international journals and one currently under review, this thesis aims to analyze the impacts of global environmental changes on a selection of representative rural Cultural Landscapes, through specific objectives (SO). It firstly examines two major climatic threats: drought and high temperatures (SO-A) and extreme precipitation events (SO-B). In the first, various Cultural Landscapes in Europe are analyzed, evaluating future climatic scenarios and proposing new methodologies for mapping and identifying at-risk areas to guide mitigation measures. For the second, innovative methods are developed for prioritizing maintenance interventions at field scale, alongside global analyses of cultural ecosystem services. Finally, SO-C explores how human management practices influence the resilience of Cultural Landscapes, with case studies on Argentine vineyards, traditional viticulture, and water management in steep slope terrains. The thesis concludes with an investigation of UNESCO World Heritage Cultural Landscapes, moving beyond "representative case studies" to globally analyze future climatic evolutions and their impacts on the identity of these landscapes.

Thanks to the inherent flexibility of the Cultural Landscape's topic, the thesis addresses the impacts of global environmental changes with a broad perspective, employing innovative spatial data analysis techniques and providing valuable insights for Cultural Landscape managers. This contributes to ensuring a future for these unique landscapes encouraging sustainable management.

Sommario

I paesaggi culturali sono testimoni di una profonda connessione tra uomo e natura in un mondo che cambia rapidamente. Il cambiamento climatico e l'intensificazione dell'attività antropica minacciano l'equilibrio delicato che garantisce la loro sopravvivenza, soprattutto nei siti con forte identità rurale, dove le tecniche tradizionali di agricoltura e gestione dell'acqua rischiano di essere compromesse.

Arricchita da nove articoli scientifici pubblicati su riviste internazionali e uno attualmente in revisione, questa tesi analizza gli impatti dei cambiamenti ambientali globali su una selezione di paesaggi culturali rurali rappresentativi, attraverso obiettivi specifici (SO). Si esaminano inizialmente due delle principali minacce climatiche: gli eventi di siccità e alte temperature (SO-A) e le precipitazioni estreme (SO-B). Per il primo, vengono analizzati vari paesaggi culturali in Europa, valutando scenari climatici futuri e proponendo nuove metodologie di mappatura e identificazione delle aree a rischio per guidare le misure di mitigazione. Per il secondo, si sviluppano metodi innovativi per la prioritizzazione degli interventi di manutenzione a scala di campo e analisi globali sui servizi ecosistemici culturali. Il terzo obiettivo (SO-C) esplora come le pratiche di gestione umana influenzino la resilienza dei paesaggi culturali, con casi studio su vigneti argentini, viticoltura tradizionale e gestione dell’acqua in terreni ripidi. La tesi si conclude con un’indagine sui paesaggi culturali UNESCO a livello globale, analizzando le evoluzioni climatiche future e i loro impatti sull’identità di questi paesaggi.

Grazie alla flessibilità offerta dal tema dei paesaggi culturali, la tesi analizza gli impatti dei cambiamenti ambientali globali con una visione ampia, utilizzando tecniche innovative di analisi dei dati spaziali e fornendo preziose informazioni ai gestori dei paesaggi culturali, contribuendo a garantire, attraverso una gestione sostenibile, un futuro per questi paesaggi unici.

1. Introduction

1.1. The Context: Cultural Landscapes

Since its origins, humans have shaped the environment to meet their needs. The strong man-nature interaction has led to one of the most known definitions of *landscape*, namely an anthropocentric concept where the environment is the result of the action and interaction of natural and/or human factors (European Union, 2000). Among others, *agriculture* has played a key role in sculpting the land over the millennia, with the emergence of a rich variety of traditional farming systems around the world. With ever-evolving technological innovation, rural landscapes have increasingly intersected with urban and industrial agglomerations (Vos and Meekes, 1999). When the traditional features of an area survive over the centuries while respecting the natural its character, a Cultural Landscape is born (Sirisrisak and Akagawa, 2007). The term "Cultural Landscape" was introduced for the first time by Sauer (1925):

> *"The Cultural Landscape is fashioned from a natural landscape by a cultural group. Culture is the agent, the natural area the medium, the Cultural Landscape is the result".*

Another widely used definition come from Wagner and Marvin (1962):

> "A *concrete and characteristic product of the interplay between a given human community, embodying certain cultural preferences and potentials, and a particular set of natural circumstances. It is a heritage of many eras of natural evolution and of many generations of human effort*."

Academia considers a Cultural Landscape a complex and broad concept that contain any system of interaction between cultural human activity and natural habitat (Fowler, 2003). They have become increasingly popular since 1992 when they were mentioned in the World Heritage Convention by the UNESCO (United Nations Educations, Scientific, and Cultural Organization), which provides an international juridical instrument for their protection. UNESCO heritage is divided into several groups. '*Cultural heritage*' is defined as all monuments (such as architectural works), agglomerations (such as groups of buildings of historical and scientific interest) and sites (such as archaeological settings); *'natural heritage'* is definite as natural monuments (such as particular physical and biological formations), but also natural sites; finally, there are *'Cultural Landscapes'*, which contain joint creations of man and nature. Their protection can contribute to modern techniques of sustainable landscape use and the maintenance of biological diversity. (UNESCO, 2021). Cultural Landscapes are distinguished by being illustrative of the evolution of human society over time, under the influence of physical constraints and/or opportunities presented by the natural environment and subsequent social, economic and cultural forces (UNESCO, 1996). Many of those sites are included in the World Heritage List provided by UNESCO (World Heritage Center, 2013). However, the level of human modification beyond which a natural landscape becomes a Cultural Landscape is still an open debate (Wu, 2010).

Cultural Landscapes are often mainly identified as agricultural environments, i.e. realities that lie between natural and urban sites (Jones, 2003). Indeed, agriculture has played a key role in shaping the territory since ancient Greek time, through a complex multi-layered combination of historical landforms. Where these unique realities survive, it is referred to as Traditional Agricultural Landscapes (Vos and Meekes, 1999). As for the more general World Heritage List, there are specific plans for the protection of such landscapes, as the GIAHS (Globally Important Agricultural Heritage Systems). Introduced by the Food and Agriculture Organization of the United Nations (FAO) in 2002, it was developed to capture specific aspects of traditional agriculture and to ensure its conservation and sustainable development (FAO, 2020). GIAHS sites are some remarkable but fragile agricultural Landscapes around the world that benefit from special protection and policy that promotes tourism and the local economy (Bixia and Zhenmian, 2013). They are heritages where particular farming systems, historic villages, archaeological sites and natural beauty often coexist. Sites are also recognised for maintaining local agrobiodiversity, fragile landforms, traditional knowledge and people's identity and culture (FAO, 2018).

Figure 1.1 - Examples of Cultural Landscapes deeply shaped by traditional agricultural practices. Left: the UNESCO Cultural Landscape of Portovenere, Cinque Terre, and the Islands (Palmaria, Tino and Tinetto), Italy. Right: the GIAHS Site of Soave Traditional Vineyards, Italy. Photos: Eugenio Straffelini

1.2. Research Questions and Objectives

Scientific literature identifies drought, increased temperatures, severe rainfall, and their related consequences as key global environmental changes that challenge agriculture and impact Cultural Landscapes. Human management of these lands plays a crucial role in enhancing agricultural resilience by adapting practices to the changing environment. Based on this context, this chapter outlines the general objective, research questions, and specific objectives of this PhD thesis.

General objective

- The main objective is to analyze the impact of global environmental changes on representative agricultural Cultural Landscapes across various spatial scales, utilizing remote sensing and GIS-based approaches to enhance resilient management practices.

Research questions

- What are the impacts of increased frequency of droughts on representative Cultural Landscapes?
- What are the impacts of increased frequency of extreme rainfall events on representative Cultural Landscapes?
- How does human management influence the resilience of representative Cultural Landscapes to global environmental changes?

Specific objectives

A To analyse the impacts of drought on representative Agricultural Cultural Landscapes (SO-A);

B To analyse the impacts of extreme rainfall events on representative Agricultural Cultural Landscapes (SO-B);

C To assess how human management affect the resilience of representative Agricultural Cultural Landscapes to global environmental change (SO-C)

1.3. Baseline: Insight from Literature

1.3.1. Global Environmental Changes and their Impacts

In February 2022, the Intergovernmental Panel on Climate Change (IPCC) has finalized the second part of the Sixth Assessment Report entitled: "*Climate Change 2022: Impacts, Adaptation and Vulnerability".* This document, along with a summary for policymakers, recognizes the interdependence of climate, ecosystems, biodiversity, and human societies. It integrates knowledge across natural, ecological, social, and economic sciences (IPCC, 2022a). It is divided into few main sections, namely "*Observed and Projected Impacts and Risks", "Adaptation Measures and Enabling Conditions*" and "*Climate Resilient Development*". A clear message from these documents is that human-induced climate change often manifests in more frequent and intense extreme weather events, causing widespread negative impacts and losses to both nature and people. In some cases, these extreme conditions have already led to irreversible impacts, as natural and human systems are pushed beyond their ability to adapt.

Two opposing phenomena emerge: on one hand, drought and high temperatures causing water scarcity and imbalances in the water cycle; on the other, increasing intense rainfall causing significant risks. In addition, climate projections suggest that both extreme rainfall events and extreme droughts are likely to become more frequent and severe in the future, with profound implications for agricultural Landscapes, including those with high cultural value. Scientific observations related to both drought and extreme rainfall events underscore the increasing hazards that climate change-induced extreme weather events pose to agricultural Cultural Landscapes. Understanding and addressing these potential ramifications, particularly in vulnerable regions, is critical.

Impact of Drought and High Temperatures

Climate change is driving the intensification of extreme events of drought and high summer temperatures, posing threats also to agricultural Cultural Landscapes. Drought is a natural hazard that cause a temporary decrease in average water availability (van Loon and van Lanen, 2013). Wilhite and Glantz (1985) defined drought based on measuring approaches: *meteorological*, *hydrological*, *agricultural* and *socio-economic*. This challenge affects various human activities on regional to continental scales (Wada et al., 2013). It particularly in Cultural Landscapes where traditional farming practices survive. Drought can lead to land abandonment (Pausas and Fernández-Muñoz, 2012), influence soil ecosystem functions and structures, negatively affect plant growth (Rahdari and Hoseini, 2012; Geng et al., 2015), and have consequences on local economies, biodiversity, and hydrogeological risk (Agnoletti et al., 2019; Renwick et al., 2013), including saltwater intrusion (Rodrigues et al., 2019). High summer temperatures exacerbate these issues by increasing evapotranspiration rates, further reducing water availability and stressing crops. Prolonged heatwaves can directly damage plant tissues, reduce yields, and lower the overall resilience of agricultural systems (Lobell et al., 2011; Schlenker and Roberts, 2009). In Cultural Landscapes, where traditional farming practices are closely tied to historical and ecological contexts, such temperature extremes can disrupt established agricultural cycles, leading to shifts in planting and harvesting times, and ultimately affecting the sustainability of these landscapes (Semenov and Shewry, 2011).

Recent occurrences, such as the summer drought in 2022, exceed historical normalities in both frequency and magnitude (Ercin et al., 2021). Agricultural drought is projected to increase globally in frequency, severity, and spatial extent by the end of the 21st century (Christian et al., 2023; Kennett et al., 2022). Specific regions identified as hotspots for agricultural drought include Central America, Europe, Tropical South America, and South Africa (Lu et al., 2019). For instance, by the end of the 21st century, an estimated 53% of European cropland could be affected by drought (Christian et al., 2023). This climate-induced shift in weather patterns poses significant risks to agricultural Landscapes, particularly for the European Union's agricultural imports, with studies indicating that over 44% of these imports could be impacted by drought (Ercin et al., 2021). The implications extend beyond cultural significance to food security. For example, a severe agricultural drought in 2021 in Central Asia, an area managed with traditional agriculture, resulted in significant crop and livestock mortality (Jiang and Zhou, 2023). In China, 60% of all grain losses due to meteorological disasters are caused by drought (Wu et al., 2013); in Eastern Australia, approximately 80% of the population is affected by widespread drought caused by large-scale climate change (Zhang et al., 2019). Similar situations are observed in Africa (Ahmadalipour et al., 2019b; Ahmadalipour et al., 2019a). This is also evident in Europe for both past and future scenarios (European Commission et al., 2020). Figure 1.4A illustrates the projected increase in drought frequency in European rivers, while Figure 1.4B shows average annual losses from drought. The agricultural sector is particularly affected (Figures 1.4C and D), with significant crop damage and increased irrigation and production costs. Integrated water resource management is crucial, as future industrial water demand is expected to increase, making water a more precious and limited resource for agriculture (Kijne et al., 2003a; Kijne et al., 2003b). This trend is also expected in urban areas, with a projected 2% increase in water demand by the end of the century (European Commission et al., 2020). As several Cultural Landscapes include traditional agricultural systems, drought could be a major problem for their future management, involving impacts on ecosystems, local production and related activities (such as tourism; Ding et al., 2011).

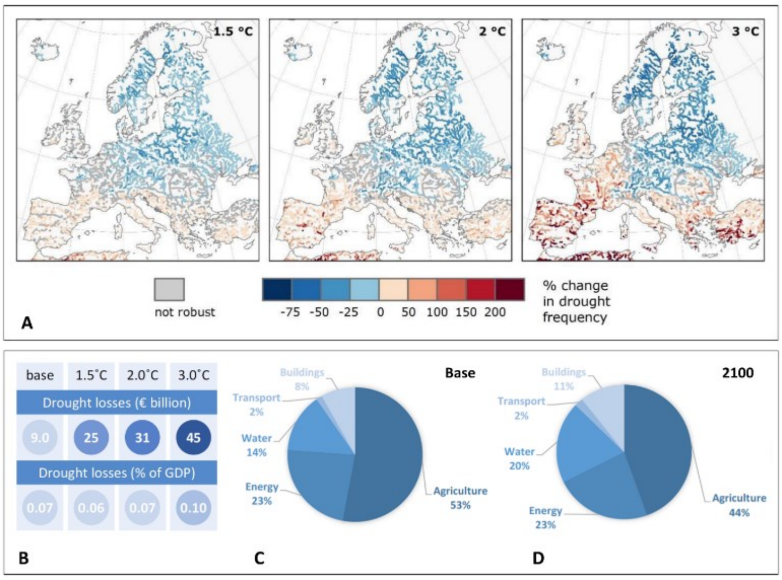

Figure 1.2 - A: projected change in drought frequency between warming levels and baseline (1981-2010) in European rivers. B: Average annual losses from drought (EU+UK) for the baseline and 2100. C and D: share of drought losses by economic sectors (EU+UK) for baseline (C) and 2100 (D). European Commission et al. (2020).

Impact of Extreme Rainfall

Conversely, during the 21st century, the frequency and intensity of precipitation are generally expected to increase (IPCC, 2022b), along with rain variability (Kundzewicz, 2008). Extreme rainfall events are becoming more frequent and severe, posing significant risks to agricultural Cultural Landscapes through flooding, soil erosion, and runoff (Ombadi et al., 2023). Projections under a high-emissions pathway (RCP8.5) suggest that globally, extreme rainfall events could increase by 55% by the end of the 21st century (Thackeray et al., 2022). In Asia, for example, long-term observations and experimental studies indicate that extreme rainfall can lead to an approximate 8.1% reduction in rice yields, a trend that may worsen under future warming scenarios (Fu et al., 2023). Additionally, the anticipated increase in extreme rainfall from 2071 to 2100 is projected to cause a notable increase in landslide occurrences in mountainous regions, further threatening these landscapes (Araújo et al., 2022; Sangelantoni et al., 2018). In northern Italy, a region with universally recognized Cultural Landscapes, precipitation is expected to increase by the end of the century (Gao et al., 2006; Zollo et al., 2016), confirming a trend observed in the Veneto region, particularly for short and intense rainfall (Sofia et al., 2017). These meteorological conditions generate surface runoff that can damage Cultural Landscapes if not properly managed. Heavy rainfall cause surface runoff due to soil insufficient infiltration capacity (Miyata et al., 2019), leading to the largely studied process of soil erosion, which largely depends on rainfall erosivity (Borrelli et al., 2017; Panagos et al., 2022). It could assume different forms and severity, from the sheet (Oakes et al., 2012), rill (Govers et al., 2007) and gully erosion (Valentin et al., 2005), to massive mass movements, such as landslides (Chan et al., 2018). In literature, studies were performed to understand water as a natural hazard in traditional cultivation systems, often examples of valuable Cultural Landscapes. For instance, (Preti et al., 2018b) analysed water paths in terraces able to create instabilities; (Calsamiglia et al., 2018) studied the sediment connectivity in similar landscapes to understand failure activations.

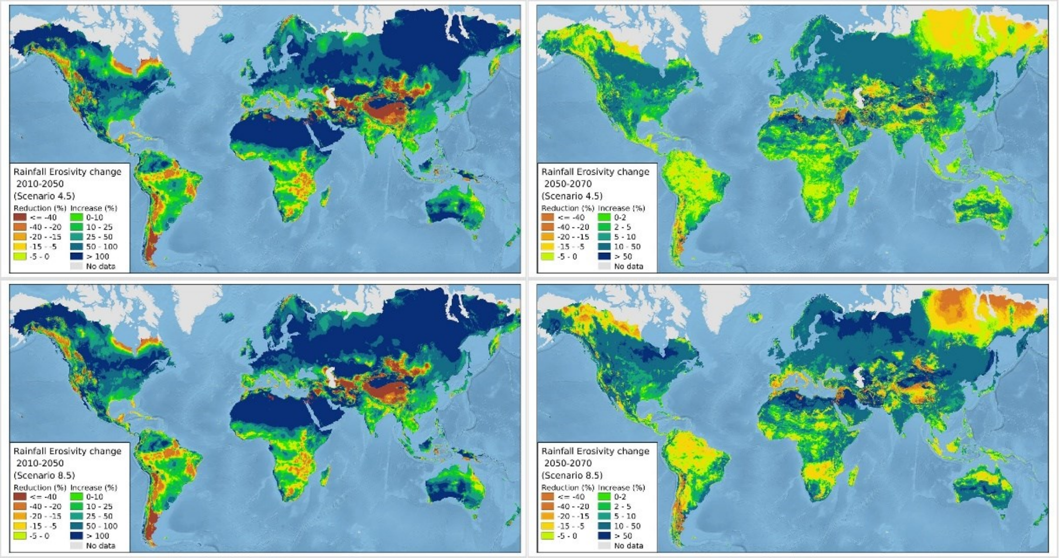

Figure 1.3 - Aggravating of global rainfall erosivity in the future due to climate change (Panagos et al., 2022)

Unsustainable Socio-Economic Development

Global environmental changes affecting Cultural Landscapes are also related to unsustainable socio-economic development. The world's population is expanding rapidly, with human activities intensifying accordingly. Steffen et al (2015) refer to this phenomenon as the "*Great Acceleration*." Future population growth is expected, with estimates projecting an increase of more than 3 billion people by mid-century (O'Neill et al., 2010). Agriculture, the primary sector providing food, has already seen strong intensification in recent decades (Gignoux et al., 2011). This trend is also evident in the expansion of urban, metropolitan, and industrial areas, as well as mining sites, leading scientists to discuss the Anthropocene (Crutzen, 2006). In this complex context, protecting areas of Cultural Landscapes is essential, often through the establishment of buffer zones, to preserve their integrity and historicity. For example, significant village expansion in a Cultural Landscape in Pakistan was observed 20 years ago, posing a threat to the local identity of the place (Nüsser, 2001). Agricultural intensification, driven by the need to sustain the growing world population, poses substantial risks to Cultural Landscapes where traditional cultivation practices prevail. Mechanization, in particular, is transforming traditional agricultural systems into forms that are more compatible with modern machinery. For instance, agricultural terraces, historically designed for manual farming, are being restructured to align with the maximum slope, facilitating the operation of agricultural tractors (Pijl et al., 2022). This alteration not only compromises the integrity of these Cultural Landscapes but also pose risk to the preservation of traditional agricultural knowledge and practices that have been transmitted across generations.

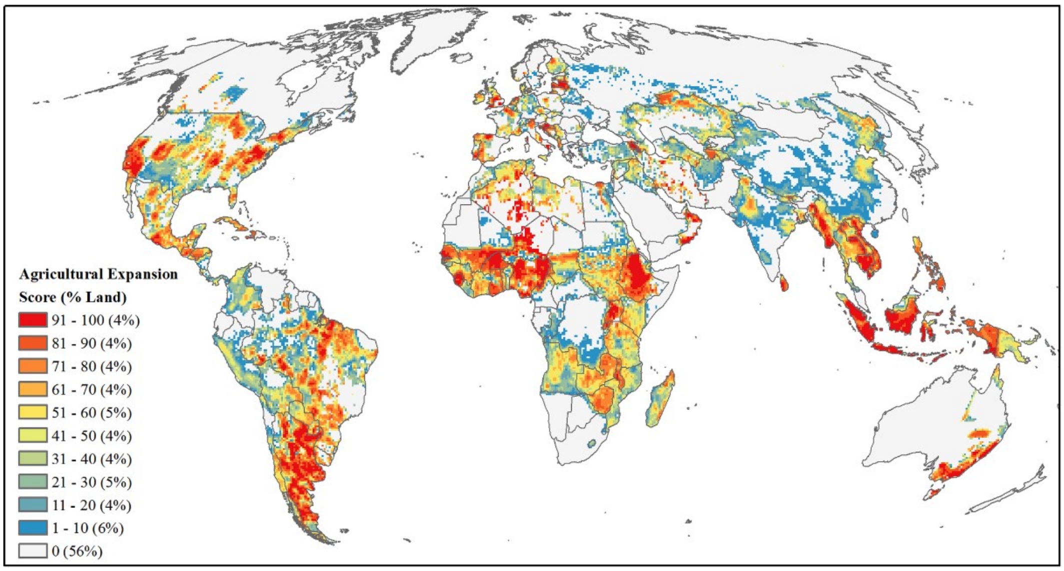

Figure 1.4 - Projected future development threat of agricultural expansion (Oakleaf et al., 2015)

1.3.2. Threats and Consequences on Cultural Landscapes: Insights from UNESCO to Shape Research Gaps and Methodology

Since 1979, UNESCO has made considerable efforts to define and update the conservation status of the heritage it preserves through the State-of-Conservation (SOC) reports. These reports identify threats using one of the most comprehensive reporting systems of any international convention (UNESCO, 2022). Fourteen primary threats (listed in Table 1.1) plus several secondary threats of natural and/or anthropogenic nature are recognized.

Primary factors affecting UNESCO properties	Buildings and Development	Transportation Infrastructure
Services Infrastructures	Social/cultural uses of heritage	Other human activities
Climate change and severe weather events	Biological resource use/modification	Physical resource extraction
Local conditions affecting physical fabric	Invasive/alien species or hyper-abundant species	Management and institutional factors
Sudden ecological or geological events	Pollution	Other factors

Table 1.1 - List of primarily factors affecting UNESCO propeties. Source: UNESCO (2022).

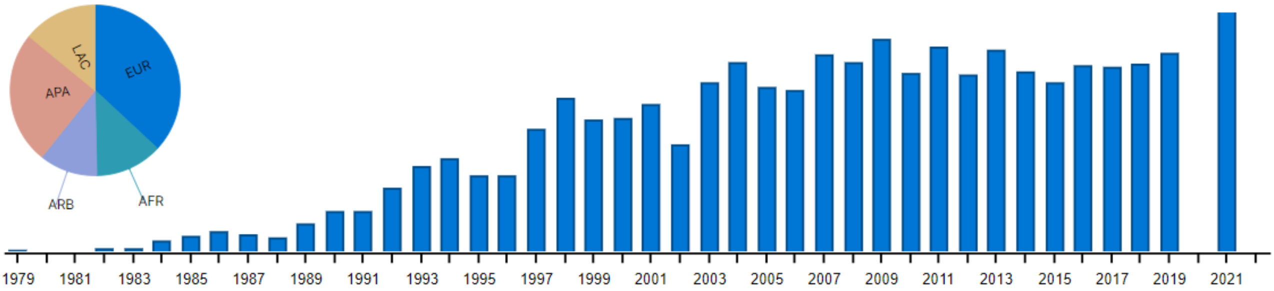

Figure 1.5 - Number of properties examined each year due to threats identified by the convention (UNESCO, 2021).

Since the first observation, more than 4000 reports have been created for about 600 properties in 147 states (UNESCO, 2022). The reporting evolution over time highlights a gradual increase in the number of sites at risk, underscoring the necessity of scientific research to analyze issues impacting cultural sites and support appropriate protection measures. Figure 1.6a represents the reports submitted due to climate change-related threats (e.g., changes to oceanic waters, desertification, drought, flooding, storms, temperature changes; 323 reports, 89 properties, 62 states). Figure 1.6b indicates reports concerning significant anthropogenic causes (e.g., industrial areas, ground transport infrastructure, major linear utilities, groundwater pollution, crop production, mining, oil and gas, housing; 2139 reports, 346 properties, 128 states). Both graphs show an increasing number of reports, demonstrating that threats are becoming more significant and international interest in these issues is increasing.

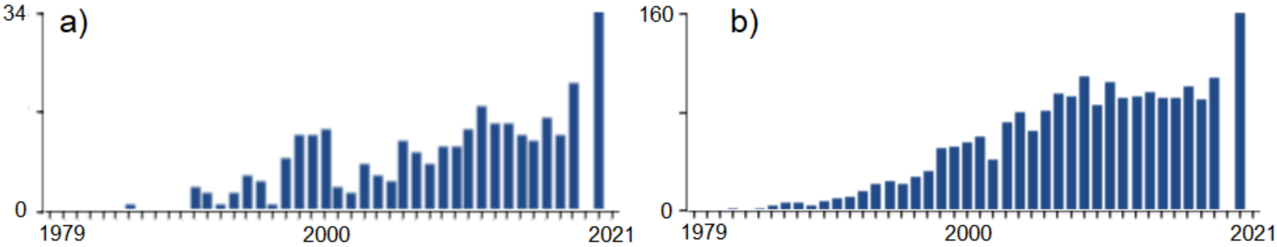

Figure 1.6 - Number of properties examined each year due to climate change-related (a) and anthropic-related (b) threats identified by the convention (UNESCO, 2021).

Figure 1.7 narrow the reporting research on Cultural Landscape: a) climate change and anthropic threats, b) anthropogenic only, c) climate only. Interestingly, the latter shows that from 1979 to 2021, only 10 reports were recorded on 8 properties, mostly post-2000. Also, almost three-quarters of these reports concern sites in Europe, such as *'Portovenere, Cinque Terre, and the Islands,'* threatened by floods and landslides in 2013.

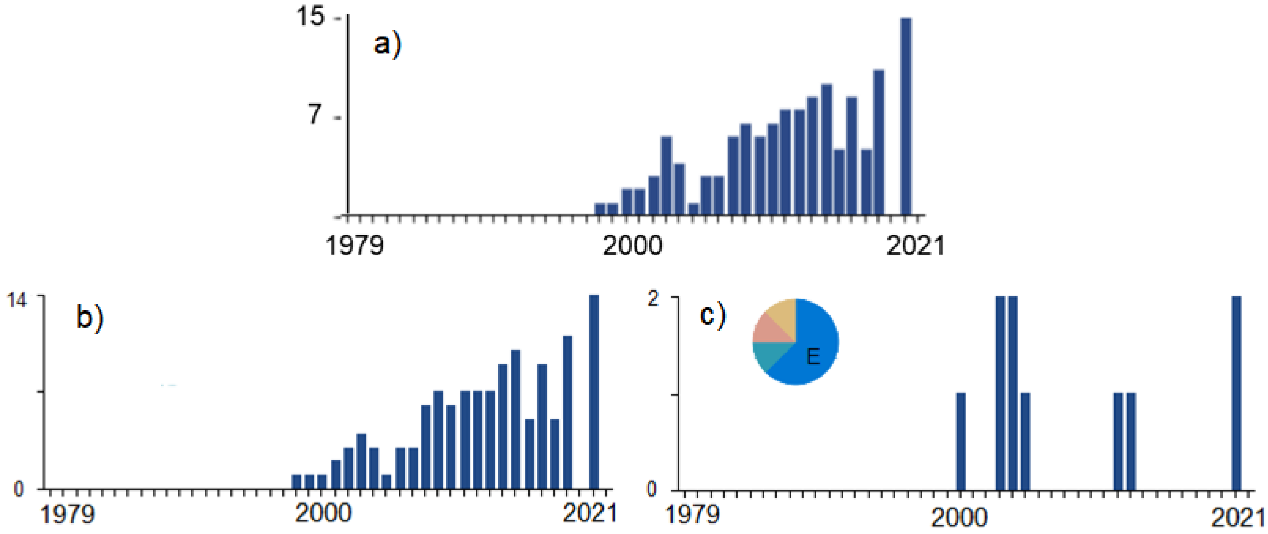

Figure 1.7 - Number of Cultural Landscape properties examined each year due to climate change-related and anthropic-related threats (toghetr in a, alone in b) for climate and c) for anthropic impact) identified by the convention (UNESCO, 2021). In general, the number of reports related to anthropic impact is higher. Therefore, during the PhD, more focus will be given to climate change (there is a need for this, also expressed by the scientific community with an increase of papers related to it in recent years - see next graph), but not neglecting some interesting anthropogenic impacts. Pie chart in c) describes the geographic distribution of the properties, with E for Europe.

This raises several questions:

a) Is it possible that despite the clear progression of climate change, only eight sites worldwide have reported related issues since 1979?
b) Is it realistic that most of these sites are in Europe?
c) Could there be a reporting bias between developed and developing countries?

Analyzing the history of the UNESCO convention highlights the importance of scientific research in defining mitigation solutions for global change-related impacts. The first document recognizing these changes as a threat dates back to 2005 (especially climate change; UNESCO, 2005b), with the first official report published in 2007, titled: "Policy Document on the Impacts of Climate Change on World Heritage Properties" (UNESCO, 2007). After the publication of this document in 2007, technology and science have made great strides and mitigation strategies have drastically improved. It is interesting to look at the international focus of scientific articles on this topic in recent years (especially after 2007) where *'Cultural Landscape'* (one of the major type of World heritage) and *'Climate change'* are combined using the Scopus platform and the following query:

> *(TITLE-ABS-KEY (cultural W/5 landscape) AND (climate W/5 change)*

The result, shown in the graph on the left of the following figure 1.8, contains 1762 documents (until 2023) and a positive trend over time, demonstrating a steady increase in interest in the topic. This is also confirmed with the addition of anthropogenic impacts, as researched with the following query and the graph on the right (682 documents).

> *TITLE-ABS-KEY (cultural W/5 landscape) AND (climate W/5 change) AND (anthro* AND impact)*

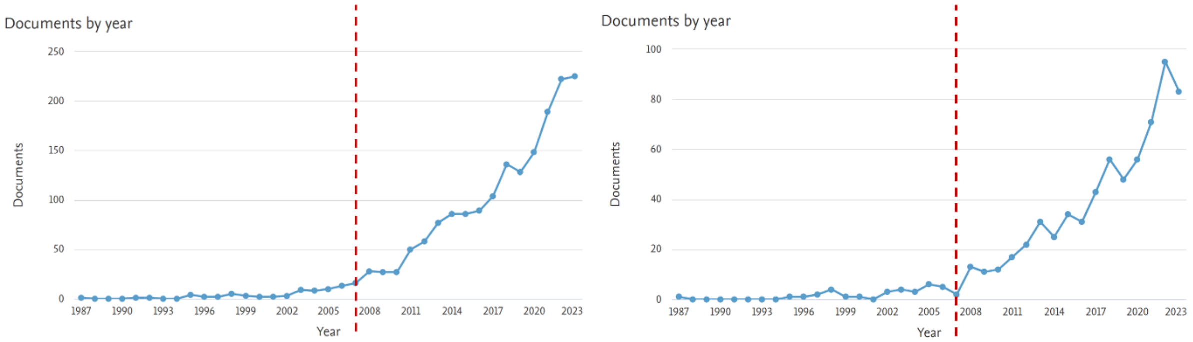

Figure 1.8 - Number of scientific articles on Cultural Landscapes related to climate change alone (left) and including anthropogenic impacts (right). The number of papers dealing with climate change issues and Cultural Landscapes is an increasingly popular topic.

Recognizing the significant progress in innovation after 2007, the World Heritage Committee in 2016 requested periodic reviews and updates of the policy document to ensure the latest knowledge and technology guide the decisions and actions of the World Heritage community (Decision 40 COM 7, paragraph 16). Consequently, discussions on updating the document began between December 2019 and January 2020, aiming to gather feedback from key stakeholders of the Convention. Among the aspects highlighted for inclusion in the updated document was the need for scientific research to assess the impacts of climate change on World Heritage properties and associated communities (UNESCO, 2020). This document thus serves as an inspiration for research opportunities, outlining key challenges and gaps, which form the pillars of this PhD project.

For example, the document indicates a lack of awareness of the alarming rate of climate change impacts on World Heritage sites, as well as the absence of concrete materials such as manuals, guidelines, and toolkits to implement mitigation policies. **Additionally, it underscores the need to implement site- or region-specific guidelines, stimulating case-study research. Notably, remote sensing is highlighted as a significant method for efficiently collecting spatial data at different scales, forming the basis of this PhD thesis**.

A literature analysis on the topics covered in this PhD project shows a steady increase in the scientific community's interest in the topic, with 1,209 scientific articles identified using the query below:

> *TITLE-ABS-KEY ((cultural W/5 landscape) AND ((cultural W/5 landscape) OR (climate W/5 change) OR gis OR (remote W/5 sensing) OR impact OR unesco OR heritage OR anthro* OR climate AND extreme OR severe OR heavy OR desertification OR drought OR flood* OR storm OR rainfall OR rainfall OR precipitation OR temperature OR erosion OR mining OR heat OR wave OR frost OR landslide OR landslides OR rockwell)) AND (EXCLUDE (DOCTYPE , "cr"))*

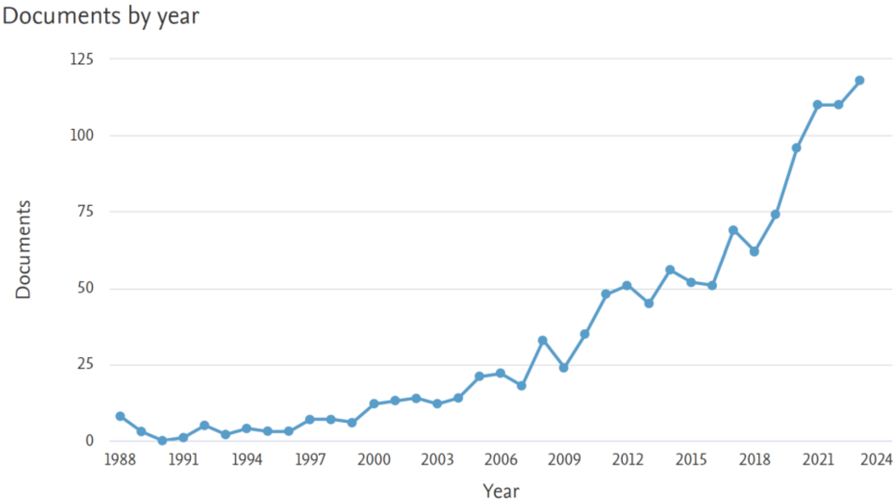

Figure 1.9 - Literature analysis on the topics covered in this PhD project such as Cultural Landscape with some of the most common climate change and anthropic-related issues.

The detailed analysis of the evolution of UNESCO policies, which clearly outline the critical issues to be addressed, the gaps to be filled, and the long-term strategic goals to be pursued, inspired the objectives of this doctoral project. The aim is to create knowledge and data for developing strategies to mitigate the impacts of global environmental changes on Cultural Landscapes.

Research can also be utilized to report critical situations, such as specific threats from climate change or anthropogenic impacts. The World Heritage Centre and Advisory Bodies may receive information from various sources other than the State Party, including NGOs, private individuals, press articles, and scientific articles. In such cases, according to Operational Guidelines, the information received is communicated to the State Party to verify the source and content and to obtain clarification on the reported issue. The State Party's response is then reviewed by the relevant advisory bodies and incorporated into the conservation status report (SOC) if the threat is confirmed.

1.3.3. Remote sensing, Geographic Informative System (GIS) and Modelling

Remote sensing could open up innovative frontiers of knowledge for global environmental changes impact assessment in Cultural Landscapes. It offers opportunities in terrain surface observation and processes investigation (Lillesand et al., 2015) and Geographical Information System (GIS) cloud be used for data management and visualization (Cooperative and Collins, 1988). Earth’s surface researches are performed using several techniques, at different spatial scales, observing past trends or simulating future scenarios. These technologies are particularly strategic to investigate climate change issues on cultural heritage.

Numerous international space missions provide constantly updated open-source information at global scale. Satellites are useful tools for assessing the risks threatening our planet, both of environmental and anthropogenic nature (Traore and Tangara, 2017). They allow land monitoring, identifying critical issues related to climatic adversities (such as drought; (Golian et al., 2019) and potential negative effects on the landscapes. Furthermore, through land use analysis, it is possible to exploit this information to outline trends in human developments, such as the expansion of urban areas or industrial districts, or to monitor the agriculture condition (e.g. through the analysis of crop vigour; (Karthikeyan et al., 2020). While remote sensing data provide a past/current overview of the planet's characteristics, models permit to hypothesise possible future scenarios. For instance, climate change could be studied by future climate projections. One of the most advanced research in this field is provided by (Beck et al., 2018). The authors show the present and future climate world maps (scenario RCP8.5) created by ensembling 32 climate models.

A similar approach could be used to investigate socio-economics future developments. For example, (Kii, 2021) shows how the population will evolve according to 5 future scenarios (Shared Socioeconomic Pathways; SSPs), in more than 16000 cities worldwide, from 2010 until 2100. This expansion will be reflected in the evolution of urban land. (Chen et al., 2020) show through an artificial neural network (ANN) approach based on demography, urbanisation rate and GDP data an increase in urban land demand for scenarios SSP1-5 (baseline 2015-2100). Such data could be used to identify potentially unsustainable population growth (and related change in land use) in the surrounding area of Cultural Landscapes, as they pose a potential risk to these fragile sites. Agricultural sites are those most at risk. Indeed, according to Chen's projections, 50-63% of new urban expansion will occur on land currently devoted to agriculture. This knowledge can be used to compare actual and future conditions of Cultural Landscapes identifying potential critical developments that should be investigated at a more detailed scale.

By focusing the research on a local scale, it is possible to study in detail the impacts of Global Environmental Changes on specific Cultural Landscapes. Three-dimensional reconstruction of land surfaces represents a first step in developing mitigation strategies. Indeed, digital elevation models (DEM) allow a detailed representation of the often complex morphology of such sites. Some DEM-based algorithms for semi-automatic surface features detection are available in the literature. For example, (Sofia et al., 2014) proposed a terraces extraction method based on slope analysis, or (Pirotti and Tarolli, 2010) show a channel extraction technique using terrain curvature. In addition, DEMs could be used for processes investigation purposes.

Understanding the movement of water on the Earth's surface is important for mapping areas potentially susceptible to erosion and collapses (such as in traditional agricultural Landscapes (Tarolli et al., 2019, 2014). This can be determined using geomorphological indicators or physical models for runoff and soil erosion investigations (Pandey et al., 2016). There are several methods for generating 3D models of landscapes. Two widely used techniques are the LiDAR (airborne laser scanner) and the UAV-SfM (Uncrewed Aerial Vehicles paired with the Structure-from-Motion technique). Both provide high-resolution point clouds of the surface, a preliminary output for DEM generation. LiDAR is widely used for landscape and regional investigation purposes. For instance, it was used for research in historical landscapes (Chase et al., 2017), or traditional cultivation systems (Godone et al., 2018). UAV-SfM represents a flexible and cost-effective surveying method for DEMs generation (James and Robson, 2014). Providing very high resolution, it is often applied at local/farm scale to understand runoff and soil erosion phenomena in steep slope agriculture using a modelling approach. A very interesting aspect of these surveys is their replicability over time. In fact, by planning surveys at different moments, or assuming future topographic variations by working on digital models, it is possible to understand the geomorphological evolution of a landscape. For example, (Mauri et al., 2021) used two multi-temporal UAV-SfM surveys to understand the activation of landslides in an agricultural terraced system.

1.3.4. Literature gaps

Appreciating the priceless value of Cultural Landscapes requires understanding that the world is changing. Literature research examines these landscapes from both a humanistic perspective—such as international debates for site identification based on social, historical, and cultural examination—and an environmental point of view, including the analysis of the physical processes affecting them. However, there are still gaps in scientific knowledge that need to be addressed to better identify the threats posed by Global Environmental Changes and to support protection actions. This section delineates the primary research gaps identified in current scientific literature and policy documents, which support the focus and objectives of this PhD project. Addressing these gaps is crucial for advancing the understanding and management of the impacts of global environmental changes on Cultural Landscapes.

A significant literature gap is the current insufficiency of data specifically relevant to understanding climate change impacts on World Heritage properties, particularly those shaped by traditional agricultural practices. UNESCO states:

> *"There is presently a lack of data that is specifically relevant to understanding climate change impacts on World Heritage properties, particularly cultural properties. This situation is further compounded by a lack of adequate capacity and financial resources for research and its application, especially in developing countries, to understand and address climate-related issues. Such lack of knowledge and capacity makes it difficult to assess the loss of key values of World Heritage properties as a consequence of climate change. Addressing these gaps in knowledge, information and capacity, and performing vulnerability assessments will assist in determining priorities for management action" https://whc.unesco.org/uploads/activities/documents/activity-397-2.pdf.* (UNESCO, 2007)

This gap underscores the necessity for targeted research to provide detailed, site-specific data on climate change effects on cultural heritage sites. The scarcity of such data limits the ability to develop effective mitigation and adaptation strategies. Therefore, this PhD project aims to generate new insights and data to fill this crucial gap, particularly focusing on under-researched areas and properties in developing countries.

Furthermore, UNESCO highlights the necessity of developing guidelines tailored to specific sites or regions. These guidelines are vital for the effective management and protection of Cultural Landscapes threatened by global environmental changes. UNESCO notes a clear need to implement site- or region-specific guidelines, stimulating case-study research. Remote sensing is highlighted as a significant method for efficiently collecting spatial data at different scales (UNESCO, 2007). For this reason, this PhD project utilise remote sensing technologies to gather detailed spatial data across various scales, contributing to the creation of comprehensive guidelines applicable to specific agricultural Cultural Landscapes. By conducting case-study research, this project aims to produce insights and practical recommendations for policymakers and site managers.

Finally, a prevalent issue in current research is the tendency to assess the vulnerability of cultural heritage through static observations of past conditions, which fails to account for future scenarios and the dynamic nature of environmental processes. Cook et al., (2019) and (Fatorić and Biesbroek, 2020) emphasize the limitations of this static perspective, highlighting the lack of knowledge about climate change vulnerabilities and natural hazard risks as significant barriers to developing effective mitigation strategies. These authors suggest that analyzing the potential impact of global environmental changes on representative Cultural Landscapes globally could help fill these gaps. To address this, this PhD research adopt a forward-looking approach, integrating future climate scenarios and their potential impacts on agricultural Cultural Landscapes. By analyzing these dynamic interactions, the research aims to provide a deeper understanding of vulnerability and resilience, thereby aiding in the development of robust, long-term mitigation and adaptation strategies.

1.4. Thesis Scope and Organisation

Scope

The thesis aims to select Cultural Landscapes where traditional rural landscapes, agricultural practices, and water management techniques persist, in order to analyze the potential impacts of Global Environmental Changes on these areas. Specifically, it examines climate change as manifested through extreme weather events (such as high temperatures, droughts, and heavy rainfall), as well as unsustainable anthropogenic practices. The analyses were conducted using remote sensing and spatial data analysis within a GIS environment. The results contribute to understanding the risks Cultural Landscapes face due to global environmental changes, propose possible mitigation measures for each case study, and collectively raise awareness among stakeholders, policymakers, and other scientists, encouraging further research on the topic.

Selected Representative Cultural Landscapes

The study areas analyzed in this PhD project adhere to the original definition of Cultural Landscapes by Sauer (1925) (see section 1.1), including, but not limited to, representative sites listed in official lists (such as international conventions). The case studies are highly diverse to capture the vast complexity and variety of Cultural Landscapes.

A Multi-Scale and Multi-Technology Remote Sensing Approach

The methodology is based on using various remote sensing platforms to acquire spatial data at different scales. For global, continental, and regional analyses, satellite data was utilized. For detailed scale analysis (landscape), LiDAR and Drone remote sensing data were also employed. Additionally, for some study areas, the methodology included literature reviews.

Thesis Structure

This thesis is structured around ten scientific articles—nine of which have been peer-reviewed and published, with one conference paper currently under review—along with a concluding chapter that explores the need of zooming out from representative case studies to the entire UNESCO Cultural Landscape's list.

These articles collectively address the three specific objectives of the thesis:

- **SO-A**: Investigating the impacts of drought on Cultural Landscapes.
- **SO-B**: Examining the effects of extreme rainfall events on Cultural Landscapes.
- **SO-C**: Analyzing the role of human management on the resilience of representative Cultural Landscapes to global environmental change.

The thesis is organized into three main parts:

- **Part A**: Articles mainly addressing SO-A.
- **Part B**: Articles mainly focusing on SO-B.
- **Part C**: Articles mainly related to SO-C.

While some articles may touch on multiple specific objectives, they are placed in the section that best aligns with their primary focus. Each article employs a range of methodologies and covers various spatial scales, from global to local perspectives. Figure 1.10 provides an overview of the distribution of objectives, methodologies, and spatial scales across the articles.

The chapter 12 presents a preliminary exploration of climate change threats to UNESCO agricultural Cultural Landscapes, offering a broader perspective on the implications of global environmental changes on these critical areas.

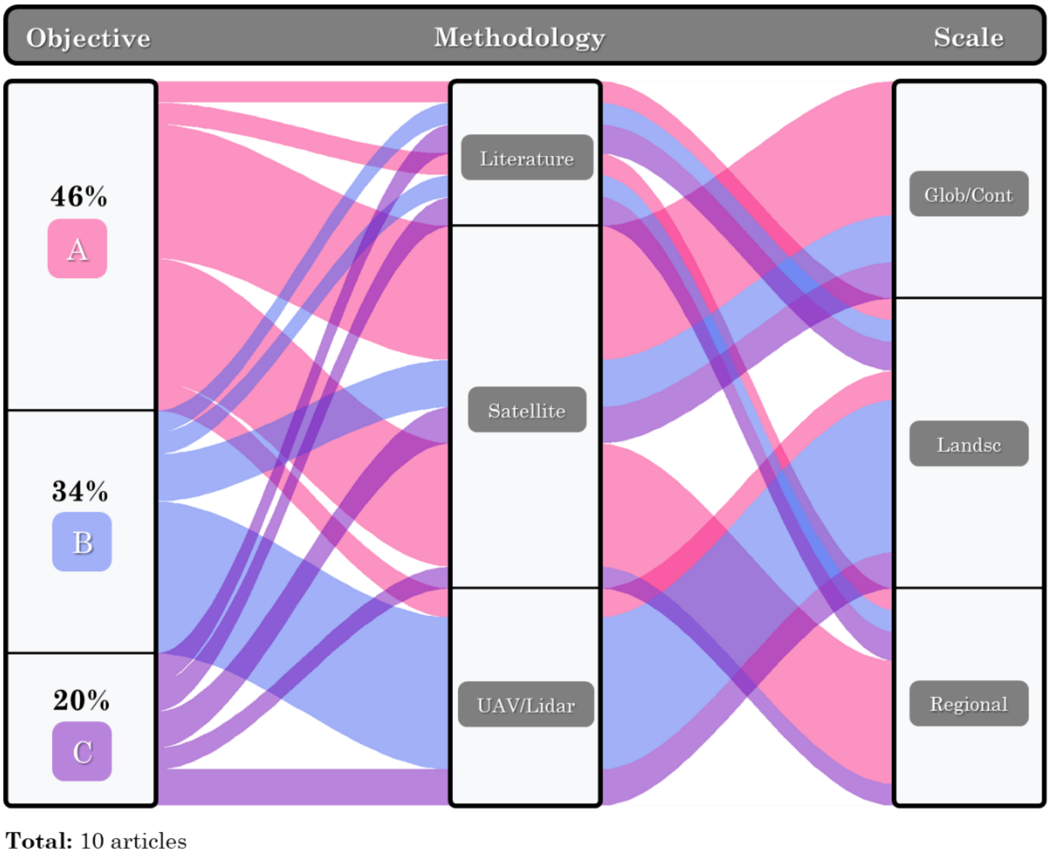

Figure 1.10 - Conceptualization of the PhD structure, illustrating the connection between the Specific Objectives (A, B, and C), the selected Remote Sensing and GIS Methodologies (UAV/LiDAR, Satellite, and Literature), and the corresponding spatial scales (Global/Continental, Regional, and Landscape for the highest resolution).

Table 1.2. The scientific articles included in this PhD thesis. With color the main Specific Objective addressed foe each article; in grey, secondary ones.

Scientific Article	**SOC-A** (PART A)	**SOC-B** (PART B)	**SOC-C** (PART C)
Straffelini, E., Wang, W., & Tarolli, P. (2024). European vineyards and their Cultural Landscapes exposed to record drought and heat. *Agricultural Systems*, 219, 104034. https://doi.org/10.1016/j.agsy.2024.104034. Q1-IF (2023): 6.1	🟥		▨
Wang, W., Straffelini, E., & Tarolli, P. (2024). 44% of steep slope cropland in Europe vulnerable to drought. *Geography and Sustainability*, 5(1), 89-95. https://doi.org/10.1016/j.geosus.2023.12.001. Q1-IF (2022): 9.7	🟥		▨
Straffelini, E., & Tarolli, P. (2023). Climate change-induced aridity is affecting agriculture in Northeast Italy. *Agricultural Systems*, 208, 103647. https://doi.org/10.1016/j.agsy.2023.103647. Q1-IF (2022): 6.6	🟥		▨
Luo, J., Straffelini, E., Bozzolan, M., Zheng, Z., & Tarolli, P. (2024). Saltwater intrusion in the Po River Delta (Italy) during drought conditions: Analyzing its spatio-temporal evolution and potential impact on agriculture. *International Soil and Water Conservation Research, 12(3), 714-725.* https://doi.org/10.1016/j.iswcr.2023.09.009. Q1-IF (2023): 7.4	🟥		▨
Straffelini, E., Luo, J., & Tarolli, P. (2024). Climate change is threatening mountain grasslands and their cultural ecosystem services. *Catena*, 237, 107802. https://doi.org/10.1016/j.catena.2023.107802. Q1-IF (2022): 6.2	▨	🟦	▨
Straffelini, E. (2024). Multitemporal remote sensing for monitoring hydro-erosive process dynamics in terraced Cultural Landscapes. AIIA Conference Under Review.		🟦	▨
Wang, W., Straffelini, E., & Tarolli, P. (2023). Steep-slope viticulture: The effectiveness of micro-water storage in improving the resilience to weather extremes. *Agricultural Water Management*, 286, 108398. https://doi.org/10.1016/j.agwat.2023.108398. Q1-IF (2022): 6.7	▨	🟦	▨
Straffelini, E., Carrillo, N., Schilardi, C., Aguilera, R., Orrego, M. J. E., & Tarolli, P. (2023). Viticulture in Argentina under extreme weather scenarios: Actual challenges, future perspectives. *Geography and Sustainability*, 4(2), 161-169. https://doi.org/10.1016/j.geosus.2023.03.003. Q1-IF (2022): 9.7	▨	▨	🟪
Straffelini, E., & Tarolli, P. (2022, November). Viticulture and Cultural Landscapes: remote sensing and Earth surface processes modelling to promote sustainable agricultural practices. In 2022 IEEE Workshop on Metrology for Agriculture and Forestry (MetroAgriFor) (pp. 292-297). *IEEE.* https://doi.org/10.1109/MetroAgriFor55389.2022.9964716	▨	▨	🟪
Wang , W., Straffelini, E., Pijl, A., & Tarolli, P. (2022). Sustainable water resource management in steep-slope agriculture. *Geography and Sustainability*, 3(3), 214-219. https://doi.org/10.1016/j.geosus.2022.07.001. Q1-IF (2022): 9.7	▨	▨	🟪

Part A – Drought & High Temperature in Cultural Landscapes

The increased frequency of droughts and high temperature events poses significant threats to Cultural Landscapes, as demonstrated by recent research on various European and Italian agricultural areas. The **Part A** of this PhD thesis (sections 2-3-4-5) incorporates studies that reveal how such threats affect not only the environment but also the cultural heritage embedded in agricultural practices. It delves in the following case studies:

- **In European Vineyards**, the article *"European vineyards and their Cultural Landscapes exposed to record drought and heat"* examines the severe drought and hot conditions of summer 2022. The research highlights that extended droughts and high temperatures have caused substantial impacts to vineyards, influencing both the plants and the cultural traditions of viticulture. The study emphasizes the need for sustainable irrigation and management practices to protect these historically significant landscapes.
- **In Steep-Slope Croplands**, the paper *"44% of steep slope cropland in Europe vulnerable to drought"* extends this analysis to mountainous regions in Europe. These areas, with their limited water retention and high runoff, could be susceptible to drought. The study found that nearly half of the steep-slope croplands experienced significant stress due to the 2022 drought, threatening traditional farming practices integral to these Cultural Landscapes. Adaptation strategies discussed in the paper are crucial to mitigate these impacts.
- **In Northeast Italy**, *"Climate change-induced aridity is affecting agriculture in Northeast Italy"* highlights how increased aridity threatens traditional agricultural systems in culturally significant areas, including UNESCO and GIAHS sites. The study compares historical and projected climate data, revealing risks to food security and cultural heritage. Effective water management and sustainable agricultural practices are essential to preserving these landscapes.
- **In the Po River Delta**, the study *"Saltwater intrusion in the Po River Delta (Italy) during drought conditions"* addresses how drought exacerbates saltwater intrusion, adversely affecting crop health in this UNESCO World Heritage site. The findings stress the need for preventive measures to safeguard the delta's cultural and agricultural significance.

2. Record Drought and Heat Threaten European Vineyards and Their Cultural Value

Context

Europe, especially the Mediterranean region but not exclusively, boasts a millennia-old history of wine production. Over the centuries, new grape varieties and production methods have led to significant territorial expansion of vineyards, shaping entire landscapes, creating traditions and cultural exchanges, and supporting the economy from a local scale to a global market worth billions of dollars. Viticulture in various diverse areas still strives to protect its roots and preserve its traditions, resulting in numerous culturally significant landscapes. Remarkable examples are vineyards inscribed in UNESCO and FAO lists. However, climate change and, at times, unsustainable cultivation practices pose significant threats to European viticulture. While scientific literature mainly focuses on understanding potential territorial shifts in viticulture due to climate change or analyzing extreme events at a local scale, a comprehensive overview of the entire European viticultural system under threat from exceptional events is still lacking. Extended periods of drought combined with high temperatures are particularly problematic, as they cause direct damage to plants and fruits but also challenge vineyard management systems. In addition, such conditions can require the installation of irrigation systems to address water shortages and lower temperatures, with significant repercussions for water resource management. Understanding the vineyards are risk due to drought and excess heat is the first step for planning mitigation strategies for protecting European vineyards and their cultural value.

The article

This section is based on the scientific article "*European vineyards and their Cultural Landscapes exposed to record drought and heat*". Published in 2024 in the "*Agricultural System*" scientific journal (*Q1 in Agriculture, Multidisciplinary; IF 2023: 6.1*), it serves as a crucial starting point for analyzing which vineyards in Europe are most at risk due to drought and heat during extreme events, including those officially recognized as Cultural Landscapes by international conventions. The paper examines one of the most severe periods ever recorded in Europe: the summer of 2022. It first analyzes the main climatic parameter anomalies (such as temperature, precipitation, and soil moisture) across European vineyards compared to historical records. It then maps the vineyards that experienced a decrease in vegetation health due to water stress and high temperatures during this period. Finally, it focuses on potential sustainable strategies that farmers, stakeholders, and decision-makers can pursue to enhance the resilience of European vineyards.

> This article primarily addresses SO-A by evaluating the impact of extreme drought and heat on European vineyards, including those recognized as Cultural Landscapes. It uses satellite data and GIS to identify vineyards at risk during the summer of 2022, highlighting the need for sustainable water management. It partially contributes to SO-C by suggesting mitigation strategies to enhance resilience against similar future events.

PEER-REVIEWED & PUBLISHED SHORT COMMUNICATION

European vineyards and their Cultural Landscapes exposed to record drought and heat

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CRediT authorship contribution statement:
Eugenio Straffelini: Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Abstract

CONTEXT

European vineyards, producing over 50% of the world's wine and hosting significant Cultural Landscapes, face threats from climate change and related severe weather events. The summer of 2022, especially July, posed significant challenges due to extreme drought and high temperatures. However, this period also provided an opportunity to study how such events might involve viticulture in Europe and to explore mitigation solutions.

OBJECTIVE

The objectives are (1) to characterize the severity of the extreme event of July 2022 in European wine regions regarding primary climatic parameters, (2) map vineyards at risk due to agricultural drought and high land surface temperature, and (3) discuss the role of various water-related interventions for mitigating similar events.

METHODS

After identifying the locations of European vineyards using the Corine Land Cover 2018 (CLC2018), open-access satellite data were employed to: (1) assess anomalies in Maximum Air Temperature (NAT_m), Land Surface Temperature (LST), Precipitation (P), and Soil Moisture (SM) in July 2022 compared to long-term averages; (2) identify regions at higher risk that experienced extreme agricultural drought (Vegetation Health Index, VHI = Extreme) and LST > 35°C.

RESULTS AND CONCLUSIONS

In July 2022, European vineyards experienced an average increase of 11% in NAT_m, a 9% rise in LST, and a reduction of 47% in P and 30% in SM compared to historical averages. 18% of European vineyards were at risk of drought and excessive heat, particularly in Portugal (31%), France (27%), and Italy (21%), including 10 viticultural Cultural Landscapes. Findings highlight the urgent need for long-term sustainable water management practices over emergency interventions. This research supports informed decision-making, emphasizing that climate resilience is necessary for preserving the cultural heritage of European wine-growing areas.

SIGNIFICANCE

This research provides an overview of the dynamics of extreme events on viticulture at a continental scale, promoting climate-aware viticultural systems and offering insight scalable to global viticulture under changing climatic conditions.

Keywords. European viticulture; Drought; Heatwave; Remote Sensing; Sustainable Water Management

2.1. Introduction

Vineyards are widespread agricultural systems in both hemispheres, and Europe plays an important role in managing about 45% of the global vine area in 2.2 million holdings (Eurostat, 2023a). Viticulture often involves a multifaceted integration of agricultural products, tourism, artistic endeavors, and traditional cultivation practices (Flores and Medeiros, 2016). Wine-growing Cultural Landscapes are optimal cases. Unique characteristics such as indigenous water management, terraces, and distinctive vine cultivation systems contribute to enriching these landscapes beyond economic considerations, embodying them with historical and cultural significance. Their importance is evidenced by their inclusion in protection lists such as UNESCO Cultural Landscapes and FAO-GIAHS (Globally Important Agricultural Heritage Systems). Notable examples of grape-growing regions include UNESCO sites like the "Alto Douro Wine Region" in Portugal (known for Port wine) and the Prosecco Hills of Conegliano and Valdobbiadene in Italy (famous for Prosecco wine), along with the FAO-GIAHS site of the "Malaga Raisin Production System in La Axarquía" in Spain.

The sustainability of European vineyards and related Cultural Landscapes is increasingly at risk due to climate change (Tarolli et al., 2023b; van Leeuwen et al., 2024). This growing threat is manifested in different ways. On the one hand, impacts include the occurrence of heavy rains that cause soil erosion and flooding (Ramos and Martínez-Casasnovas, 2010). Conversely, periods of drought lead to severe water shortages that further challenge the delicate balance of these systems and their management (Santillán et al., 2019). Furthermore, rising temperatures characterized by excessive heat inflict direct damage on plants, altering physiological processes, and affecting the overall resilience of vineyards (Costa et al., 2019). Steep-slope agricultural areas, hosting some of the most high-value vineyards, are particularly challenged by climate change and drier and hotter conditions (Wang et al., 2022a).

Although 2023 set a record in Europe in terms of high temperatures (+0.83°C compared to the 1991-2020 average; (Copernicus, 2024a)), and 2024 is shaping up to be another possible exceptionally hot year (Copernicus, 2024b), summer 2022 presented a more complex scenario, making it one of the toughest moments for European viticulture. Compared to 2023, particularly in July, 2022 experienced not only high temperatures but also scares precipitation and widespread drought (European Drought Observatory, 2024). This event posed a significant danger to European agriculture, affecting more than 300,000 km^2 of cropland and leading to consequences on production (European Environment Agency, 2023). For example, the event caused significant damage to Italian agriculture, affecting 10% of the sector and resulting in 6 billion euros in losses, particularly affecting key products such as olive oil (30%), tomatoes for sauce (10%), and durum wheat (5%), despite an increase in sown areas (Coldiretti, 2022). The wheat yields of Spain and Portugal in 2022 decreased by 29% and 23% from the best five-year period 2012-2012; Hungary and Romania lost 60% and 46% of corn; Spain and Hungary lost 26% and 20% of barley; and Hungary and Romania lost 42% and 28% of sunflowers, resulting in an economic loss up to 3,500 million euros (Pinke et al., 2024). In several sectors, growers implemented emergency measures to cope with anomalous weather conditions, trying to mitigate the tangible threat of losing part of their production, with possible economic and social consequences, and implications for food security.

Whether the potential risk faced by some corps has been already assessed, such as main cereals (Eurostat, 2023b), there is still a lack of understanding regarding the potentially affected European vineyards and related Cultural Landscapes. To fill this gap, our study aims to initially analyze some primary climate parameters for Europe during July 2022, including Near Max Air Temperature (NAT_m), Land Surface Temperature (LST), Precipitation (P), and Soil Moisture (SM), with a specific quantification for vineyards. In detail, we focused on mapping vineyards that were at risk due to the combination of extreme agricultural drought (employing the Vegetation Health Index; VHI) and critically high LST. We utilized open-access satellite products in Google Earth Engine to conduct a European-scale overview. This single but exceptionally severe drought and heat event is scientifically significant and can provide insight into how similar combined events could affect viticulture on a European scale. Therefore, the broader goal is to provide key information for a more informed and targeted response to support viticulture that needs to adapt to new climate scenarios. In addition, we intend to promote more specific research on vineyard management during critical events and emphasize the importance of sustainable water use.

2.2. Materials and methods

2.2.1. Study area

The spatial data related to the vineyards (Figure 2.1) were extracted from the CORINE Land Cover (CLC) for 2018, currently the most up-to-date available within the project. CLC includes over 40 classes, encompassing artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands, and water bodies, with a thematic accuracy of over 85%. The Minimum Mapping Unit (MMU) for areal features in the product is set at 25 ha, while for linear features, it has a minimum width requirement of 100 m (Büttner and Kosztra, 2017). In addition, the European grape-growing Cultural Landscapes under study were identified and mapped by consulting the official UNESCO Cultural Landscape and FAO-GIAHS lists.

2.2.2. Climate analysis in European vineyards

The parameters (X) employed in the investigation of the extreme drought and heat event in July 2022 included Near Max Air Surface Temperature (NAT_m; 2 m above the surface), Land Surface Temperature (LST), Precipitation (P), and Soil Moisture (SM), assessed monthly and summarized in Table 2.1. They are key parameters for understanding the possible impacts of extreme weather events on vineyard health and management, as well as wine production quantity and quality. NAT_m helps identify extremely hot periods that could have a significant impact on vineyard health (Fraga et al., 2020). Similarly, LST provides insights into the overall heat balance of vineyards (Magarreiro et al., 2019); while high temperatures

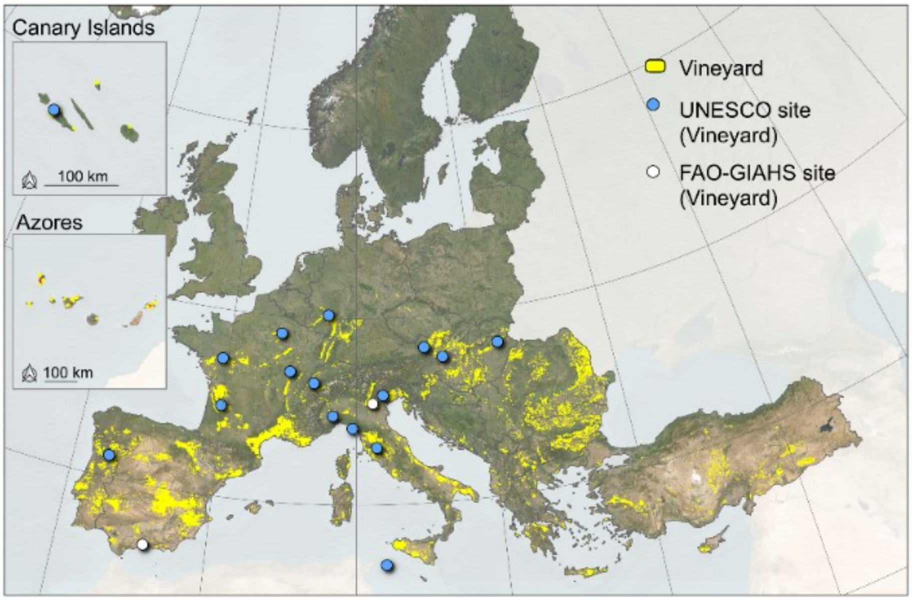

Figure 2.1 – The spatial distribution of European vineyards based on CLC2018, together with the locations of notable Cultural Landscapes of wine production listed in UNESCO (blue dots) or FAO-GIAHS (white).

can accelerate grape ripening and, in some cases, improve wine quality, high temperatures can lead to excess evapotranspiration and plant damage. P, especially during summer, controls water availability in vineyards (Romero et al., 2022). This is particularly crucial for historic and Cultural Landscapes without irrigation. SM directly affects the availability of water for plant roots (Webb et al., 2013). It can help to understand water scarcity or excess, guiding irrigation planning. We explored their anomalies in percentage terms using Google Earth Engine by comparing the observed values for July 2022 with the long-term average, as defined by Equation (1) (Touati et al., 2020).

$$XAnomaly_{LTA\,(m,y)} = \frac{(x_{(m,y)} - x_{LTA(m)})}{x_{LTA(m)}} \qquad (1)$$

$XAnomaly_{LTA\,(m,y)}$ is the anomaly calculated for the parameter X (NAT_m, LST, P, and SM); $X_{(m,y)}$ represents the observed value of the X for July 2022; $X_{LTA(m)}$ is the long-term average of X for July, calculated based on historical data availability. All parameters were investigated both for Europe and specifically for its vineyard locations.

NAT_m was chosen due to its strong correlation with heat stress on vines, which for the northern hemisphere can be a significant risk already when exceeding 30°C during July (Bois et al., 2014). Temperature data were extracted from the ERA5-Land Monthly Aggregated database for Europe (Muñoz-Sabater et al., 2021), which provides data with a spatial resolution of 0.1° (approximately 11 km). In addition to air temperature, we analyze daytime LST, a crucial factor in causing damage to vines, both to the above-ground portion of the plant and the root system (Costa et al., 2023). LST data were acquired from the MODIS satellite at a resolution of 1 km. For NAT_m and LST, positive hot (e.g.: 1°C - 4°C) and very hot (e.g.: >4°C) anomalies could indicate an alert for potential impacts on vine health and possible severe plant damage, respectively (Moutinho-Pereira et al., 2004). Negative cold (e.g.: -1°C – -4°C) or very cold (e.g.: <4°C) anomalies may indicate a possible decrease in plant growth and fruit production.

Precipitation data were also obtained from the ERA5-Land Monthly Aggregated database. Positive wet (e.g.: 1mm/day – 4mm/day) and very wet (e.g.: >4mm/day) anomalies could indicate beneficially increased water availability, however, with a possible risk of flood and soil erosion for extreme values. Instead, negative dry (e.g.: -1mm/day – -4mm/day) and very dry (e.g.: <4mm/day) anomalies are associated with potential water stress for vines, further investigated by SM. The latter was estimated utilizing the NASA-USDA Enhanced SMAP Global program, which offers surface soil moisture data at a spatial resolution of 10 km every three days (Entekhabi et al., 2010; Mladenova et al., 2020). These data are valuable for understanding areas that suffer from insufficient precipitation and can provide support to irrigation strategies (Wyatt et al., 2021). Positive wet (e.g.: 3mm – 12mm) and very wet (e.g.: >12mm) anomalies could indicate potentially optimal or excessive soil moisture conditions, for example increasing the risk of diseases. Instead, negative dry (e.g.: -3mm – -12mm) and very dry (e.g.: <12mm) anomalies could be alarms for potential water stress for vines. Class data provided are indicative, as local conditions such as soil characteristics or grape wine variety can have a significant influence.

2.2.3. Mapping vineyard at risk

While analyzing anomalies in temperature, precipitation, and soil moisture offered insights into the extreme event in July 2022, directly applying these findings to study vineyards at risk is challenging due to the significant influence of local vineyard conditions. To overcome this issue, we employed a satellite-based observation methodology to identify vineyards at risk on the European scale, a methodology already successfully tested for agricultural systems in northern Italy (Straffelini and Tarolli, 2023). This approach enabled to mapping of the areas exhibiting deteriorated vegetation health conditions and elevated LST during July 2022 compared to historical data. The severity of agricultural drought was assessed using the Vegetation Health Index (VHI), a tool suggested by the United Nations Platform for Space-Based Information for Disaster Management and Emergency Response (UN-SPIDER, 2024). VHI values greater than 40 indicate non-drought conditions while decreasing values show increasing agricultural drought severity (extreme severity for VHI < 10). It was classified into five classes of severity of agricultural drought, following the UN-SPIDER recommendations. VHI combines the Vegetation Condition Index (VCI) and the Temperature Condition Index (TCI), as reported in Equation (2):

$$VHI = \alpha * \mathrm{VCI} + (1 - \alpha) * \mathrm{TCI} \qquad (2)$$

The VCI was used to analyze vegetation health during July 2022 by assessing the deviation of the month's Normalized Difference Vegetation Index (NDVI) from historical minimum and maximum values over a long-term reference period. Similarly, TCI assessed heat by examining the deviation of LST, an effective indicator of crop water stress as non-optimal conditions can lead to rapid surface temperature change (Ahmad et al., 2021; De Rességuier et al., 2023) UN-SPIDER (2024). However, to avoid limiting the study solely to the LST deviation captured by the VHI, we also identify vineyards experiencing very high average day LST (> 35°C) as a critical condition for plant stress (Huang et al., 2005).

Table 2.1 - Summary of parameters analyzed in this study.

Parameter	Abb.	Data Source	Period	Raw Data Freq.	Unit
Vineyard		CLC2018	2018		ha
Vineyard Cultural Landscape		UNESCO Cultural Landscapes; FAO-GHIAS			
Near Max Air Surface Temperature	NAT_m	ECMWF ERA5 – Land	07/22	Monthly	°C
NAT (max) – Anomaly		ECMWF ERA5 – Land	07/2022 vs. 07/1950-2021		°C
Land Surface Temperature	LST	MODIS	07/22	8-Day	°C
LST – Anomaly		MODIS	07/2022 vs. 07/2000-2021		°C
Precipitation	P	ECMWF ERA5 – Land	07/22	Monthly	mm/ month
Precipitation – Anomaly		ECMWF ERA5 – Land	07/2022 vs. 07/1950-2021		mm/ day
Soil moisture	SM	NASA – USDA; Enhanced SMAP	07/22	3-Day	mm
Soil moisture – Anomaly		NASA – USDA; Enhanced SMAP	07/2022 vs. 07/2015-2021		mm
Normalized Difference Vegetation Index	NDVI	MODIS	07/2022 vs. 07/2000-2021	16-Day	
Vegetation Condition Index	VCI	MODIS	07/2022 vs. 07/2000-2021		
Temperature Condition Index	TCI	MODIS	07/2022 vs. 07/2000-2021		
Vegetation Health Index	VHI	MODIS	07/2022 vs. 07/2000-2021		

2.3. Results

2.3.1. Weather of 2022 in Europe and European vineyards

The results concerning climatic parameters during July 2022 across Europe, with a specific focus on European vineyards, are depicted in Figure 2.2. Overall, NAT_m was very high in southern European countries, especially in Spain, France, Italy, the Balkans up to Romania and southeastern Turkey, with persistent maximum temperatures of even over 38°C (Figure 2.2a). Examining deviations from historical measurements (Figure 2.2b) revealed widespread increases in maximum temperatures across the continent, with particularly noticeable variations (+5°C) observed in both southern and northern regions. In European vineyards (Figure 2.1), NAT_m increased by an average of +10.59%. Likewise, LST registered high values across much of Europe (Figure 2.2c), surpassing 35°C (dark orange color) and 40°C (brown) in several areas, especially in Portugal, Spain, Italy, the Balkans, Hungary and Turkey. Greater temperature anomalies were observed in northern Spain, northern Italy, France, and southern England (Figure 2.2d). Vineyard areas in Europe witnessed an average increase of +9.19% in LST, posing a significant challenge for vine cultivation.

Furthermore, precipitation levels were generally low (Figure 2.2e), particularly in western European regions such as Portugal and France, where rainfall fell below 25 mm/month. Except for a few spots with higher rainfalls (e.g., the Austrian Alps and the Scandinavian peninsula), much of Europe experienced dry conditions, as depicted in the anomaly map (Figure 2.2f). In areas hosting vineyards, rainfall was notably sparse, with a remarkable average reduction of -46.55%.

The combination of high temperatures and limited precipitation also resulted in diminished SM content across much of Europe (Figure 2.2g), with regions north of Spain, eastern France, southern Italy, the Balkans, and Romania experiencing the most pronounced anomalies (Figure 2.2h). Within the vineyards, the average SM exhibited a notable decrease of -29.78% compared to the long-term average, underscoring the imperative need for sustainable management of water resources to face similar weather events.

2.3.2. European vineyard exposed to agricultural drought and excess heat

In July 2022, 18% of the European vineyard area experienced the combined occurrences of drought and high land surface temperatures, also including 10 wine-growing Cultural Landscapes. Figure 2.3 illustrates and summarizes the most affected vineyards (VHI = Extreme & LST > 35°C; red color) with the total vineyard area (yellow color; CLC2018 data; Figure 2.1). Portugal experienced the highest percentage of impacted vineyards at 31%, notably encompassing the UNESCO Cultural Landscape "Alto Douro Wine Region". This event directly affected local viticulture, resulting in an approximately 20% compromise in the 2022 yields (International Organisation of Vine and Wine – OIV, 2023). Beyond the repercussions for production, this occurrence holds significant scientific and cultural implications, posing a tangible risk to the unique cultural heritage associated with viticultural practices in the region.

In France, drought and high temperatures affected 27% of vineyards, particularly in southern regions along the Mediterranean coast and the western areas, including the Cultural Landscapes of the "Jurisdiction of Saint-Emilion" and "The Loire Valley". In Italy, 21% of the vineyards were affected by drought and excess heat, placing several Cultural Landscapes at risk. Representative examples include UNESCO sites such as the "Prosecco Hills of Conegliano and Valdobbiadene", "Vineyard Landscape of Piedmont", "Val d'Orcia", and Pantelleria Island, home to the Intangible Cultural Heritage "Vite ad Alberello" practice, as well as the FAO-GIAHS site "Soave Traditional Vineyard".

Hungary and Romania both experienced one of the most severe droughts on record, involving 19% and 18% of the respective countries' vineyards. This included the Hungarian UNESCO site "Fertö / Neusiedlersee," a transboundary property shared with Austria. Spain observed 13% of its vineyards affected, especially in the central areas between the provinces of Ciudad Real and Albacete and the northern zone along the Ebro River. The FAO-GIAHS site of the "Malaga Raisin Production System in La Axarquía" in the south was also affected. Other main countries involved included Germany (11%) and Austria (7%).

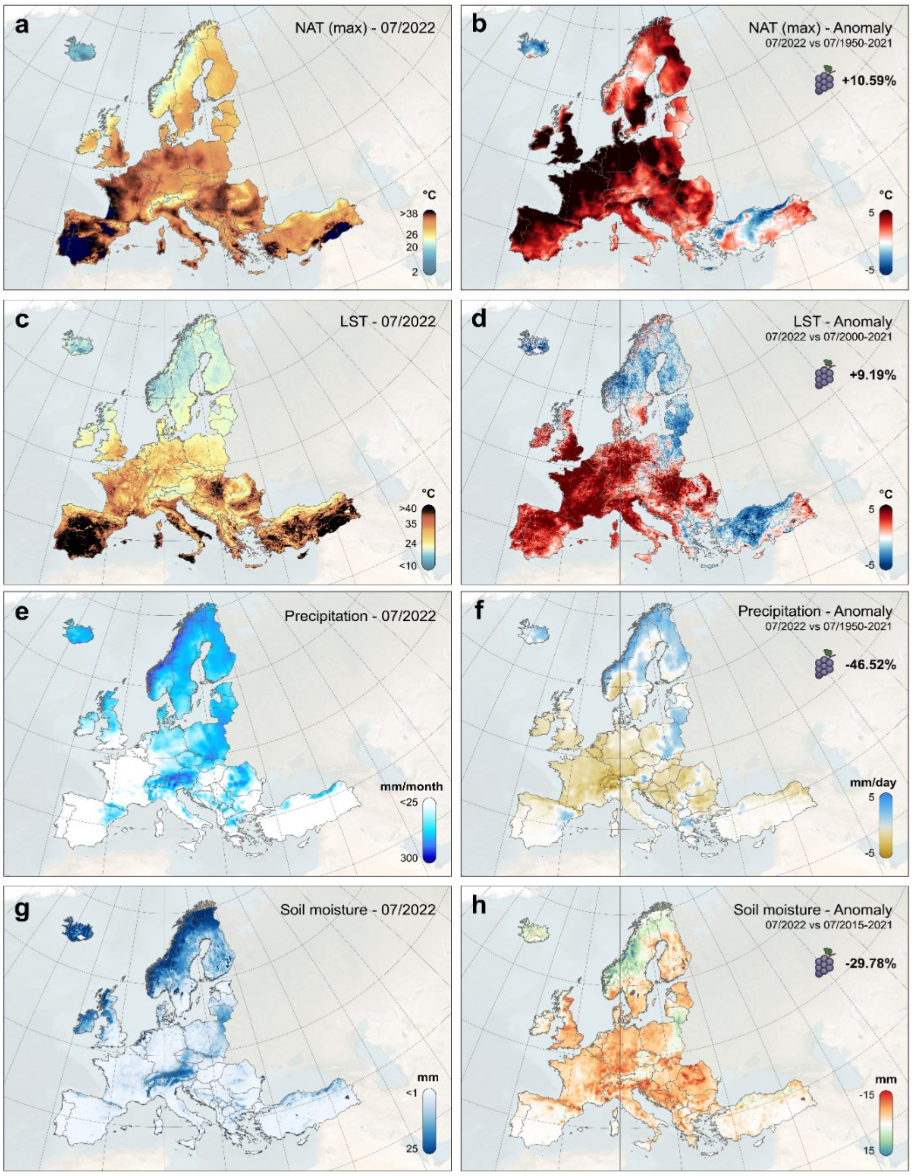

Figure 2.2 – Examination of key climate parameters for Europe in July 2022. The left column depicts each parameter's values for July 2022, while the right column illustrates anomalies compared to a long-term average. The percentages in bold indicate the anomalies specific to European vineyards.

2.4. Discussion

2.4.1. Need for adaptation: from emergency to a new normality

During the 2022 growing season, heat and drought raised significant concerns in the wine industry regarding possible decreases in grape yields. At the

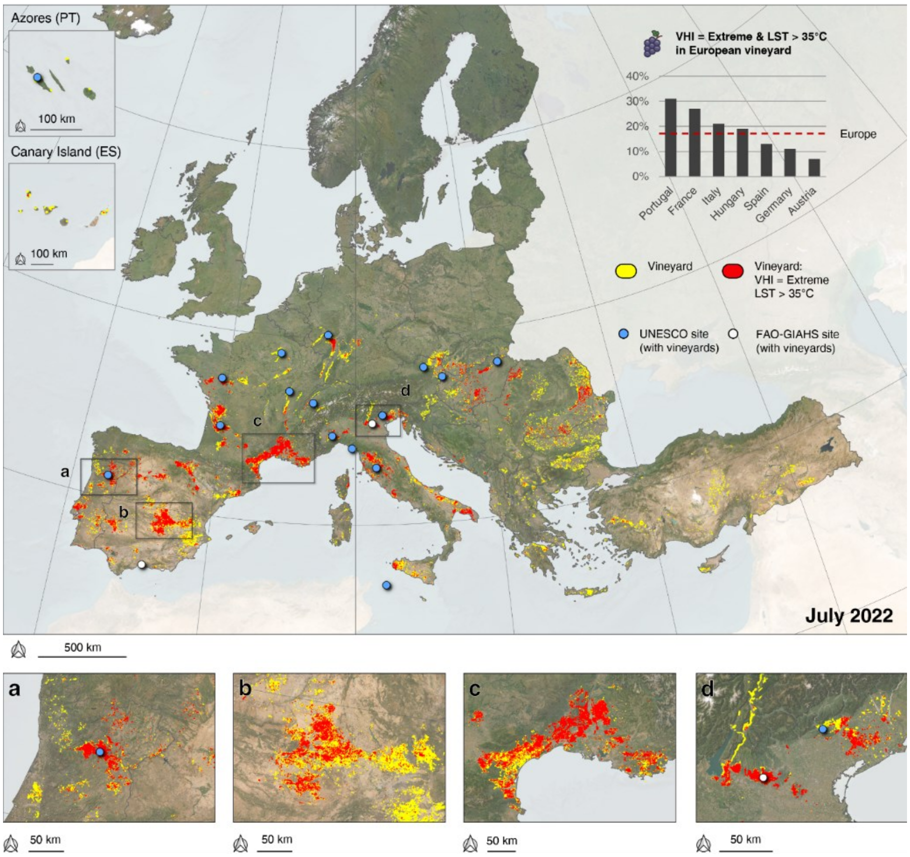

Figure 2.3 – July 2022: extreme drought and heat waves in European vineyards. In yellow are vineyards in Europe; in red are those affected by the combination of extreme drought and land surface temperatures > 35°C. The bar graph shows the percentage of vineyards involved out of the total in the most affected counties.

end of the season, late summer rains and limited plant diseases contributed to higher-than-expected yields in certain countries, thereby helping to alleviate the challenges faced by European viticulture during this critical period (GDO, 2022; OIV, 2023). Increases in wine production were observed in France (21%) and Germany (6%) compared to 2021. Spain and Italy maintained stable production levels (+1% and -1%, respectively), while other countries experienced severe reductions in production, such as Romania (19%), Portugal (8%), Hungary (6%), and Austria (5%).

Even in countries that ultimately experienced stable or positive production trends, and sometimes also in regions with tolerant grapevine varieties (such as Grenache in southern France), farmers were compelled to implement a series of challenging emergency measures to cope with drought and heat. This situation has led to uncertainties, doubts, and concerns regarding the management of European wine systems. In some countries, such as Spain, Italy, and France, grape harvest was anticipated from mid-September to August. Additionally, the use of irrigation increased in several areas, a practice that may not be sustainable during severe droughts. Notably, extraordinary irrigation measures were approved for some Bordeaux areas, attempting to address the problem, resulting in one of the highest water-use vintages in recent years (Mercer, 2022). Furthermore, important is to note that some emergency practices may compromise wine quality. For example, actions like pruning to reduce water use during heat waves can lead to uneven growth, delayed ripening of red varieties, and altered pH levels in wine (Riedo, 2019).

Particular attention must be paid to Cultural Landscapes. Despite their historical adaptation, our results show that extreme events like that of 2022 can put them at risk on a European scale, exposing conditions of fragility and susceptibility to climate change perhaps greater than for modern vineyards. For example, historic vineyards often lack vine irrigation or cooling systems, and there may be landscape or administrative constraints in implementing mitigation solutions, an issue that future research should explore further.

Therefore, the 2022 event underscores the need to shift from emergency response to structured vineyard management to address more frequent extreme heat and drought events. This need for adaptation is a growing concern in the scientific literature, both globally (van Leeuwen et al., 2024) and specifically in Europe (Santillán et al., 2020). The long-term sustainability of European viticulture requires exploration and refinement of cultivation practices to minimize water losses, improve the efficiency of irrigation systems, and incorporate water harvesting techniques. The responsibility for driving this transformation also lies with scientific research, which plays a key role in informing effective adaptation strategies.

2.4.2 Long-term strategies for mitigation of drought and heat wave

Addressing the challenge of drought and excessive heat in vineyards under climate change requires several long-term strategies. First, it is imperative to characterize the region by analysing trends in various climate parameters. The open-access satellite data utilized in this research could prove invaluable for this task, providing a cost-effective and scientifically based solution for identifying optimal adaptation strategies. Such analysis can be complemented by monitoring procedures that utilize field or remote sensors to aid decision-making, ensuring the efficient use of water resources and prioritizing economic and environmental sustainability. Indeed, technological advancements, such as sensors and artificial intelligence, can integrate traditional knowledge with high-tech solutions for more effective mitigation strategies.

Severe negative P and SM anomalies, along with positive NATm and LST ones, such as those observed in July 2022, should prompt investments in sustainable water management solutions combined with efforts to decrease canopy temperature. For instance, smart irrigation frameworks with automatic cooling systems maintain optimal environmental conditions by monitoring temperature and humidity, and activating spray systems when necessary. Prioritizing water use efficiency is critical in the context of increasingly frequent droughts and heat waves which could require increased irrigation. Water deficit irrigation is recognized as a promising strategy to mitigate yield losses and enhance berry quality by imposing controlled water stress conditions (Zarrouk et al., 2015). These conditions not only foster water conservation but also offer environmental and economic advantages.

Furthermore, despite the initial investments, methods like drip and subsurface irrigation could be used to optimize water usage delivering minimal amounts of water directly to plants or roots (Jogaiah, 2023). This system could be supplemented with rainwater and surface runoff harvesting techniques. These methods are often traditional knowledge that is being lost in Europe. While some authors, like Wang et al. (2023), have already initiated studies to explore their application in steep vineyards, additional scientific research is required to evaluate their functionality and delve further into their historical significance. Recommendations also include hydrocooling techniques such as overhead sprinklers and misting systems to mitigate heat stress (Rogiers et al., 2022). During heatwaves, grape clusters may experience considerable damage, resulting in a significant impact on their overall quality (Martínez-Lüscher et al., 2020). This system can be employed to control temperatures, allowing optimal foliar photosynthesis and preventing excess heat from compromising foliar gas exchange (Costa et al., 2023), while extending the period for leaf and berry expansion, resulting in larger berries (Rogiers et al., 2022). This method could be complemented by heavy shading, which can reduce canopy temperatures by up to 6°C, effectively decreasing evapotranspiration and enhancing the accumulation of dry matter in berries.

Soil management practices oriented toward protecting and promoting biodiversity can play a key role during droughts and heatwaves, providing cost-effective benefits also during years without severe anomalies in climatic parameters. For instance, specific inter-row grass cover or mulching has demonstrated promising performance in soil and water conservation, enhancing organic matter content, soil moisture retention, and temperature regulation in vineyards (López-Vicente et al., 2023; Straffelini et al., 2022). These nature-based solutions are often more affordable and environmentally sustainable than technological alternatives. While implementation costs may include labor and materials, the long-term benefits can outweigh the investment.

Several studies advocate for the selection of rootstocks due to their robust resistance to water stress, enabling them to sustain optimal growth even amidst drought conditions (Jogaiah, 2023; Rogiers et al., 2022). Drought-tolerant cultivars offer an advantageous strategy for coping with climate change in viticulture. This is due to the wide variety of cultivars available that can thrive at a wide range of temperatures. Lamarque et al. (2023) conducted a comprehensive analysis of the main European grapevine varieties, assessing their vulnerability to drought and heat stress and projecting their resilience in dry climates. Genetic studies could develop drought-tolerant grapevine varieties providing long-term resilience to water stress conditions (He et al., 2018). This strategy should be pursued where severe anomalies in climatic parameters could occur frequently, such as in central Spain, western France or northern Italy. However, they require significant initial investment in research and development, and they could face social and ethical barriers.

Depending on farmers' willingness to invest, production priorities, grape wine variety, and the technical, geographic, and socioeconomic characteristics of the vineyard, a combination of these strategies could be the most effective approach to mitigating the impacts of drought and heat waves in European viticulture.

2.4.3 Limitations and future development

Despite our intention to investigate all European wine-growing areas, vineyard selection was based on CLC2018, which has a minimum spatial requirement in its classification. Therefore, isolated and small-sized vineyards are not included. Analysis of air and surface temperature, precipitation, and soil moisture, as well as assessment of agricultural drought, was carried out using large-scale data supported by satellite information, characterized by a margin of error. Furthermore, we did not extensively explore the relationship between the 2022 drought and heat event and wine production or the consequences on vineyards for that year, including the role of different wine grape varieties and local conditions. These aspects could be explored in more detail in future specific research considering multiple years of investigation. Instead, this study aims to highlight the risks posed by such events in European vineyards and their Cultural Landscapes by quantifying and mapping hotspots and underscores the need for adaptation using long-term strategies. We are aware that similar events could recur more frequently due to climate change, and we therefore aim to stimulate future developments for structured vineyard management in response to extreme events.

2.5. Conclusions

This research sheds light on how European viticulture was exposed to drought and excess heat events during July 2022, one of the most severe combined events ever recorded. It quantifies anomalies in key climatic parameters compared to a long-term average and maps vineyards at risk, including major UNESCO and FAO-GIAHS wine-growing Cultural Landscapes. The main findings reveal that European vineyards experienced an average increase of +10.59% in NAT_m (Near Max Air Surface Temperature), a +9.19% increase in LST (Land Surface Temperature), and a reduction of -46.52% in P (Precipitation) and -29.78% in SM (Soil Moisture) compared to their respective historical averages for the same month. Furthermore, the combination of extreme agricultural drought and high LST involved 18% of European vineyards and 10 Cultural Landscapes, particularly in Portugal, France, and Italy. The research aims to emphasize the need for robust and structured measures to address similar events on a European scale in the context of climate change, especially considering the potential for an increased frequency of similar events in the future. This involves moving beyond the concept of emergency interventions to save production, toward a more structured and efficient approach to water resource management, and implementing solutions to protect vines from drought and excessive heat.

3. Drought and Heat in Almost Half of Steep Slope European Cropland

Context

Throughout Europe, there are extensive areas of mountainous agricultural land and rural landscapes with significant cultural value. Among these, steep slope agriculture (areas with a slope greater than 7°) is particularly vulnerable to climate change and weather extremes. Despite this importance, researches on the topic are still limited. The previous chapter highlighted the dramatic impact of drought on European vineyards. This section extends the analysis of the severe drought and heat of the summer of 2022 to all European steep slopes and for several agricultural systems. This event had a profound impact on agriculture across Europe, and this survey aims to deepen the understanding of its effects on agricultural practices in Europe's steep slope areas.

The article

This chapter of the thesis focuses on the research paper (open access) titled *"44% of steep slope cropland in Europe vulnerable to drought"* published in the peer-reviewed journal "Geography and Sustainability" *(Q1 in Earth-Surface Processes; Ecology; Geography, Planning and Development; Nature and Landscape Conservation, IF: 9.7)*. The main objective of this chapter is to provide a comprehensive analysis of the impact of the 2022 summer drought on steep-slope croplands in EU countries. The analysis was conducted using the Vegetation Health Index (VHI) as a mapping tool.

> This article primarily addresses SO-A by analyzing the impact of the 2022 drought on European steep-slope croplands, realities that includes several recognized Cultural Landscapes. It also partially contributes to SO-C by exploring the need for improved water management and sustainable practices to enhance resilience in these vulnerable areas.

PEER-REVIEWED & PUBLISHED RESEARCH ARTICLE

44% of steep slope cropland in Europe vulnerable to drought

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CRediT authorship contribution statement:
Eugenio Straffelini: Conceptualization, Formal analysis, Investigation, Project administration, Software, Supervision, Writing – original draft, Writing – review & editing.

Abstract

Steep-slope cropland plays a vital role in food production, economic development, ecosystem diversity, and European cultural heritage. However, these systems are susceptible to extreme weather events. The 2022 summer drought significantly impacted European agriculture, but the specific effects on steep-slope crops remain uncertain. Clarifying this is essential for comprehending similar future events and for implementing effective water management strategies to ensure the sustainability of steep-slope agriculture and associated ecosystem services. This study quantitatively analyzes the spatial distribution of twelve major European steep-slope (>12%) crops and assesses agricultural drought severity during the 2022 events using open-access spatial data. The satellite-based Vegetation Health Index (VHI) is utilized to identify critical hotspots. Results show that olive grove is the most widespread crop in steep slope agriculture (34% of total area), followed by wheat (24%), maize (16%), and vineyard (11%). Almost half of the steep-slope agriculture in Europe suffered drought during summer 2022. Vineyards were hardest affected at 79%, primarily in northern Portugal, northern Spain, southern France, and central Italy. Sunflowers followed at 62%, mainly in Spain, central Italy, southern France, and northern Romania. Olive groves ranked third at 59%, with the most impact in northern Portugal, southern and central Spain, and southern Italy. Maize was also significantly affected at 54%. In this paper, we therefore highlight the need to increase steep-slope agriculture resilience by improving water management and promoting sustainable land practices.

Keywords: Drought; Steep slope cropland; Europe; Sustainability

3.1. Introduction

FAO defined steep-slope agriculture when the terrain slope exceeds 1% (Wang et al., 2022a). Steep-slope agriculture is an integral component of European rural systems, contributing to food production, economic growth, and ecosystem services (Tarolli et al., 2021). Slopes are often cultivated by incorporating traditional knowledge of soil and water management, and this can result in considerable variation depending on the site location. These characteristics make these lands unique and of cultural significance. FAO and UNESCO have identified and protected at least 22 steep slope agriculture landscapes across Europe, which possess diverse functions, including producing food and livelihood security, preserving biodiversity and ecosystem sustainability, sustaining cultures and social organizations, and featuring remarkable landscapes with peculiar water resources management. Noteworthy examples include the FAO-GIAHS site “Territorio Sénia” in Spain, housing the world’s largest concentration of ancient olive trees, and Italy’s UNESCO site “Cinque Terre”, a coastal agricultural Landscape demonstrating centuries of local resilience in the face of mountainous challenges.

Climate change-related weather extremes represent a threat to the entire agricultural sector. The issues are different and impact various agricultural systems differently. Lowlands face crop damage from drought and high temperatures, as well as flooding from heavy rainfall. Sloping fields are even more sensitive due to their geomorphological complexity, experiencing soil erosion and land degradation due to heavy precipitation and crop damage during droughts. Summer 2022 witnessed one of the most severe droughts in Europe’s history, prompting concerns regarding the sustainability and resilience of agricultural practices. Crop yields suffered from the consequences of water shortage. According to the yield report, maize, sunflowers, and soybeans have experienced notable yield reductions of −8.6%, −5.5%, and −9.6% in the European Union (JRC, 2022). Spain, the world’s biggest producer of olive oil, in 2022 lost about 50% of the olive precedent season’s yield while oil prices have risen by 80% in two years. The projected occurrence of extreme droughts is anticipated to increase in frequency, particularly in Europe, as supported by multiple studies (Hari et al., 2020). For instance, Hari et al. (2020) demonstrated a seven-fold increase in drought events and the potential to impact 40 million hectares of agricultural Landscapes from 2050 to 2100 in central Europe based on their climate model. Furthermore, Naumann et al., (2021) predicted that a 4 °C increase by 2100 in Europe may result in a 10% reduction in agricultural economic output. The impact of drought induced by climate change on steep-slope agriculture is comparatively severe and leads to a higher risk of water scarcity than in other agricultural areas (Wang et al., 2022a).

Thus, effective management of water resources is crucial for ensuring the sustainability of such systems. However, factors such as surface instabilities, climate, and unsustainable human activities (such as heavy mechanization or the removal of terraces) pose challenges to water resource management (Tarolli et al., 2021). Identifying the crops and regions most vulnerable to drought during extreme events is crucial for the development of efficient water and soil management strategies. This, in turn, enhances the sustainability of agriculture on steep-slopes, offering potential benefits also in addressing other climate change-related concerns like land degradation. This significant knowledge gap highlights areas that urgently require enhanced irrigation or improved water resource management. Indeed, despite its recognized value as cultural heritage, steep-slope agriculture is less considered by policy and subsidies since it covers a small part (5.6%) of the global agriculture surface. Thus, the present study aims to analyze the effects of the 2022 summer droughts on steep-slope cropland in EU countries, specifically to map drought severity by the satellite-based Vegetation Health Index (VHI). Firstly, we identified crops distribution in European steep-slope agriculture. Secondly, we measured the effects of the major drought in 2022 on the EU countries steep-slope cropland based on VHI. Lastly, we highlighted critical hotspots in steep-slope areas which are more susceptible to droughts identifying crops at risk. The findings specifically target crop types and regions vulnerable to drought conditions, offering valuable insights tailored to the water management of local communities.

3.2. Materials and methods

3.2.1. Data source

The distribution of steep cropland in Europe (Figure 3.1) was determined using a combination of open-access data related to land cover (for mapping crop locations) and topography (for focusing on steep-slope areas only). The former was obtained by integrating the "EUCROPMAP 2018" and "Copernicus CORINE Land Cover" datasets, while the latter relied on the quasi-global "USGS/GMTED2010" Digital Elevation Model (DEM), following Wang et al. (2022a). We selected crop types with clearly defined crop calendars from "EUCROPMAP 2018," which include "Wheat," "Barley," "Rye," "Oats," "Maize," "Potatoes," "Sugar beet," "Sunflower," "Rapeseed," and "Legume." Crop types that lacked crop calendars, such as “other root crops”, and non-crops like “grass”, were excluded from the study. We also not focused on Orchards, because they are not investigated as independent categories in the two official datasets. To complete information on crop types, “vineyards” and “olive groves”, which are widely distributed in some regions of Europe, were obtained from “Copernicus CORINE Land Cover”. The output of the combined data was 100 m resolution. In total, 12 crop types were measured in steep-slope cropland in Europe (Figure 3.1.). All the data analysis was performed by Google Earth Engine.

3.2.2. Identifying the optimal timeframe for drought analysis

The first step in evaluating agricultural drought severity on crops involved selecting the most appropriate month for VHI application. This selection considered the typical growing seasons of various crops across multiple European countries and aimed to assess agricultural drought accurately. Our selection aimed to avoid detecting drought during harvest or the pre-growing season (when no crops are present) in the affected regions, thereby enhancing the effectiveness of drought monitoring. This was achieved by identifying the crop calendar for each crop type and ensuring that all drought monitoring activities aligned with the agricultural growing period. Given the variability of growing seasons across different European countries, our study selected a month that typically falls within the growing season for each crop. To accomplish this, we conducted a systematic investigation, employing various datasets to gather information about crop calendars for distinct categories of croplands. The details are presented in Table 3.1, which includes an inventory of crop types, their respective percentages, common growing seasons across countries, and data sources for the crop calendar. Given the variability of growing seasons across different

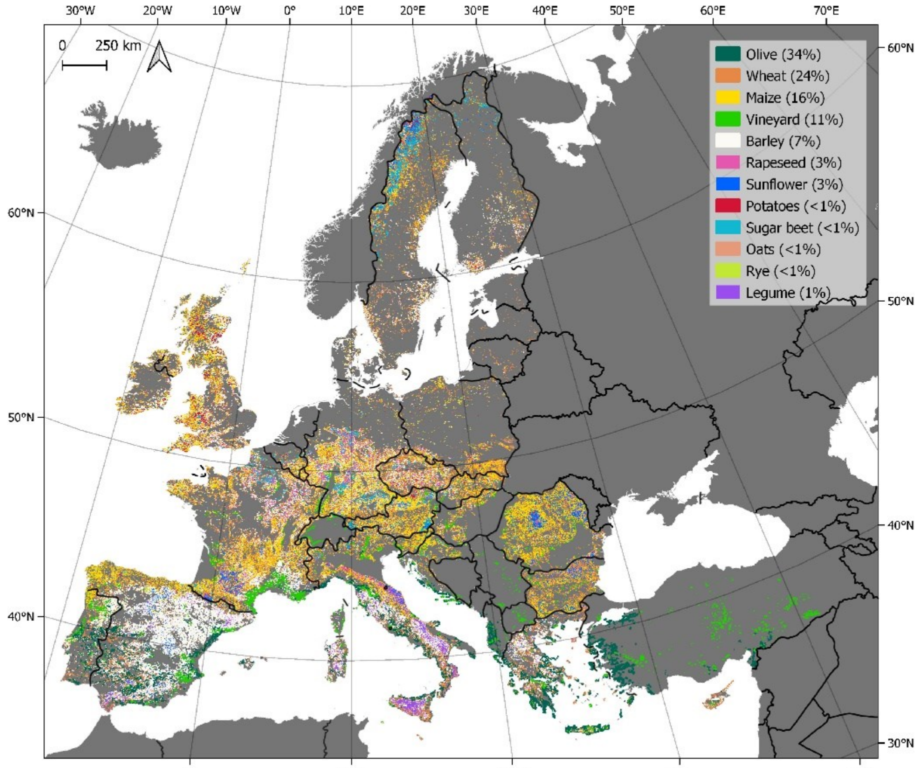

Figure 3.1 – Spatial distribution and percentage of crop types in steep slope landscapes of Europe

European countries, this study selected a month with a typical growing season for each crop.

3.2.3. Definition of satellite-based VHIs

We use the VHI to assess the 2022 agricultural drought severity for steep-slope agriculture in Europe. It is based on two other indicators: Vegetation Condition Index (VCI) and Temperature Condition Index (TCI). The VCI is a proxy for water stress conditions, whereas TCI represents the spatial temperature condition based on LST. VCI is a function of the Normalized Difference Vegetation Index (NDVI) over the years. The NDVI is an indicator of greening. VHI were calculated as follows the formula.

$$VHI = \alpha * \mathrm{VCI} + (1 - \alpha) * \mathrm{TCI} \qquad (4)$$

where a is the coefficient to identify the contribution of the VCI and TCI for VHI calculation. Generally, a is set as 0.5 to the contribution of the VCI, and the TCI is equal when measuring drought stress (Kogan, 2001). The value of VHI varies from 0 to 100. We categorized the drought severity zones into five classes following the criteria recommended by (UN-SPIDER, 2024). We identified 5 classes based on VHI: extreme drought (<10), severe drought (<20), moderate drought (<30), mild drought (<40) (United and Nations, 2016).

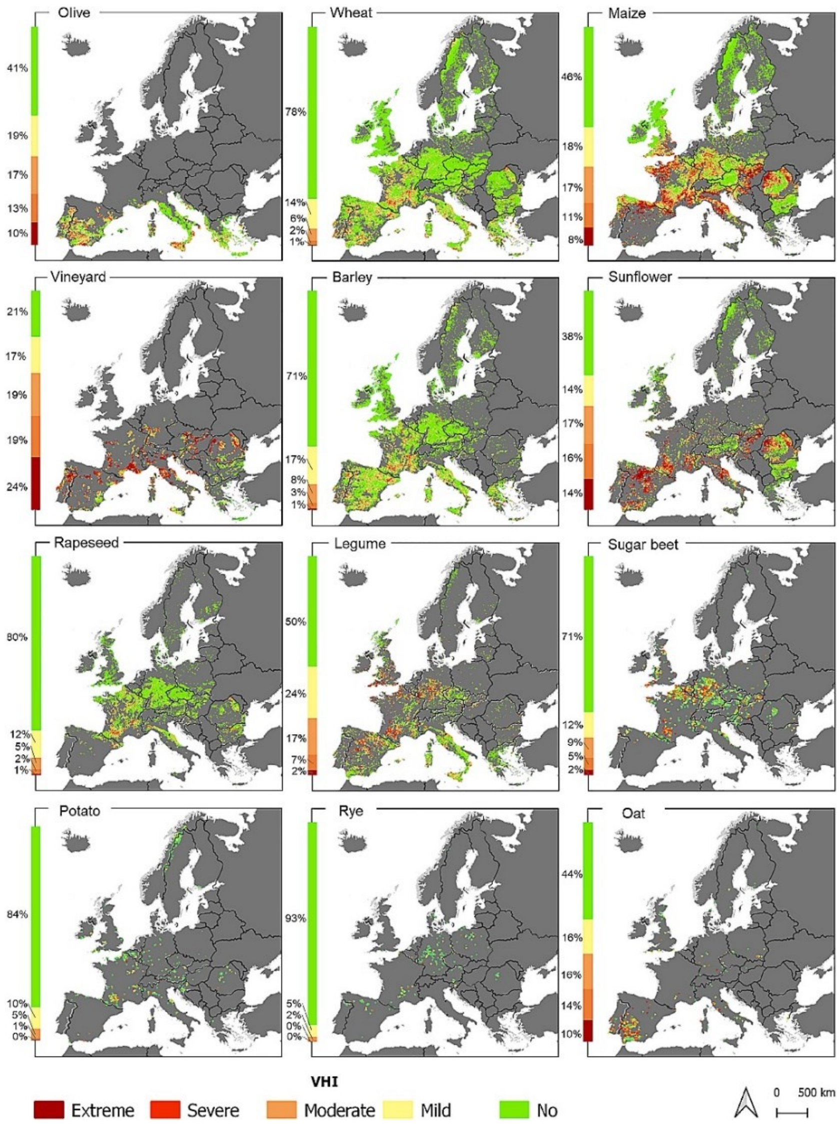

Figure 3.2 – Spatial distribution of the severity of drought for each crop type and the fraction of different five classes of Vegetation Health Index (VHI)

3.3. Result

3.3.1. Distribution of crop types in steep-slope landscapes of Europe

The spatial distribution of steep-slope agriculture in Europe is shown in Figure 3.1, where 12 crop types were identified: olive, vineyard, wheat, barley, rye, oats, maize, potatoes, sugar beet, sunflower, rapeseed, and legume. Olive comprises the largest area (Table 3.1) among all the crop types, accounting for 34% of the total area, and is primarily concentrated in southern Europe, such as Portugal, Spain, Italy, and Greece. The second largest crop type is wheat (Table 3.1), which is scattered throughout Europe and accounts for 24% of the area. Maize occupied 16% of the total area vhi
(Table 3.1) and is concentrated in the central part of Europe, including France, Germany, Romania, and northern Italy. Vineyards and barley account for 11% and 7%, respectively. Sunflower accounted for approximately 3% of the total area and is mostly produced in Romania, Bulgaria, France, and central Italy. Rapeseed is scattered in central Europe, and legumes are widely distributed in Italy, accounting for 3% and 1%, respectively. Other crop types (e.g., oats, sugar beet, rye, and potatoes) distributed only a small portion of steep slope cropland, less than 1%.

Table 3.1 - Common growing season for each type of crop in European countries based on multiple datasets.

Crop type	Area (%)	Common growing season	Data source for crop calendar
Olive	34	June	https://onlinelibrary.wiley.com/doi/10.1111/j.1744–7348.2002.tb00167.x#:~:text=Eight%20principal%20growth%20stages%20for,secondary%20growth%20stages%20are%20described.7348.2002.tb00167.x
Vineyard	11	August	https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx
Wheat	24	May	https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx
Barley	7	May	https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx
Rye	< 1	May	https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx
Oats	< 1	June/July	https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx
Maize	16	June/July	https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx
Potatoes	< 1	May	https://www.teagasc.ie/crops/horticulture/vegetables/potatoes—veg-growing-guide/
Sugar beet	< 1	June/August	https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx
Sunflower	3	June/July	https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx
Rapeseed	3	May	https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx
Legume	1	June/August	https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx

3.3.2. The spatial distribution of drought for each crop

Figure 3.2 displays the spatial distribution of drought severity for each crop. At the same time, the fraction of the different categories of the VHI is presented in the bar chart on the left side. The vineyard under analysis was predominantly affected by the summer drought of 2022, with 79% of its area located in the drought-affected region, including northern and middle parts of Italy, southern France, northern Spain, and Portugal, western German. Within the affected area, 17% experienced mild drought, 19% experienced moderate drought, while severe and extreme drought accounted for 19% and 24%, respectively. The drought significantly impacted the sunflower crop, with 62% of its area being influenced, mostly in northern Spain, southern France, middle Italy, northern Hungary, and northwest Romania. The olive crop presented a mixed pattern of drought impact up to 59% (Spain and south Italy), and 10% experienced extreme drought. 54% of maize was under drought stress (northern Spain, France, northern and middle part of Italy, Hungary, and north Romania), mostly in the form of moderate (17%) and mild drought (18%). Oats showed a similar pattern to maize, with 56% of its area suffering drought in south Spain, mainly in moderate and mild drought. Half of the legume area was affected by drought (middle Spain, southern France, and middle German), concentrated in the form of mild (24%) and moderate drought (17%). Barley was significantly affected by drought in Spain and France, with 29% of its area experiencing drought stress, primarily in mild drought (17%). Wheat showed a similar pattern to barley, with 22% of its area being affected by drought, mainly in the form of moderate (6%) and mild drought (14%), while severe or extreme drought only accounted for 3% and primarily located in Spain and France. The potato data showed 16% of the area being affected by drought, mainly in mild (10%) and moderate (5%), and no extreme drought. 29% of its sugar beet being affected by drought, with 12% under mild drought, 9% under moderate drought, and 5% under severe drought, while extreme drought only accounted for 2%. The rapeseed crop was significantly affected by drought, with 20% of its area experiencing drought stress, primarily in mild drought (12%). The rye crop was less affected by drought than other crops, with only 7% of the area experiencing drought stress, primarily in the form of mild drought (5%). Our analysis indicates that the summer drought of 2022 threatened a total of 44% of steep-slope agriculture, which is a warning for the agricultural sector and food security.

3.4. Discussion

3.4.1. A risk of losing agricultural, traditional and economic value

The 2022 extreme summer drought profoundly affected European steep-slope agriculture, highlighting climate change’s increasing threat to often unprepared traditional rural landscapes. The primary concern is the direct damage caused by drought to crops and related production. This phenomenon not only exacerbates the preexisting complex socio-economic dynamics within European steep-slope regions, but also accelerates the abandonment of agricultural land, deeply affecting mountain communities and reducing related ecosystem services. Furthermore, the risk is to undermining culturally significant aspects, especially in regions tied to historical traditions such as wine production (e.g., the UNESCO-designated Porto wine production site, Portugal) or extra virgin olive oil (e.g., the FAO-GIAHS landscape of Assisi and Spoleto, Italy). As steep-slope agriculture faces drought threats, these multifaceted values are in danger of disappearing. Therefore, the risk extends beyond food production and affects social-ecological systems, traditions, heritage, and ecosystem values. Thus, it is imperative to prioritize sustainable solutions, particularly in terms of water management.

3.4.2 The significance of sustainable management on hotspots

Findings reveal that steep-slope vineyards in Spain, northern and central Italy, northern Portugal, and southern France, along with olive groves in Spain and Italy, and maize and sunflower fields in northern Spain, central Italy, southern France, and northern Romania, suffered major agricultural drought during the 2022 extreme event. Southern Europe is widely recognized as a hotspot for its vulnerability to drought, which is why farmers have employed a variety of traditional Soil and Water Conservation (SWC) techniques. Nevertheless, our research indicates that despite centuries of SWC efforts in such lands, addressing extreme drought events requires even more comprehensive measures. High severity droughts have impacted landscapes under different soil managements. For instance, it affected several terraced systems, some of which hold significant cultural value. This occurred despite they are key elements of land management in steep slope areas that facilitate effective water and soil retention and thus allow crops to efficiently access water in the soil (Panagos et al., 2015; Pijl et al., 2022). Examples of severe drought impacts include terraced vineyards in the Alto Douro region (Portugal), wine-producing areas of Soave and Prosecco (northern Italy), and the Priorat wine region (Spain). Also, some terraced olive groves, such as those in the Malaga Region (southern Spain) and Sicily (Southern Italy). Serious drought effects also occurred in fields managed with other SWC practices. For instance, vineyards cultivated along the maximum slope in Provence and the Languedoc regions (southern France), or different herbaceous crops like maize and sunflowers in central Italy (mainly the Apennines) and northern Spain. A key challenge is addressing the need for irrigation due to precipitation changes, which has become essential even in regions not historically irrigated. The available techniques are diverse, including surface (for example, for vineyards and olive groves, using drip tapes) and subsurface drip irrigation (also suitable for other crops). It is also important to support irrigation systems by implementing rainwater harvesting and micro-storages. They are small-scale reservoirs that can store excess water during rainfalls, making it usable during droughts. (Wang et al., 2023) successfully tested a remote sensing and modeling approach to quantify storable rainwater in steep slope vineyards. For olive trees, it is strongly suggested to use Fish scale pits, which are widely applied in the Loess Plateau in China. These pits are semi-circular holes dug into the soil along the slope (1.0 m in diameter, 0.2 m deep) and prevent water from running off, increase infiltration, and trap sediment (Wang et al., 2021). Another water conservation solution is the Level terrace, suitable for relatively gentle gradients (Lü et al., 2009). Ditches are dug along the contour lines of the slope, and the excavated soil is used to form a wall on the outside of the ditch. Surface flow from the slope is stored in the ditch, promoting soil moisture. Trees can then be planted in the ditches, as with the fish-scale pits. However, considering the complexities of managing irrigation or proposing SWC techniques on sometimes >30% slopes, it is also essential to urgently identify efficient crop types and areas for effective water resource management in these hotspots. Drought significantly influences crop harvest time (Cook and Wolkovich, 2016). Thus, the corresponding solution, including efforts to breed more resilient varieties, should prioritize selecting those capable of withstanding high temperatures during the flowering stage, paired with appropriate plant management. For example, in vineyards, some selected red wine grapes are suggested in case of water scarcity (International Organisation of Vine and Wine – OIV, 2023). Farmers should also optimize vine canopy and spacing management to enhance sunlight exposure, reduce water competition among vines, and minimize water stress, combined with effective pruning (Allegro et al., 2022). Moreover, the maintenance of optimal soil conditions, encompassing factors such as favourable soil structure, water retention capacity, soil fertility as well as nutrient content play a crucial role in SWC (Diop et al., 2022; Hu et al., 2023; Veisi et al., 2023). To enhance SWC capabilities, diverse strategies can be potentially contributing to the improvement of soil condition. Mulching, for instance, exhibits the potential to conserve the soil moisture and control soil temperature thereby promoting water retention (Iqbal et al., 2020), however, it is imperative to note that the utilization of plastic mulch has been associated with environmental concerns (Shah and Wu, 2020). Benefits of crop rotation on prevent nutrient depletion, pests diseases, enhances soil fertility as well as boost system productivity have long been recognized (Shah et al., 2021). The critical role of soil organic matter in sustaining soil health and ecosystem services cannot be overstated (Wezel et al., 2002). A decline in soil organic matter, such as the reduction from 7% to 3%, has been shown to correspond with a 10% decrease in soil water retention (Gregory et al., 2009), thus it is recommend incorporating organic materials such as compost or well-rotted manure or planting cover crops like legumes that not only adds organic matters but also fix nitrogen (Wezel et al., 2002). Notably, the combined treatments are more efficient in land management. For example, Jiang et al. reported the combination of crop rotation and organic matter addition can not only improve soil and water conservation, but also increase 40% of crop production, based on a 12 years experiment (Jiang et al., 2022).

3.5. Conclusion

We assessed agricultural drought severity on 12 key crop types in European steep-slope agriculture during the extreme events of summer 2022. Findings indicate that a remarkable 44% of these landscapes were affected. Vineyards and olive groves were the most adversely involved, experiencing drought across 79% and 59% of their areas. Also, sunflowers, maize, oats, barley, sugar beets, rapeseed, and legumes displayed varying degrees of drought stress. The widespread impact observed across various crops highlights potential implications for the agricultural sector and food security due to climate change. Therefore, we advocate for improved water resource management measures in the most critical regions and crop types. Key strategies include implementing rainwater harvesting solutions, improving irrigation efficiency, carefully selecting crops to align with new climate threats, and embracing sustainable land and soil management practices, including traditional solutions. These measures are essential to enhance the resilience of Europe's steep-slope rural heritage.

4. Climate Change is Inducing Aridity in Northern Italian Cultural Landscapes

Context

This section focused on North-eastern Italy, a vital agricultural region rich in agricultural Cultural Landscapes from the coast to the Alps, such as the UNESCO site and regional parks of the Po Delta, to the historic vineyards for the production of Soave (GIAHS site) or Prosecco (UNESCO Cultural Landscape). Despite the importance of agriculture in the area, future climate-change scenario and potential implications for related Cultural Landscapes are still missing. To fill this gap, the study investigates the distribution of current and future climate zones for eight major agricultural systems across 14 key Italian provinces. By comparing historical data with future projections under the RCP8.5 scenario, it reveals a significant shift towards drier conditions, threatening traditional agricultural practices. The findings indicate significant risks to food security and cultural heritage. The 2022 extreme drought event is used as a case study to analyze agricultural vulnerability, employing multi-temporal Aridity Index (AI) and Vegetation Health Index (VHI) alongside high Land Surface Temperature (LST) data. The study also highlights the role of human activities, especially cultivation practices and water management, in the. The study analyzes and discusses how agricultural decisions in terms of cultivation practices and water management are crucial to minimizing the impacts of extreme weather events such as drought, as well as how sustainable choices can help ensure a future for crops and its traditions.

The article

This section is based on the research paper: "*Climate change-induced aridity is affecting agriculture in Northeast Italy*", published in 2022 in the journal "*Agricultural Systems*" (Q1 in *Agriculture, Multidisciplinary*; IF 2022: 6.6). It contributes to the overall objectives of the PhD thesis by examining the impacts of global environmental changes on representative Cultural Landscapes, with a primary focus on Northeast Italy.

> The study primarily addresses SO-A, which investigates the impacts of drought on Cultural Landscapes, while also touching upon SO-C, related to the effects of anthropic development. In the context of SO-A, the research employs remote sensing and GIS-based approaches to map and quantify the risk of climate zone shifts in eight major agricultural systems across key provinces in Northeast Italy. The study's findings highlight the transition towards drier conditions, posing significant challenges to traditional agricultural practices and water management systems that define the region's Cultural Landscapes. Regarding SO-C, the study also examines how unsustainable practices, such as intense irrigation or not optimal crop selection in potentially arid area could aggravate the already critical situation.

PEER-REVIEWED & PUBLISHED RESEARCH ARTICLE

Climate Change-induced Aridity is affecting Agriculture in Northeast Italy

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Eugenio Straffelini: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft.

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 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 toward 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.

Keywords. Climate change; Italy; Agriculture; Aridity; Remote sensing

4.1. 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 (Al-Ghussain, 2019; IPCC - Intergovernmental Panel on Climate Change, 2021). 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 (Allan et al., 2020; Milly et al., 2002; Vermeer and Rahmstorf, 2009). Global warming alters atmospheric circulation patterns and exacerbates the severity of droughts (IPCC, 2022a), 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), China (GIEWS - Global Information and Early Warning System on Food and Agriculture, 2011), Chile (Muñoz et al., 2020), North America (Mann and Gleick, 2015), and Europe (Global Drought Observatory, 2022). Drought impacts the environment, such as ecosystems (Ahmed et al., 2020; van der Molen et al., 2011), 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. 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, characterized 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 minimum of 114 m^3s^{-1}, much 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 more than 40 kilometres (Tarolli et al., 2023a). Drought caused severe damage to agriculture, which in some areas resulted in the total loss of production (e.g. rice yield dropped by more than 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. 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 (World Meteorological Organization (WMO) Global Water Partnership (GWP), 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 (Centro Euro-Mediterraneo sui Cambiamenti Climatici (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.

4.2. Material and methods

4.2.1. Study area

The investigated area is in Northern Italy (see Figure 4.1). 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 STAT - Istituto Nazionale di Statistica (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 Figure 4.1(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 - United Nations Educational, 2022). 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 (Tumiatti, 2005). Today, agriculture, together with fishing, is

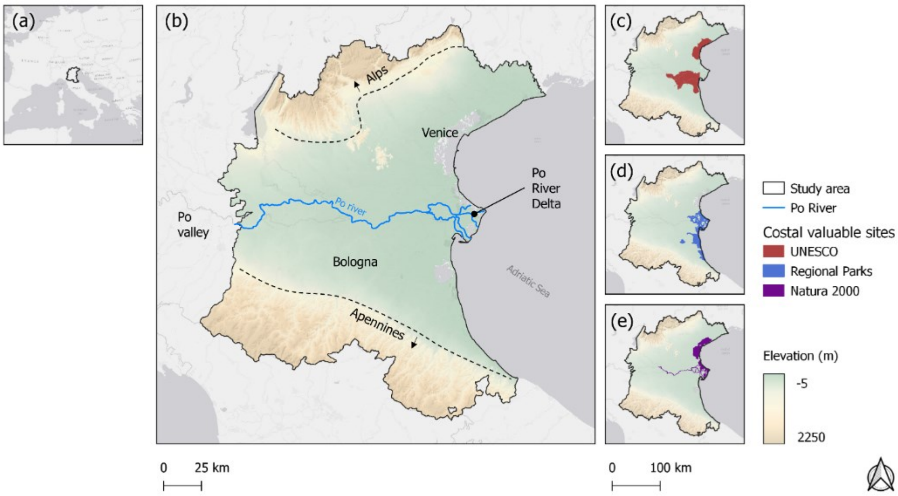


Figure 4.1 - (a) The study area covers 14 provinces in northern Italy. It is crossed by the Po River, which flows eastwards into the Adriatic Sea, where its Delta is located. (b) Elevation ranges from -5 m asl (in reclaimed coastal areas) to over 2200 m asl in the Alps. The central part is occupied by 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.

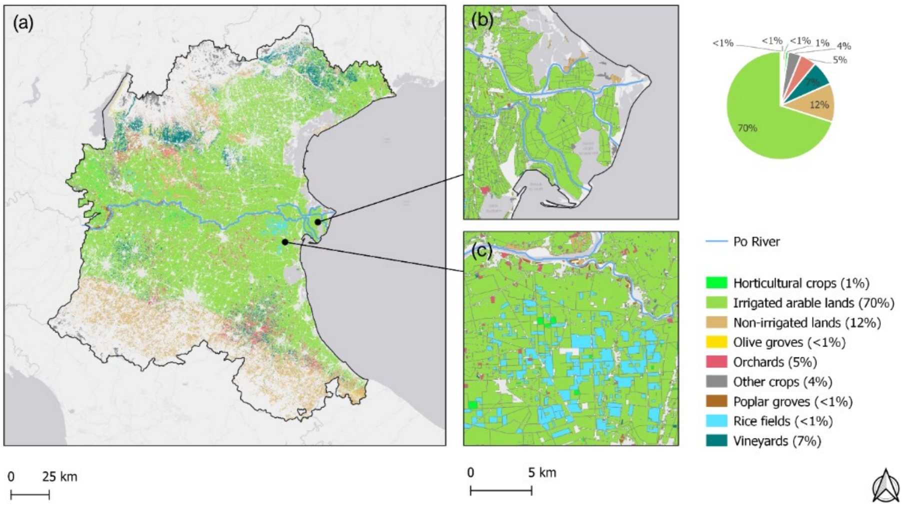


Figure 4.2 - (a) The distribution of agricultural fields. A large part of the surface is occupied by irrigated arable land (mainly in lowlands); (b) Enlargement in the Po River Delta; (c) Enlargement on rice fields along the Adriatic coast.

among the main economic activity. 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.

4.2.2. Agriculture

Data about agriculture was obtained from the up-to-date open-access data of the Veneto, Emilia-Romagna and Lombardy (regions. They were homogenised into a single information layer related to 'Agriculture' (Figure 4.2). 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 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 Figure 4.2 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.

4.2.3. Climate

4.2.3.1. 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$_{\text{FAO-UNEP}}$) 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 Equation 1 (EU Joint Research Center, 2022).

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

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 greater than 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. 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.

4.2.3.2. 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 Nations Office for Outer Space Affairs as it considers both climatic variables and vegetative response. For the calculation of VHI (Equation 2), MODIS satellite data was implemented to classify 4 drought classes (extreme, severe, moderate, and mild) for June, July, and August (2020, 2021, 2022) at 500 m resolution.

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

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. The second is the Temperature Condition Index (TCI). It is similar to VCI in its formulation, but it implements the LST as a measure of the energy balance of the Earth's surface. We also separately mapped the LST for summer 2022 to detect extreme temperature hotspots. MODIS satellite data processed in Google Earth Engine were used. 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.

4.2.3.3. 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). 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.

4.2.4. 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.

4.2.4.1. 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, 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.

4.2.4.2. 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.

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

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

4.3. Results

4.3.1. Towards drier climates

4.3.1.1. Aridity index (AI) mapping

Figure 4.3 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 thanks to 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 ($p\text{-value} < 0.05$) and supports the hypothesis of ongoing climate change. The values distribution is represented by the boxplot in Figure 4.3 and shows a decrease in the median values of roughly 10%. The main direction of aridification is from the Adriatic

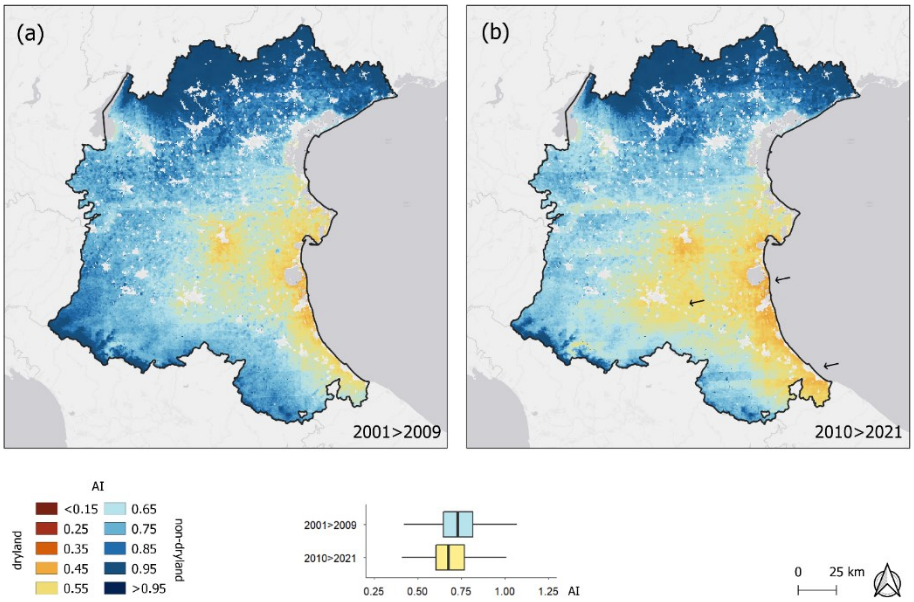


Figure 4.3 - Application of the aridity index (AIFAO-UNEP). (a) refers to the period 2001>2009; (b) to 2010>2021. Classification according to Middleton & Thomas (1997). Warmer colour indicate progressively drier conditions. Black arrows indicate some illustrative areas of worsening of the index towards drier states. Below, are two boxplots with index-value distributions ($p\text{-value} < 0.05$).

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.

4.3.1.2. 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; Figure 4.4). 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, more than 40 mm of rain (cumulative) was reported in the eastern part of the investigated region (GDO, 2022a). 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. 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 (Figure 4.4, 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).

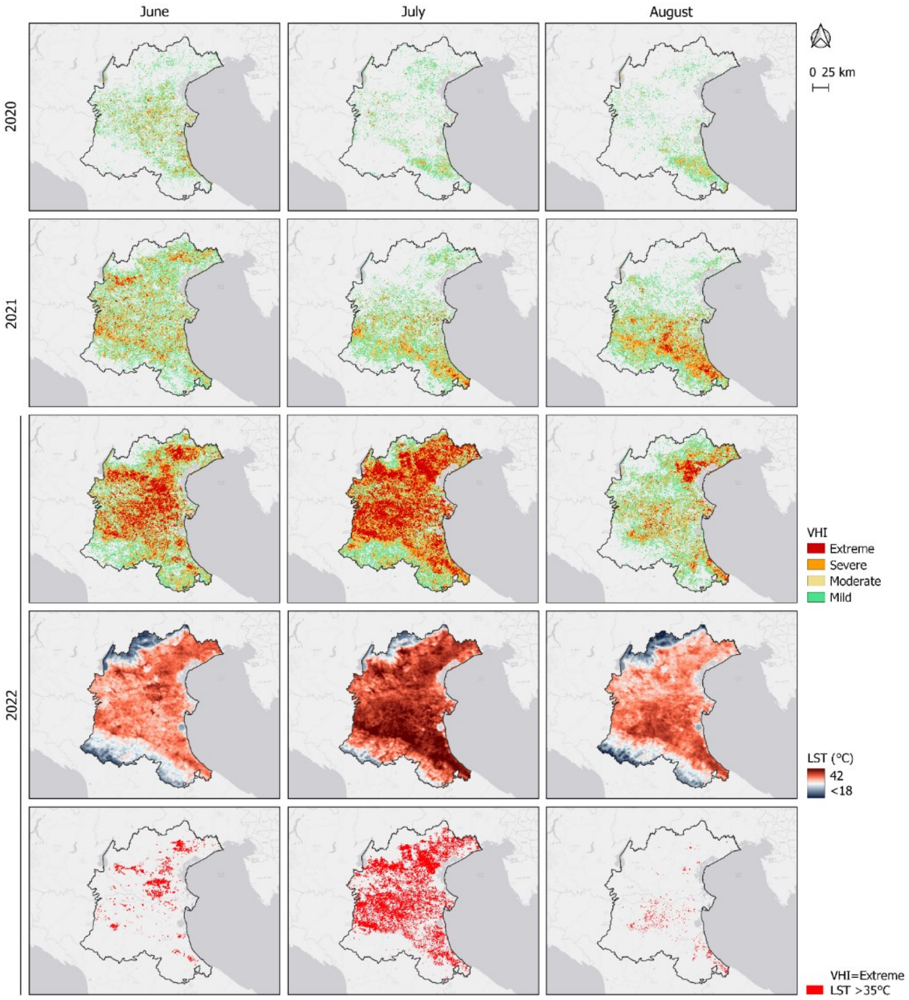


Figure 4.4 - Application of the drought index based on the VHI for the study area in June, July and August (2020, 2021, 2022). The summer of 2022 was characterised by large areas of extreme agricultural drought, which led to a severe impact on agriculture. For this year, average LST and areas characterised by the combination of extreme agricultural drought and LST greater than 35°C were also mapped. The delineation of these critical areas could have implications for the development of more climate change-resilient agricultural systems.

4.3.1.3. 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). 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 toward more dry conditions. Figure 4.5(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. Figure 4.5(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.

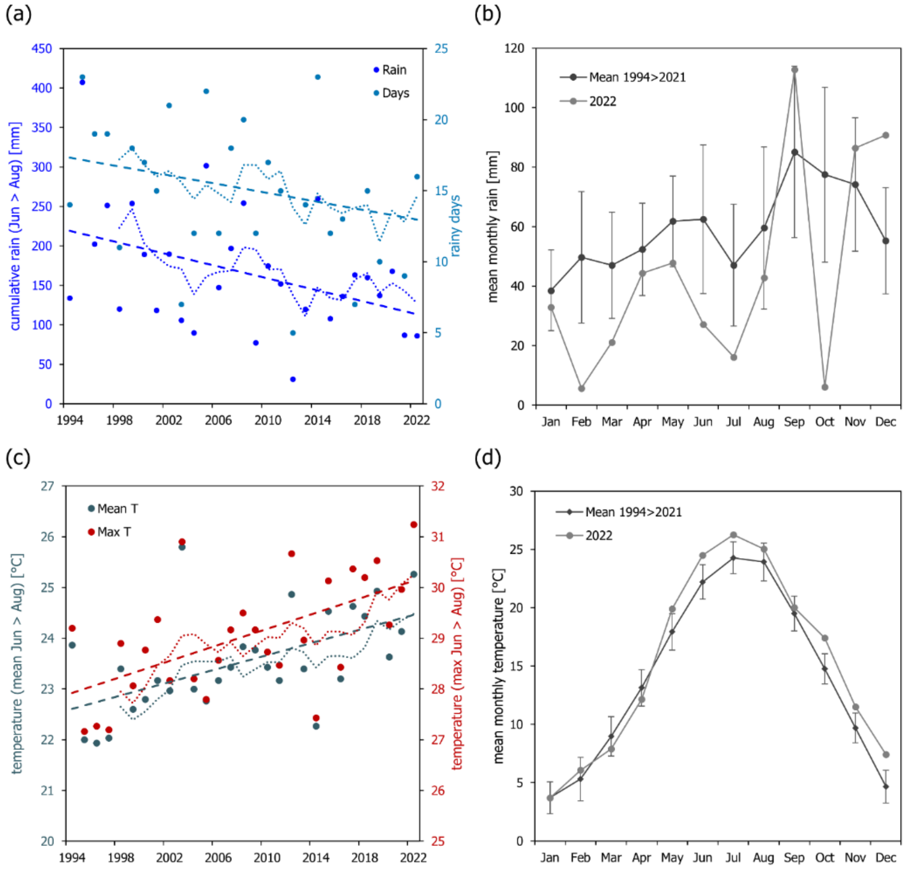


Figure 4.5 - Climatic analysis of the Po River Delta Cultural Landscape. (a) cumulative rainfall trend during the June-August period (left axis) and the relative number of rainy days. Both series have a negative trend (linear trend line and 5-year moving average are reported). (b) average monthly rainfall 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.

The average annual temperature was 14.0°C and the average maximum was 18.8°C. Both series are gradually increasing (ARPAV, 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, 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 Figure 4.5(c), and the comparison of mean monthly temperatures with those recorded in the year 2022 in Figure 4.5(d).

4.3.2. Climate shifts is threatening Agriculture in Northern-Italy

The current Köppen-Geiger climate zone distribution is proposed in Figure 4.6(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 Figure 4.6(b). Warmer and drier conditions are predicted for the future. Two main-class climate variations can be observed in Figure 4.6(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 Figure 4.6(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, Figure 4.7 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 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.

4.4. Discussion

4.4.1. 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; CMCC, 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 Fergus et al., 2020), which analysed climate indicators at a European scale and less representative of local conditions. Thanks to 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 (GDO, 2022a; GDO, 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 NOOA 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 more than 40 km and causing extensive damage to agricultural systems (Tarolli et al., 2023a). The rising sea level and temperature are also worsening the situation (Raicich and Colucci, 2019; Vilibić et al., 2017).

4.4.2. 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 (Zollo et al., 2016). This is alarming and in line with other findings (Appiotti et al., 2014; Brunetti et al., 2000; 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

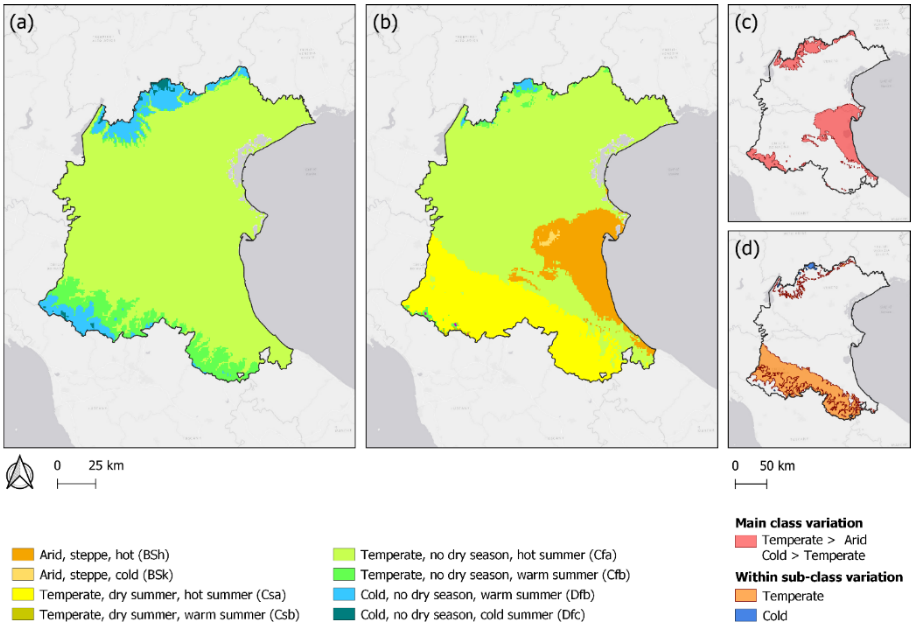
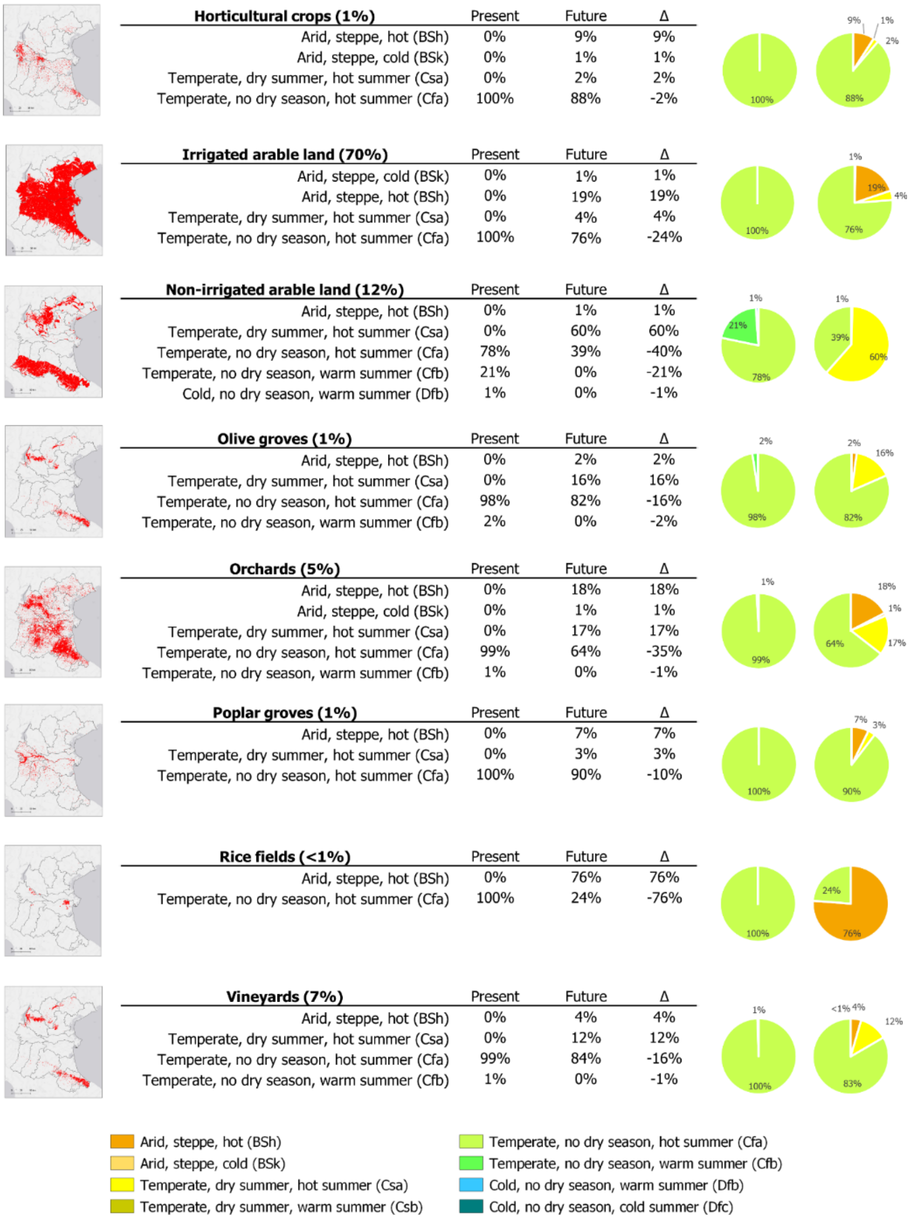


Figure 4.6 - Climate maps modified from Beck et al (2018) for the study area. (a) Present climate zones. (b) Future climate zones (2071>2100; RCP8.5 scenario). (c) Areas subject to main climate class change. (d) Areas subject to sub-climate class

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., 2023). This can also be valid for vineyards. High-efficiency drip irrigation is recommended, selecting drought-resistant varieties, and carefully evaluating the vineyard structure (Gutiérrez-Gamboa et al., 2021; Ortuani et al., 2019). 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).



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%

Figure 4.7 - 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.

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).

4.4.3. 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 analysing 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 & 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.

4.5. 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 ($p\text{-value} < 0.05$). 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.

5. Drought Side-Effect: Salinization of Historical Coastal Agricultural Landscapes

Context

This study examines the spatial-temporal variation of saltwater intrusion in the Po River Delta and its impact on agriculture. The Po River Delta is a significant region for agricultural production, natural value (it is one of the largest wetlands in Europe containing natural parks) and cultural heritage, as it is part of a UNESCO World Heritage site. However, the area faces considerable risks due to climate change, particularly from severe and prolonged drought events. Droughts, compounded by unsustainable human practices, have exacerbated saltwater intrusion, presenting major challenges to agriculture in the Delta. Although research on climate change in the Po Valley is expanding, there is still limited understanding of how saltwater intrusion specifically affects agricultural practices in the Delta. Employing advanced techniques such as the Hilbert-Huang Transform (HHT) and time-dependent intrinsic correlation (TDIC), this research analyzes the dynamic relationship between salinity and river discharge and relations with agricultural greening. The findings reveal significant long-range correlations between salinity and discharge, with pronounced variations during drought periods. Notably, the year 2006 was identified as experiencing severe saltwater intrusion, with the intrusion extending up to 22.3 km upstream. Remote sensing data, including the normalized difference vegetation index (NDVI), demonstrated a negative correlation between salinity and agricultural greening. This indicates that increased salinity adversely impacts crop health and yields, leading to micro-desertification in some areas. The study highlights the urgent need for preventive measures to safeguard the Po River Delta's Cultural Landscape. By providing a detailed analysis of saltwater intrusion risks and proposing actionable mitigation strategies, the research supports informed decision-making aimed at protecting this vital and culturally significant region.

The article

This section is based on the scientific article: "*Saltwater intrusion in the Po River Delta (Italy) during drought conditions: Analyzing its spatio-temporal evolution and potential impact on agriculture*", published in 2024 in the journal "*International Soil and Water Conservation Research*" (*Q1 in Environmental Sciences, Soil Science, and Water Resources; IF 2023: 7.3*).

> This paper primarily addresses SO-A by analyzing the impact of drought-induced saltwater intrusion on agriculture in the Po River Delta. It also partially addresses SO-C by discussing how human activities exacerbate these effects. The study employs advanced techniques to reveal significant correlations between salinity and agricultural greening, highlighting the vulnerability of Cultural Landscapes to climate change.

PEER-REVIEWED & PUBLISHED RESEARCH ARTICLE

Saltwater intrusion in the Po River Delta (Italy) during drought conditions: Analyzing its spatio-temporal evolution and potential impact on agriculture

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CRediT authorship contribution statement:
Eugenio Straffelini: Conceptualization; Software, Formal analysis, Writing - review & editing.

Abstract

Saltwater intrusion along rivers is a complex process controlled by multiple factors and thus fluctuates with a highly nonlinear nature and time-varying characteristics. It is challenging to monitor saltwater intrusion. The objective of this study was to clarify the spatial-temporal variation of saltwater intrusion and its potential impact on agriculture in the Po River Delta (Italy). 2006 was the most severe year of saltwater intrusion in the period we considered. 2022 was even worse, but the data are still under validation. In this study, the Hilbert-Huang transform (HHT) and rescaled range (R/S) were used to identify the multi-time scales and change trends of the salinity and discharge in 2006. After that, the time-dependent intrinsic correlation (TDIC) was used to depict intrinsic relationships between salinity and discharge at different time scales. The results showed that discharge and salinity exhibited behaviours of positive long-range correlation during different periods. The temporal series of salinity and discharge was decomposed into six intrinsic mode functions (IMF) and residuals based on the ensemble empirical mode decomposition (EEMD). The sum of variance contribution rates of IMF1 (4 days), IMF2 (10 days), and IMF3 (12.1 days) of salinity was more than 75%. All measured TDICs have highlighted strong correlations between salinity and discharge. Furthermore, we used spatial interpolation techniques to map salinity data along rivers. This allowed the investigation of dynamic changes in saltwater intrusion patterns during periods of severe drought. Outcomes show a significant negative correlation between salinity and normalized difference vegetation index (NDVI), indicating that the study area's agricultural greening was affected by saltwater intrusion.

Keywords: Saltwater intrusion; Hilbert-Huang transform; Time-dependent intrinsic correlation; NDVI; Po River Delta

5.1. Introduction

Saltwater intrusion is a complex phenomenon that has important effects not only on rivers but also on aquifers. In this study, we mainly focused on saltwater intrusion in river deltas. Along with drought, it can significantly impact the environment and agricultural production. It may hinder the use of surface water for irrigation or drinking and may threaten the livelihoods of coastal communities dependent on freshwater supply (Tian, 2019). It alters the salt content in surface waters, which leads to soil salinization (Chen et al., 2019). Soil salinization can change plants' photosynthesis, protein synthesis, and metabolism, resulting in the gradual degradation of vegetation and the reduction of plant species (Barbarella et al., 2015; de la Reguera et al., 2020; Nguyen et al., 2020). It worsens soil properties and fertility, resulting in reduced agricultural productivity and severe yield reductions (Tosi et al., 2022; Tully et al., 2019).

The primary controlling factor of saltwater intrusion along rivers is river discharge, as indicated in the studies by Matsoukis et al. (2023) and (Tarolli et al., 2023a). However, under extreme conditions, other factors like tide (Qiu et al., 2012), terrain (Chen et al., 2019), sea levels (Bellafiore et al., 2021), wind (Li et al., 2012) and subsidence due to anthropogenic activities (Tarolli et al., 2023a) also exert an influence. It represents a complex physical process with highly dynamic and non-linear characteristics (B. Liu et al., 2014). The effects of different processes on multiple scales do not follow the superposition principle. Interpreting the variables based on a single scale may disregard some characteristics of different time scales, leading to confusing outcomes (Ma et al., 2022). The Hilbert-Huang transform (HHT) is considered a novel method approach to clarify the nonlinear process of saltwater intrusion with multiple time scales. Using the HHT, a time series can be decomposed into a finite number of components associated with specific time scales. Every component has a physical meaning that reflects the essential oscillation characteristics in each time scale (Sahoo et al., 2020). Several studies have evaluated the relationship between salinity and discharge (Becker et al., 2010; Liu et al., 2001). Indeed, the latter is a significant control factor of saltwater intrusion (Wu et al., 2006; Xu et al., 2019). Many studies have already shown the relationship between discharge and salinity through classical statistical results. However, the traditional method is based only on a single scale and may distort the true cross-correlation information through time and space (Plocoste et al., 2019). The time-dependent intrinsic correlation (TDIC) is a powerful tool that can track the temporal evolution of the local correlation between two-time series by using adaptive sliding windows based on empirical mode decomposition (EMD) (Adarsh and Janga Reddy, 2019; Plocoste et al., 2019). The Po River is the longest and most important river of Italy. Located in northern Italy, it originates from the Alps and flows eastward into the Adriatic Sea near Venice (Maicu et al., 2018), with a total length of 652 km. A vast delta is formed at the estuary, including hundreds of fine streams and five main streams (Maistra, Pila, Tolle, Gnocca, and Goro). Po River Delta is one of the largest wetland area in Europe. Since the 14th century, the territory has undergone extensive land reclamation with the drainage of swathes of swampland and the construction of waterways and roads to allow the development of agriculture. The saltwater intrusion in the channel network of the Po River Delta (isohaline of 2 g/l limits) affected an area of about 300 km2, mainly used for a wide range of agricultural activities (Bellafiore et al., 2021). Agricultural irrigation, industrial usage, power generation and other human activities can lead to increased water consumption in the entire Po River Basin, especially during drought periods, potentially reducing the discharge of fresh water. This reduced freshwater flow can make the Po River Delta more vulnerable to saltwater intrusion during dry periods (Figure 5.1). Due to saltwater intrusion, salt rises to the farming layer with the underground salt water, and the salt content in the soil increases. The problem of soil salinization is inevitable. It affects the soil fertility and degrades coastal plants (Guerra-Chanis et al., 2019). It also influences water management by land reclamation authorities. To mitigate the effects of saltwater intrusion and improve the supply of fresh water for irrigation, land reclamation authorities can implement various strategies. Some of these strategies include constructing mobile barriers (that will be activated during low discharges to mitigate the intrusion of seawater) and freshwater storage facilities (to store water and reuse for irrigation during emergency periods) (Tarolli et al., 2023a). Some of these projects have already been implemented in the Po River Delta, while new ones have been financed and will be operational in a few years. Meanwhile, soil salinization inhibits the growth of crop roots, hinders the upper part of crops from absorbing water and inorganic salts, weakens the ability of leaves to conduct photosynthesis, reduces the yield of nutrients, and thus reduces the yield of agricultural products. Only a few studies have reported saltwater intrusion dynamics in the Po River Delta (Antonellini et al., 2008; Bellafiore et al., 2021). Especially in the context of climate change, the spatiotemporal variation of saltwater intrusion under extreme drought needs to be further evaluated. Moreover, the quantification of the effects of saltwater intrusion on agriculture (the primary activity in the area) has not yet been investigated in the Po Delta region, therefore, our work is the first attempt in fixing this gap. Multispectral satellite images could be interesting tools for this purpose. For example, the Landsat program with the Landsat 5 satellite has been covering the Po Delta area since the 1980s, thus including the severe saltwater intrusion events occurred in the last 40 years. Hence, it provides a significant historical dataset for investigating this phenomenon.

The objectives of the study were to (1) characterize the temporal variations in discharge and salinity under extreme drought periods in the Po River Delta, (2) investigate the spatial evolution of saltwater intrusion under extreme drought conditions along the Po River branches, and (3) analyze the potential impact of saltwater intrusion on agriculture using satellite-based NDVI (Normalized Difference Vegetation Index).

5.2. Materials and Methodology

5.2.1. Study area

The Po River delta (44°57′28″ N， 12°24′18″ E) is located in the north-western boundary of the Adriatic Sea. Agriculture is a major socio-economic sector. Main crops are cereals such as wheat (*Triticum aestivum*; planted in October-November for winter crop or March-May for spring crop; the latter is harvested from June), maize (*Zea mays*; planted in April and harvested from late August to October), rice (*Oryza sativa*; planted in April-May and harvested from September), and some other crops such as soybean (*Glycine max*; planted in April-May and harvested from September) and sugar beet (*Beta vulgaris var. saccharifera*; planted in March-April and harvased from August). A significant part of the territory is situated below sea level (with areas reaching –3.5 m a.s.l.). Soils in the study area are classified as slightly saline, with an EC1:2 value ranging from 0.4 to 1 dS/m (ARPAV, 2020). This information is based on measurements conducted in the Po Delta and published in 2020, covering a 25-year observation period. Generally, surface salinity values are not elevated due to the predominantly rainy climate. Surface salinity values in the Po Delta are typically mitigated through freshwater irrigation (ARPAV, 2020). Most of the area is characterized by loamy soils ranging from moderately to extremely calcareous. These are in reclaimed and artificially drained lagoon zones, with minor areas having a sandier texture (ARPAV, 2019). As the largest river in Italy, the Po River has an average discharge value of 1500 m3 s-1 and its basin surface area is 74000 km2, accounting for a quarter of the total surface of Italy (Bellafiore et al., 2021). The Po River daily discharge was measured at Pontelagoscuro (44°53′19.34″ N, 11°36′29.6″ E) from 2005-2017, that is the historical station for official measurements of streamflow. Its elevation is 7 m a.s.l. During the summer of 2006, the minimum water level was –7.46 m (relative to the hydrometric zero). The average aquifer depth (calculated based on the elevation from the fixed reference point used by the Regional Agency responsible for measurements) was –2.95 m, while –4.19 m was the maximum depth and –1.97 m was the minimum depth (ARPAV, 2022). Before 2010, a flow rate of 330 m3/s was set by the local reclamation consortia as the "first threshold" to meet the irrigation demand, supporting agricultural activity and counteracting salt wedge intrusion. Later, the value was updated by a "second threshold" of 450 m3/s to guarantee the river's ecological functionality. These values are reference parameters for monitoring drought conditions (Consorzio di bonifica Delta del Po, 2021b). From the original dataset, we investigated the years 2006, 2007, 2012, 2015, and 2017, in which the flow rate of the Po River decreased below the limits identified by the above thresholds.

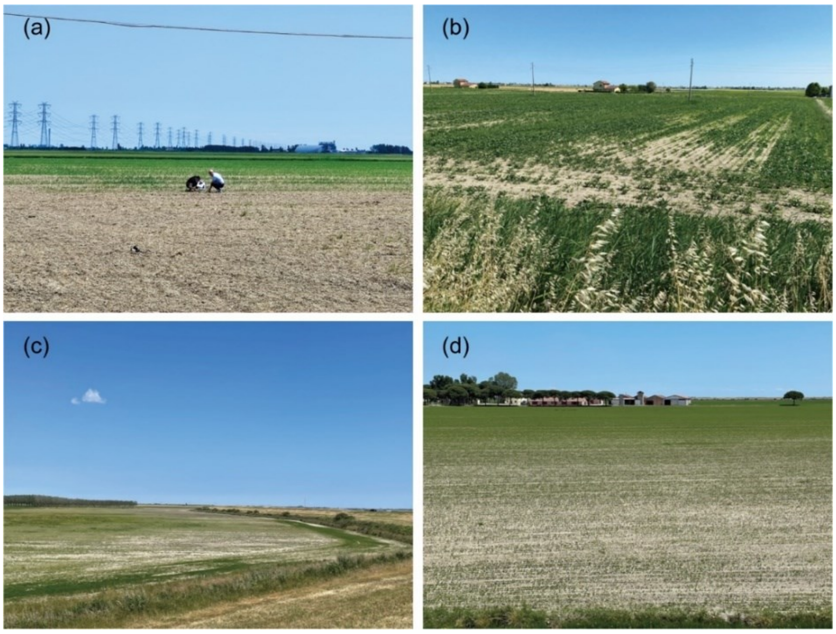

Figure 5.1 - Areas affected by soil salinization due to saltwater intrusion in the Po River Delta (Italy) (photos by P. Tarolli). Locations are reported in Fig. 5.2.

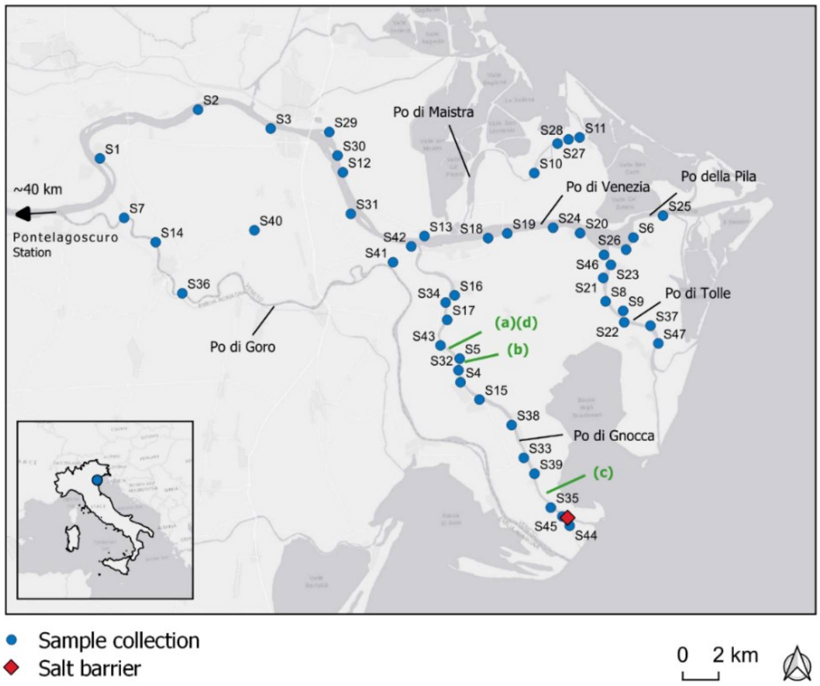

Figure 5.2 - The location map of the Po River Delta in northern Italy along the Adriatic coast (lower box). In the map details the location of water sampling points used for salinity measurement are shown. The map also shows the locations of the Po Gnocca Valle salt barrier (in red) and the areas where the photographs shown in Fig. 5.1 were taken (a-d; in green). The black arrow indicates that Pontelagoscuro station.

5.2.2 Water sample collection for salinity measurement

Data collection was performed by the land reclamation authority called "Consorzio di Bonifica Delta del Po" from July 3, 2005, to September 6 2017. The dataset consisted of 47721 salinity measurements at 47 georeferenced points (locations measured using a Global Navigation Satellite System; Figure 5.2). In most cases, these measuring points were located in the area adjacent to the irrigation inlet, and four measuring points using fixed instruments installed upstream and downstream of the salt barriers. All the measurements of the salinity data were carried out manually in the water of the Po River. We used two mobile conductivity meters devices and one set measuring instrument at the dams: the Eutech COND 6+ portable meter and the WTW Cond. 340i portable meter and the Prominent DULCOMETER DMT fixed salinometer. Correlation between conductivity and total dissolved solid was performed following Rusydi (2018). To better understand and acknowledge the process of saltwater intrusion in the Po River, measured point data of salinity were interpolated using the spline method. The latter allows a smooth reconstruction of a surface even in the case of irregular point data and therefore already applied in the river environment (Merwade et al., 2006).

5.2.3. Rescaled range analysis

Rescaled range (R/S) analysis based on fractal theory can scale the nonlinear dynamic characteristics of time series. Moreover, this method can identify whether the time series follows a random or deterministic structure pattern and then predict its future change trend (Hamed, 2007; Li et al., 2018; Luo et al., 2019; Sharma and Chattopadhyay, 2021; Shi et al., 2015; Szolgayova et al., 2014). The R/S analysis has been widely used in many scientific fields (Hamed, 2007; Shi et al., 2015; Szolgayova et al., 2014).

The R/S method divided the original time series X_t equally into n consecutive subsequences x_i (i=1, 2, 3, …, n), the average value $\bar{x_i}$ of subsequence time x_i can be expressed as follows:

$$\bar{x_i}=\frac{1}{\tau}\sum_{j=1}^{\tau} x_i(j) \quad (1)$$

Where τ is the observational length scale ($\tau=t/n$); $x_i(j)$ is the jth element of subsequence x_i; j is the serial number where $j = 1, 2, \ldots, \tau$.

The accumulated deviation $x(i, t)$ can be expressed as follows:

$$\mathrm{x}(i, t)=\sum_{j=1}^{t} (x_i(j)-\bar{x_i}),\ 1 \le t \le \tau \quad (2)$$

The calculation formula of the range of the time series $R(\tau)$ is as follows:

$$R(\tau)=max(x(i, t))-min(x(i, t)) \quad (3)$$

The calculation formula of the standard deviation of the time series $S(\tau)$ is as follows:

$$\mathrm{S}(\tau)=\sqrt{\frac{1}{\tau}\sum_{j=1}^{\tau} (x_i(j)-\bar{x_i})^2} \quad (4)$$

The calculation formula of the R/S statistic Q_τ can be expressed as follows:

$$Q_\tau = R(\tau)/S(\tau) \quad (5)$$

Based on the Q_τ, the following relationship was established:

$$Q_\tau = C\times\tau^H \quad (6)$$

where C is a constant, and H is the Hurst index.

The H values were obtained by linear fitting in double logarithmic coordinates of formula (7).

$$logQ_\tau=logC+Hlog(\tau) \quad (7)$$

Meanwhile, the autocorrelation coefficient B and fractal dimension D were adopted to analyse the correlation and the continuity of the temporal sequence, respectively.

$$B = 2^{2H-1}-1,\ B \in [-0.5, 1] \quad (8)$$

$$D = 2-H,\ D \in [1,2] \quad (9)$$

$H = 0.5$ indicates that the time series is a random variable. When $H \neq 0.5$, the time series have a long-term correlation, i.e., long-range correlation. 1) When $0 \le H < 0.5$, $-0.5 \le B < 0$ and $1.5 < D \le 2$, the salinity and discharge series is a frequently recurring reversal, the increasing trend in the past is likely to decline in the future and vice versa; 2) When $0.5 \le H < 1$, $0 \le B < 1$ and $1 < D \le 1.5$, the trends of salinity and discharge in the future will be reflected by the present.

5.2.4. Hilbert-Huang transform (HHT)

The Hilbert-Huang transform (HHT) applied for nonlinear and nonstationary data was pioneered by Huang et al. (1998). Empirical mode decomposition (EMD) is an adaptive dyadic filter bank that can decompose the input data into several intrinsic mode functions (IMFs) and extract a residue that represents the trend of the original time series. Sifting is completed when the last component is monotonic or constant, and in this case, no more IMF can be extracted (Luo et al., 2022):

$$\mathrm{X}(t)=\sum_{k=1}^{n} IMF_k(t)+R(t) \quad (10)$$

Where $R(t)$ is the residue, k represents the numerical value of each sequential IMF, and n is the number of IMFs.

The IMFs indicate the different scales of the original time series and form the physical basis of the data (Chen et al., 2010; Huang et al., 1998). An IMF can be outputted that must satisfy the two following conditions: (1) throughout the whole data set, the number of extrema and the number of zero-crossings must either be equal or differ at most by one, (2) at any point, the mean value of the envelope defined by the local maximum and the envelope defined by the local minimum is zero.

However, one of the main problems of the EMD algorithm is mode mixing. Mode mixing is when a single IMF contains multiple oscillatory modes or a single mode resides more than one IMF, likely altering the interpretation of the physical meaning of each IMF. In order to avoid such drawbacks, Wu and Huang (2009) proposed an ensemble empirical mode decomposition (EEMD) algorithm, which operates by adding white noise to the original data. In brief, the principle of EEMD depends on adding random noise to the input data, which provides a uniformly distributed reference scale in the initial time series and then cancels the problem of mode mixing during the decomposition process via the EMD filter bank. The added white noise can be eventually removed by averaging on the components during the decomposition process (Wu and Huang, 2009).

Each mode's mean period (T) can be calculated by counting the number of zero crossing points and local extrema points (Huang and Schmitt, 2014). The variance contribution (VC) indicates the percent contribution of each IMF in the overall variation of the time series, which can be computed by the following equation (Adarsh and Janga Reddy, 2019):

$$\mathrm{VC}(\%)=V_k/\sum_{k=1}^{n} (V_k+R) \quad (11)$$

Where V_k is the variance of each IMF and residue R).

In this study, we used EEMD to decompose the salinity and discharge data into multiple IMFs with different time scales.

5.2.5. Time-dependent intrinsic correlation (TDIC)

Natural processes reside in many local correlations (positive or negative) with their influential factors over time. The classical methods (e.g., Pearson correlation) are subject to limitations that can only reflect the global information based on a single scale and thus may not be suitable for nonlinear and nonstationary time series associated with multiple time scales, leading to the ignorance of important local correlation information between time series to some extent. Thus, a new technique called time-dependent intrinsic correlation (TDIC) has been introduced by Chen et al. (2010), which can track the temporal evolution of the local correlation between two modes by using adaptive windows based on the EEMD algorithm:

$$t_d = max\left(IP_i^1(t_k), IP_i^2(t_k)\right) \quad (12)$$

$$t_w = [t_k - t_d/2 : t_k + t_d/2] \quad (13)$$

$$R_i(t_k/t_w) = Corr\left(IMF_i^1(t_w) IMF_i^2(t_w)\right) \quad (14)$$

where IP_i^j is the instantaneous period of each IMF, t_k is the corresponding time, and t_w is the sliding window size which is adaptive; *Corr* is the cross correlation coefficient of two time series (Plocoste et al., 2019).

5.2.6. Satellite data and indicator of agricultural greening

The year 2006 was the driest year from 2005 to 2017, with minimal peaks in the flow of the Po River. For this reason, we chose to perform the agricultural greening analysis this year. We used satellite Landsat 5 products obtained from May 2006 to September 2006. Normalized Difference Vegetation Index (NDVI) is the widely used index for monitoring vegetation activities (de la Casa et al., 2018; Duan et al., 2017; Li et al., 2019). Before performing the analysis, we pre-filtered the images to minimize bias due to changing land cover. We created an RGB composite image using Landsat 5 bands 1, 2 and 3 for each period examined. Based on the colors in the image, we digitized and selected only areas with crops. This operation allows multitemporal comparisons between multiple images in the same agricultural region, excluding from the investigation portions that have undergone major changes in land cover during the study period (such as, for example, ploughing or crop harvesting). In this way, any reductions in NDVI could be attributable to changes in the vegetative state of the crop (such as due to saltwater intrusion impact). Plants in optimal vegetative conditions tend to have higher NDVI values. The effect of salt water can bring the crop into a stressed state, resulting in a lowering of NDVI. It is defined as follows equation 15:

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)} \quad (15)$$

Where NIR is near-infrared-band reflectance and RED is red-band reflectance.

5.2.7. The impact of salinity on crops and implications on NDVI

The impact of salinity on crops was carried out by analyzing NDVI values around the sampling points. Since there are no field measurements of the extent of salt damage for the summer of 2006 (the phenomenon was considered dangerous at the time, but is now of much greater concern due to frequent droughts caused by climate change), the extent of the area investigated

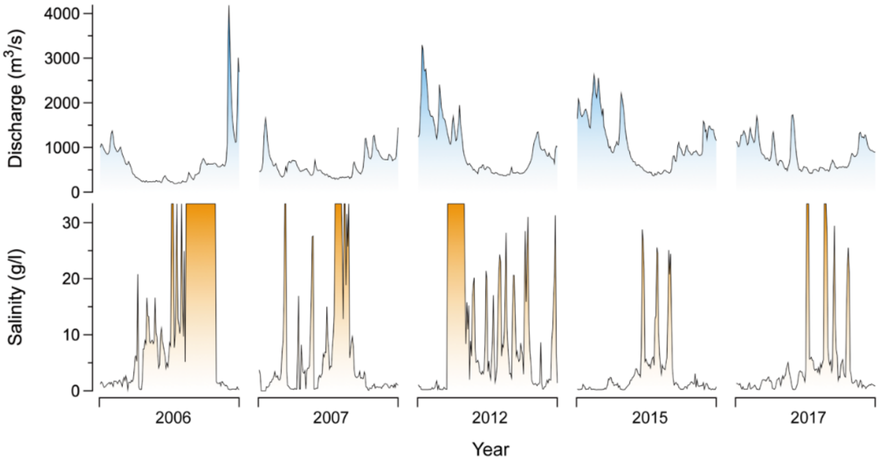

Figure 3 - Variations of discharge and salinity during the drought periods; the salinity is measured at the saltbarrier of Po Gnocca Valle permanent station and the discharge is measured at Pontelagoscuro.

Table 5.1 - Summary of input data used in different analysis.

Analytical method	Year	Month	Time scale of analysis	Salinity measuring station	Discharge measuring station
Rescaled range analysis	2006	5, 6, 7, 8, 9	Daily data	Gnocca Valle	Pontelagoscuro
Hilbert-Huang transform	2006	5, 6, 7, 8, 9	Daily data	Gnocca Valle	Pontelagoscuro
Time-dependent intrinsic correlation	2006	5, 6, 7, 8, 9	Daily data	Gnocca Valle	Pontelagoscuro
Spatial analysis of saltwater intrusion	2006	5, 6, 7, 8, 9	Daily data	47 stations are shown in Fig. 2	—
Effect of salinity on NDVI	2006	6, 7, 8, 9	Monthly data	47 stations (5 representative stations in Fig. 7 a-e)	—

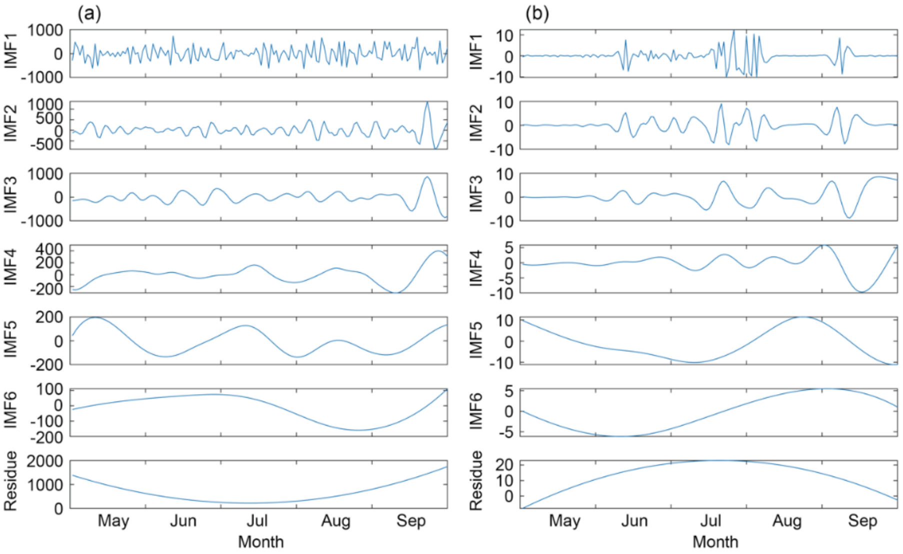

Figure 5.4 - Intrinsic mode functions (IMFs) and associated residues of discharge (a) and salinity (b) time series using ensemble empirical mode decomposition (EEMD) in 2006.

was determined by field surveys during the recent severe saltwater intrusion event of summer 2022, in collaboration with the technicians of the local land reclamation consortia and farmers. Salinity-driven crop damage in the Po Delta often occurs in well-defined areas or strips where the number of plants is drastically lower than in the surrounding, or completely devoid of living crops (see Figure 5.1). Therefore, we measured the extent of areas clearly damaged by the effect of salt on damaged in fields affected by the phenomenon along the Po River by using a topographic GNSS. Our measurements on 6 representative sites revealed that crops located within a 200 m proximity to water courses showed the most significant impact. Beyond this range, crops generally displayed ordinary vegetation conditions. To investigate the potential effects of salt, we established two buffer zones with the measuring station as the center. The first one covered a 200 m radius, where the decreases in the NDVI can be attributed to salinity. The second buffer zone, with a radius of 600 m, served as a control area where regular NDVI values were expected. To statistically assess the impact of salinity on NDVI, we conducted a t-test to compare the average of the two NDVI distributions (200 m and 600 m). Significant decreases in NDVI within the 200 m buffer zone around high salinity water samples can be attributed to the salinity effect. To gain further insights into this process, we analyzed the correlation between the average NDVI within 200 m and water salinity for the various sample locations. This analysis also considered the distance from the sea, a crucial parameter that influences water salinity in the river and is commonly referenced by citizens and stakeholders when discussing the saltwater intrusion process into the Po River.

5.3. Results and Discussion

5.3.1 Temporal variations of salinity and discharge under drought periods

According to Figure 5.3, in 2006, the average and minimum discharge values at Pontelagoscuro (the historical permanent station for official measuring the streamflow of Po River) were 662 m3/s and 189 m3/s, respectively. This station is considered by authorities and in official reports as a reference point for streamflow measurements. At the station of Gnocca Valle (considered by Consorzio di Bonifica Delta del Po as the official reference point for permanent salinity measurements), where mobile barriers for stopping the inland flow of saltwater are located, the average salinity recorded was 11.7 g/l, with 87 days surpassing the 2 g/l threshold. Notably, between August 3 and September 4, the salinity value soared to 33.3 g/l for a

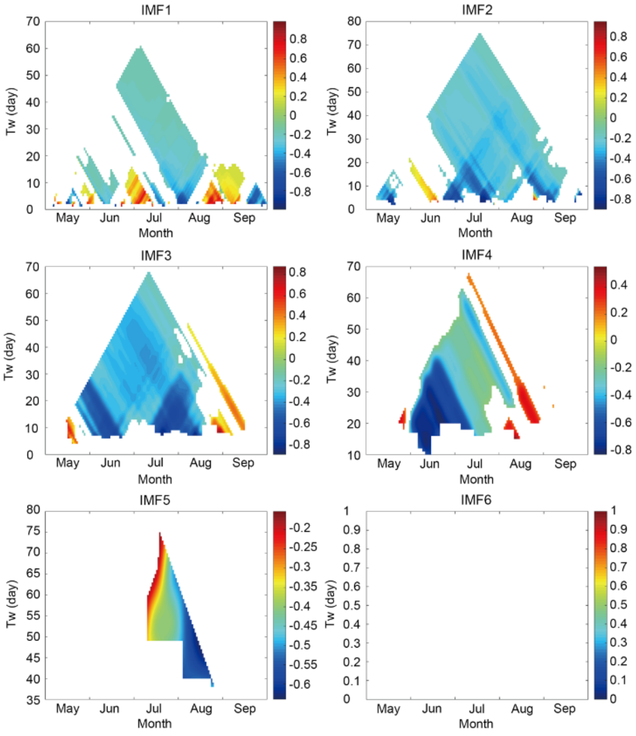

Figure 5.5 - TDIC analysis between discharge and salinity. The white space in the plots shows that the correlation is insignificant at the 5% level. Tw is the sliding window size.

continuous period of 33 days, hitting the highest measurement limit. However, it is essential to acknowledge that the salinity might have exceeded this limit. Moving on to the year 2007, the average and minimum discharge values stood at 611 m3/s and 287 m3/s, respectively. The average salinity was 6.5 g/l, and during this period, 85 days experienced salinity levels above 2 g/l. For 8 days, the salinity reached 33.3 g/l. The year 2012 showed average and minimum discharge values of 976 m3/s and 363 m3/s, respectively, along with an average salinity of 10.1 g/l. During this time, 98 days recorded salinity exceeding 2 g/l, and an extreme salinity value persisted for 19 days, spanning from June 2 to June 20. In 2015, the average and minimum discharge values were 1090 m3/s and 363 m3/s, respectively. The average salinity observed was 3.1 g/l, with 50 days surpassing the 2 g/l threshold. Finally, for the year 2017, the average and minimum discharge values were 832 m3/s and 424 m3/s, respectively. The average salinity was 4.4 g/l, and it persisted above 2 g/l for a total of 70 days. Based on the salinity and discharge data, we can conclude that 2006 was the most serious year of saltwater intrusion. In this study, we took 2006 as the object of study. We analyzed the spatial-temporal variation of saltwater intrusion and its potential effect on agricultural greening in the Po River Delta under extreme drought conditions.

Table 5.2 - R/S characteristic parameters of salinity and discharge. The salinity is measured at the saltbarrier of Po Gnocca Valle permanent station and the discharge is measured at Pontelagoscuro.

Month	Discharge			Salinity		
	Hurst index *H*	Auto-corr. coeff. *B*	Fractal Dimen. *D*	Hurst Index *H*	Auto-corr. coeff. *B*	Fractal Dimen. *D*
May	0.825	0.569	1.175	0.706	0.33	1.294
June	0.745	0.404	1.255	0.711	0.339	1.289
July	0.842	0.606	1.158	0.653	0.236	1.347
August	0.795	0.505	1.205	0.896	0.731	1.104
September	0.837	0.595	1.163	0.841	0.604	1.159

Table 3 - Periods and variance contributions of the IMFs and residuals for the salinity and discharge.

IMFs	Salinity		Discharge	
	Period (days)	Variance Contr. (%)	Period (days)	Variance Contr. (%)
IMF1	4	49.4	5	39.1
IMF2	10	16.9	16	22.8
IMF3	28	13.4	44	11.8
IMF4	172	3.4	117	8.5
IMF5	259	2.7	749	7.9
IMF6	906	1.5	1380	1.2
Residual	—	12.7	—	8.7

According to Table 2, R/S characteristic parameters of discharge during different periods in 2006 are shown as $0.5 < H \leq 1$, $0 < B \leq 1$, and $1 \leq D < 1.5$, which indicated that discharge and salinity time series were both long-range persistence series, and the future trend can be reflected by the present. While relevant former research shows that the discharge and salinity series were frequently recurring reversal (B. Liu et al., 2014; Wang et al., 2019).

To better understand the correlations between discharge and salinity in a multi-scale way, time-dependent intrinsic correlation based on ensemble empirical mode decomposition (EEMD) was used to assess the salinity-discharge relations. Before that, we used the EEMD method to characterize the multi-scale time variability of salinity and discharge time series. As shown in Figure 5.4, the discharge and salinity were decomposed into six independent IMFs and one residue. The frequency and amplitude of the IMFs decreased with the implementation of EEMD algorithm. In other words, the IMFs with lower numerical values separated the higher frequency oscillations in the data series variations that occurred at short-term scales from the lower frequency oscillations at long-term scales, which corresponded to the IMFs with higher numerical values (Ghasempour et al., 2021; Wang et al., 2015). Liu et al. (2019) obtained ten IMFs of the rainfall, runoff, and suspended sediment concentration (SSC) in the Loess Plateau, which was different from the current result. The original data showed more heterogeneity in a catchment scale. The residue showed a predominant trend over time that was not discerned from the original time series due to nonlinear and nonstationary characteristics in the data (Tsai and Treadwell, 2019). The changing trend of residue indicated that discharge decreased and then increased during the drought periods from May to September; this result confirms the prediction of many models that the discharge of Po River will decrease during the summer months (Bellafiore et al., 2021). At the same time, the residue showed that salinity increased and then decreased during the drought periods from May to September. This was mainly due to river discharge positively affecting salinity stratification and resisting saltwater

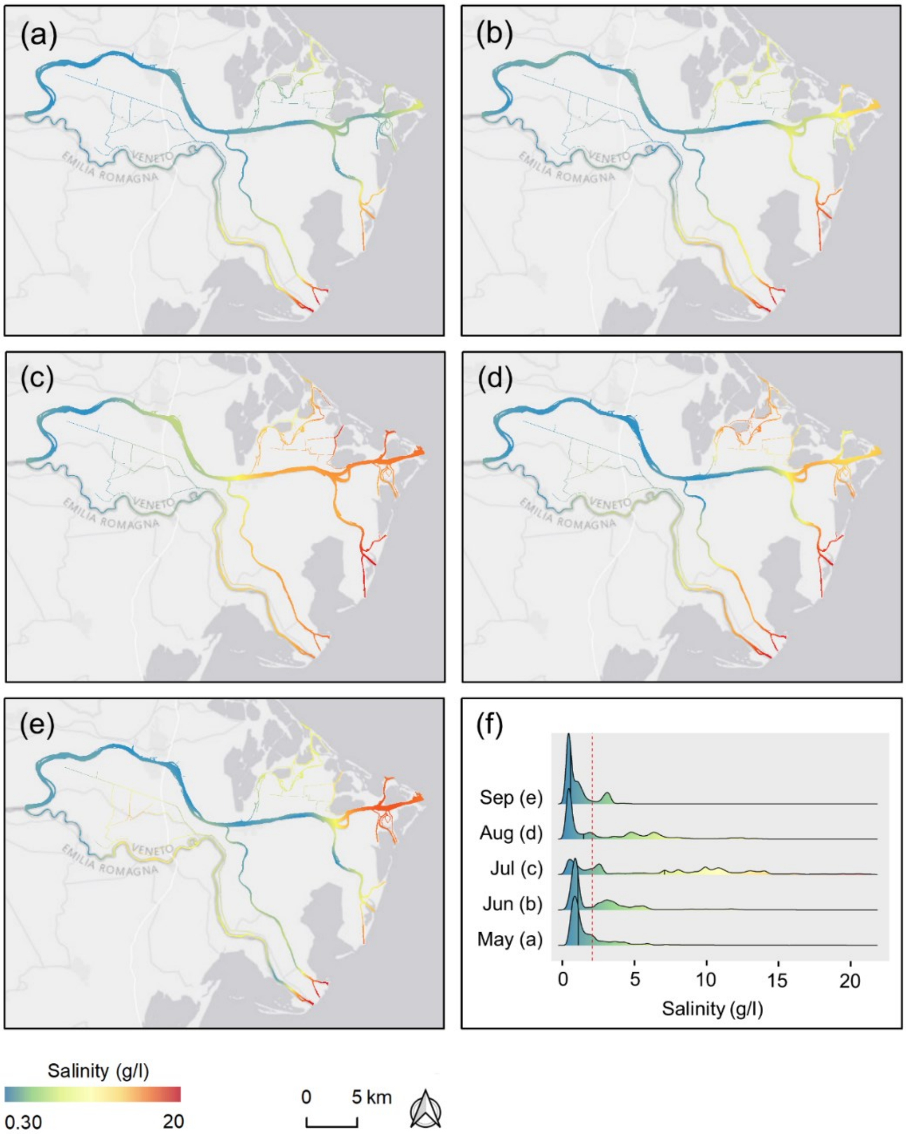

Figure 5.6 - Spatial-temporal evolution of saltwater intrusion in Po River delta in 2006. (a), (b), (c), (d) and (e) represent May, June, July, August, and September, respectively. (f) represents the PDFs of salinity values found in the study area during the months of observation. The red line in Fig. 6f indicates the critical salinity threshold of 2 g/l.

intrusion. This phenomenon was also probably caused by regional climate change, tidal oscillatory flux, and anthropogenic activities (Bellafiore et al., 2021; Da Lio and Tosi, 2019).

To highlight every IMF quantitatively, the mean period was estimated according to Liu et al. (2019). At the same time, the variance contribution showed the influence of different IMFs and residuals on the original time series (Table 2). The periods of the discharge IMFs lagged behind that of the salinity IMFs except for IMF4. The variance contributions of IMF1 and IMF2 of discharge and salinity were much higher than those of other IMFs and residues, with respective values of 49.4%, 16.9%, 39.1%, and 22.8%. The IMF1, IMF2, and IMF3 had substantial contributions accounting for 79.7% and 73.7% to the variability of the original time series corresponding to salinity and discharge. The result suggested that short-term scale oscillations played the predominant role in changes in the original time series, similar to previous studies (Liu et al., 2019; Luo et al., 2022).

The classical correlation considers the average over time defined in an integral sense based on the complete dataset. But in fact, the correlation may show rich dynamics, and a strong correlation can be quite local in the time domain (Kbaier Ben Ismail et al., 2016). To get more insight into the local moving correlation between salinity with discharge, the time-dependent intrinsic correlation (TDIC) based on the EEMD was employed in this study. Generally, with conventional statistical analysis of time series, salinity is always negatively correlated with discharge. Figure 5.5 shows the TDIC with different time scales. IMF1, IMF2, and IMF (table 3). represent 5-day, 15-day, and 35-day cycles. Under these high-frequency signals, we found that the positive and negative correlations between salinity and discharge appeared alternately, related to the strong randomness of regional precipitation, tide, and other factors in a short time. For the IMF4, with a mean period of 150 days, strong negative correlations between salinity and discharge were observed in June. The correlation between discharge and salinity decreased gradually with the increase in time scales (IMF5 and IMF6). A good understanding of the dynamics of saltwater intrusion, which is crucial for protecting human health and agriculture, is closely linked to river discharge. To investigate this relationship, we used a new cross-correlation technique called the time-dependent intrinsic correlation method (TDIC) based on EEMD decomposition. To our knowledge, this study is the first to apply TDIC to investigate saltwater intrusion dynamics, and the results show that it successfully captured both negative and positive correlations between salinity and discharge during droughts. These findings demonstrate the complex dynamics of salinity in response to discharge variability.

The TDIC method revealed that the effects of river discharge on saltwater intrusion were observed locally over time, and the results of this study can be used to parameterize models for simulating saltwater intrusion dynamics in the Po Delta region. This method is, therefore, an essential tool for local authorities to predict the risk of saltwater intrusion in the future.

5.3.2 Spatial evolution of saltwater intrusion and its effect on NDVI under extreme drought conditions

Figure 5.6 clearly shows the dynamics of interpolated salinity data along the rivers over time. On May 8, the salinity values in the delta channels were all lower than 2 g/l, except for the two survey stations near the estuary (Figure 5.6a). On June 9, saltwater began to invade from downstream of the channels to the upstream. Saltwater intruded into the delta up to 11.9, 4.86, and 5.6 km upstream of the river mouth of the Gnocca, Tolle, and Maistra branches, respectively (Figure 5.6b). This situation may hinder the irrigation of river water in the central Po River delta. On July 24, with the decrease in discharge, saltwater intrusion extended almost the entire delta system (Figure 5.6c). The maximum saltwater intruded into the delta up to 12.5, 9.2, 11.1, 20.4, and 22.3 km upstream of the river mouth of the Maistra, Pila, Tolle, Gnocca, and Goro branches, respectively. Salinity values ≥ 30 g/l are found up to 6 km from the river mouth in the Maistra and Tolle branches. This saltwater intrusion occurred four days after the Po Delta reached the historical minimum discharge record (189.24 m3/s) (during the summer of 2022 however, the 2006 record was broken by a new value of 104 m3/s, (Tarolli et al., 2023a)). About 1 month later, saltwater intrusion eased gradually with the increase of discharge (Figure 5.6d). The freshwater would weaken the salinity of the delta area in the dry season, and as time went on, the salinity downstream of the delta area was further diluted, which in turn reduced the salinity of the entire delta area (Figure 5.6e). The phenomenon of large salinity in the lower reaches of the delta area is closely related to the nearshore currents of the Adriatic Sea and the estuarine dynamics.

The salt stress to which crops are exposed can potentially negatively affect their germination, growth, and reproduction (Plocoste et al., 2019). Crops are usually more sensitive to salinity in early growth stages than in later developmental stages (Mbarki et al., 2020). However, there are differences in salinity tolerance among various crops at the same growth stage. Rice is considered a tolerant crop (Khan et al., 1997). Corn is moderately tolerant to salinity (Farooq et al., 2015), while soybean is a susceptible crop. In fact, it can be severely damaged if exposed to even low salinity values (Essa, 2002; Phang et al., 2008). This is a primary problem considering that it is a widespread

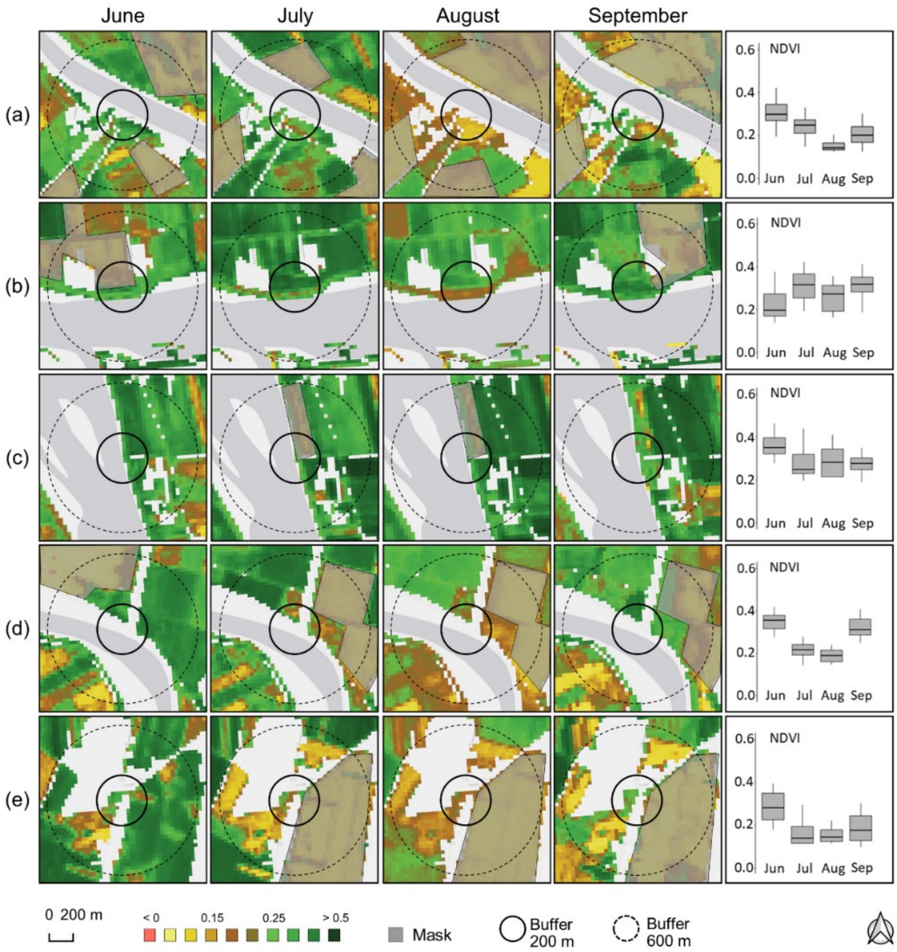

Figure 5.7 - The seasonal evolution of NDVI in summer 2006 (June to September). The maps in a-e focus on five representative measuring stations, while the panels to the right show relative boxplots representing the value distribution. The two concentric circles show the 200 m and 600 m buffers to highlight the area investigated. Regions in dark gray are land excluded from the analysis as they have undergone significant land cover changes during the period analyzed and therefore not representative of NDVI changes related to crop impacts.

crop in the Po River Delta. To mitigate the bias due to the presence of different crops in potentially different growth states, we analyzed the vegetation condition in homogeneous areas around the salinity measurement point. Several studies have indicated that NDVI is closely related to salinity (Barbarella et al., 2015; Nguyen et al., 2020). Therefore, the change in the NDVI index was used to characterize the stress of saltwater intrusion on agricultural activity in different periods. For clear visualization of the process on the map, we selected 5 representative salinity measuring stations from the upstream, midstream, and downstream of the delta river system, namely a, b, c, d, and e (Figure 5.7). By calculating the NDVI values based on Landsat 5 in the buffer zones during different periods, we can clarify the effect of saltwater intrusion on vegetation growth. Overall, the average NDVI values within the 200 m buffer around the salinity measurement points are significantly lower than those within the 600 m control buffer (t-test; p-value = 0.013). This finding indicates a clear decline in crop vigour within the proximity of salinity-affected areas. The NDVI values show a trend of decreasing first and then increasing with time. The NDVI value in June was the largest (from 0.804 to 0.859), then a small temporary decrease was observed at the beginning of July, while a decrease occurred in August (from 0.692 to 0.733). Finally, an increase emerged in September. Saltwater intrusion into river and irrigation channels caused salinity stress and impaired crop growth. This phenomenon was most obvious, especially in August. To clarify the impact of saltwater stress on crop growth, we conducted a correlation analysis between salinity values at various measurement points and the average NDVI values in a 200 m radius around each point (Figure 5.8). This measure is a representative range commonly found in agricultural lands in the Po Delta where crops are significantly affected by the effect of salt (see Section 2.7 and Figure 5.1). Results show a significant negative correlation between salinity and NDVI. Additionally, while not the primary objective of the study, we observed a negative correlation between salinity values and the average NDVI with increasing distance from the sea. This trend is consistent with the higher salinity measurements typically observed in river water closer to the sea than in inland areas (see Figure 5.6). The results are in line with previous studies by Truc et al. (2020) and Wang et al. (2019), who also reported that saltwater intrusion led to decreased crop productivity and soil property degradation due to the influx of water-soluble salts. In our study, the NDVI graph provided clear evidence of impaired crop growth resulting from salinization. The process of soil salinization can significantly impact the surrounding ecosystem, and further intensification of this phenomenon may lead to regional micro desertification.

5.4. Limitations and future perspectives

The HHT is a powerful tool to clarify the nonlinear process of saltwater intrusion with multiple time scales. However, performing highly accurate saltwater intrusion simulations remains a significant challenge, and the dataset should be very accurate in its spatio-temporal settings. In our study area, we compared the discharge of the Po River (influenced by periods of severe drought) with the water salinity. The discharge was measured at the only available stream gauge station (Pontelagoscuro), located before the delta reaches. Instead, salinity was measured by the permanent station at the Po Gnocca Valle salt barrier near the sea. The increase in flow rate at the Pontelagoscuro station also implies an increase in the different channels of the Delta. Therefore, even if it includes an error due to different measurement locations, the general pattern and meaning of the analysis do not change; indeed, no dysconnectivity infrastructures are present along delta reaches. A similar approach was already applied for investigating salinity dynamics in a Delta system in Canada (Drever et al., 2023). Despite the limited role played during the investigated saltwater intrusion process, future

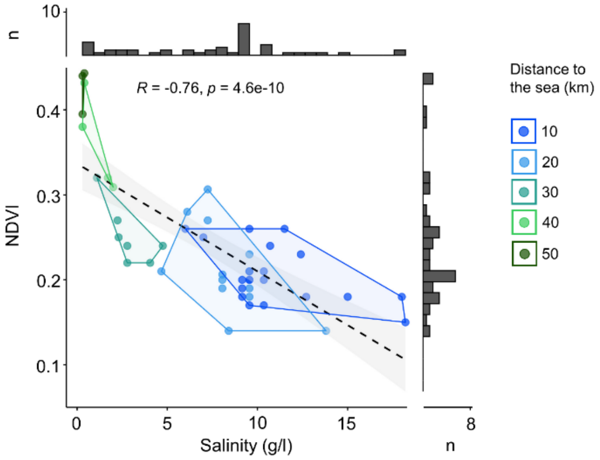

Figure 5.8 - The relationship between salinity measured at the various sampling locations and the average NDVI of agricultural areas in the 200 m neighborhood. Histograms depict the distribution of salinity (top) and NDVI (right) values (n indicates the frequency of observation). The two measures are found to be inversely proportional. The data are grouped according to distance from the sea to highlight that agriculture along river stretches closer to the sea (and with generally higher water salinity; see Figure 5.6) were characterized by lower NDVI values.

research should also consider more factors, such as tides, sea level and wind. A limitation is the potential influence of various environmental factors, such as soil moisture or crop type, on the NDVI values. Indeed, landscape heterogeneity can introduce variability and affect the accuracy of the comparison. Despite such biases, this work represents a first attempt to provide local land reclamation and irrigation authorities with a tool for planning urgent mitigation solutions. Here we provided a novel quantification (for the Po Delta) of the potential impact of saltwater intrusion on agricultural greening. For the same study areas investigated in this paper, more in-depth field collaborative research has already begun with local authorities aimed at filling gaps not addressed in this work. In fact, in the summer of 2022, due to high temperatures and drought (Straffelini and Tarolli, 2023) the discharge of the Po River dropped to the lowest value in history (104 m3/s, (Tarolli et al., 2023a)). The seawater flowed backwards with the drying up of many sections of rivers in the Po River basin. Saltwater reached more than 40 kilometres upstream of the Po River in the worst situation. More than 20000 hectares of farmland in the Po River Delta had no freshwater irrigation. Undoubtedly 2022 was another critical year of saltwater intrusion; the authors already started an analysis of 2022, and it will be concluded considering the years 2023 and 2024. For this reason, further research developments are planned, including in-depth studies on the degree of salinization of soils and quantification of the negative impact on different crop types.

5.5. Conclusions

This study provides valuable insights into the dynamic characteristics of saltwater intrusion during drought conditions, considering both temporal and spatial variations. The research collected an unprecedented amount of field data and utilized remote sensing observations to better understand the potential impact of saltwater intrusion on agricultural greening. To identify the time scales and change trends of salinity and discharge, the novel method Hilbert-Huang transform (HHT) and rescaled range (R/S) were employed. The results of the study indicate that TDIC analysis successfully captured the negative and positive correlations between salinity and discharge during drought. The results of this study can be used to parameterize models for simulating saltwater intrusion dynamics in the Po Delta region. In 2006, the salinity reached its extremum and lasted for 33 days. The maximum saltwater intrusion occurred in July, which intruded into the delta up to 12.5, 9.2, 11.1, 20.4, and 22.3 km upstream of the river mouth of the Maistra, Pila, Tolle, Gnocca, and Goro branches, respectively. A negative correlation between salinity and NDVI was observed, and the correlation decreased with the increased distance to the sea. Agricultural greening in the study area was greatly affected by saltwater intrusion; micro desertification has even occurred in some places. Soil salinization would hinder crop growth, and in some plots with severe salinization, it would also lead to a significant reduction in crop yield. This study provides compelling scientific evidence to encourage local authorities to undertake preventive measures to protect the Po River Delta's Cultural Landscape. Specifically, to protect human health and agriculture from saltwater intrusion, an increasingly threatening process due to climate change-related droughts.

Part B – Extreme Rainfall in Cultural Landscapes

The increasing frequency of extreme rainfall events poses significant threats to representative Cultural Landscapes, particularly those characterized by steep-slope and mountainous agriculture. Recent studies illustrate the multifaceted impacts of such events on these vital landscapes. The **Part B** of this PhD thesis (sections 6-7-8) incorporates researches that reveal how such threats affect not only the environment but also the cultural heritage embedded in agricultural practices. It delves in the following case studies:

- **In Global Mountain Grasslands**, the article "*Climate Change is Threatening Mountain Grasslands and Their Cultural Ecosystem Services*" examines how climate change-induced extreme precipitation accelerates soil erosion in mountain grasslands globally. These ecosystems, integral to traditional practices like transhumance, are increasingly at risk as intensified rainfall exacerbates soil erosion and degrades land. The study emphasizes the need for nature-based solutions to mitigate these effects and protect the cultural and ecological value of these grasslands.
- **In Agricultural Terraces**, the study "*Multitemporal Remote Sensing for Monitoring Hydro-Erosive Process Dynamics in Terraced Cultural Landscapes*" focuses on the UNESCO World Heritage site of Portovenere and Cinque Terre. Extreme rainfall events challenge traditional terraced agriculture, leading to erosion and instability. This research proposes a monitoring workflow using advanced remote sensing technologies, such as UAVs and LiDAR, to identify and address erosion-prone areas. By improving the management of these landscapes, the study aims to enhance resilience to extreme weather events.
- **In Steep-Slope Terraces**, the article "*Enhancing Resilience to Weather Extremes through Micro-Water Storage in Steep Slope Viticulture*" explores sustainable water harvesting techniques to counteract the impacts of intense rainfall. The research demonstrates how small-scale water storage solutions can mitigate runoff and erosion, enhancing the resilience of steep-slope viticulture against extreme weather. By integrating traditional knowledge with modern practices, the study highlights effective strategies for preserving these culturally significant landscapes amidst changing climate conditions.

6. Mountain Grasslands Worldwide and Their Cultural Value at Risk of Climate Change

Context

Mountain grasslands are widespread ecosystems found on every continent. In addition to hosting a diverse range of plant and animal species, they provide numerous ecosystem services such as water regulation and carbon storage. These grasslands are also home to traditional practices like livestock grazing, which hold significant social and cultural value, such as transhumance. However, climate change may accelerate the degradation of these biomes, with soil erosion driven by intense precipitation events being a key concern. The risks are substantial for both the ecosystems and the human communities that traditionally inhabit mountain grasslands. Yet, it remains unclear how soil erosion will affect mountain grasslands globally in a changing climate. This chapter aims to shed light on this issue by mapping the global distribution of these biomes using satellite data and estimating the acceleration of erosion processes at a continental scale. Finally, an exploratory section on the risk of extreme drought is provided, a second import issue of such landscapes due to climate change. The findings provide a global overview that is valuable for policymakers and decision-makers in planning mitigation measures, emphasizing nature-based solutions (NbS) as optimal strategies.

The article

This section is based on the scientific article published in 2024 in the journal Catena (*Q1 in Geosciences, Multidisciplinary, Soil Science, and Water Resources; IF 2023: 5.4*) titled "*Climate Change is Threatening Mountain Grasslands and Their Cultural Ecosystem Services*".

> The article primarily addresses SO-B by investigating the process of soil erosion in global mountain grasslands (detected by satellite data) under various climate scenarios. To a lesser extent, it addresses SO-A by examining the flip side of intense precipitation—drought—with a case study focused on Europe. Additionally, it partially addresses SO-C by exploring the role of sustainable strategies for the resilient management of mountain grasslands.

PEER-REVIEWED & PUBLISHED RESEARCH ARTICLE

Climate change is threatening mountain grasslands and their cultural ecosystem services

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Eugenio Straffelini: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing.

Abstract

Mountain grasslands are widespread ecosystems worldwide that provide economic and cultural ecosystem services. They serve as a source of food, carbon sequestration, clean water, and habitat, also hosting traditional practices such as transhumance. However, they are facing growing threats due to climate change, including extreme weather events like intensified rainfall causing soil erosion and prolonged droughts alongside high temperatures, impacting vegetation health and water resource management. Despite their strategic importance, there remains a gap in the comprehensive global mapping of these ecosystems and an exhaustive exploration of the critical challenges posed by climate change. In this context, we present an unprecedented satellite-based global mapping of mountain grasslands and conduct an analysis focusing on key climate change-related concerns. This includes an assessment of (1) soil erosion by water under diverse climate scenarios (RUSLE; 2015 vs. 2070-RCP8.5) and (2) the dynamics of extreme drought and high-temperature events (utilizing the Vegetation Health Index; VHI), with a specific focus on European mountain grasslands during the summer of 2022. Our findings indicate a potential future global aggravation of soil erosion in mountain grasslands (+2.3%), particularly in South America (+19.4%) and Africa (+10.0%), as well as localized hotspots. Furthermore, our analysis of the 2022 situation in Europe demonstrates the extensive impact of similar extreme events across a significant portion of grassland areas at a continental scale, with notable hotspots observed in southern Europe. Finally, we explore strategies to enhance mountain grassland management, specifically focusing on nature-based solutions (NbS) aimed at preserving their invaluable cultural ecosystem services in the face of climate change.

Keywords: mountain grassland; soil erosion; drought; nature-based solutions; climate change.

6.1. Introduction

Mountain grasslands are grassy expanses dominated by herbaceous species and non-woody plants at high elevations (Schirpke et al., 2017). They are important areas for mowing and livestock grazing, playing a crucial role in supporting local livelihoods (Montenegro-Díaz et al., 2022). In previous times, the primary focus of managing mountain grasslands revolved around providing forage. In contemporary understanding, there is a growing recognition of their significance in terms of regulating ecosystems and providing ecosystem services (Grigulis et al., 2013; Lamarque et al., 2011). They serve as habitats for a diverse array of plant and animal species, supporting biodiversity and preserving ecological balance (Wilson et al., 2012). They also act as carbon sinks, helping to mitigate climate change by sequestering carbon dioxide from the atmosphere (Ru et al., 2022; Smith, 2014). They contribute to water regulation, ensuring a stable water supply for downstream communities and reducing the risk of floods (Egoh et al., 2008; Zhao et al., 2017). Additionally, they play a crucial role in maintaining the biogeochemical cycles of biomass (Rumpel et al., 2015). In recent decades, there has been a growing recognition of the cultural ecosystem services they provide, including aesthetic appeal and recreational value (Bürgi et al., 2015). For this reason, UNESCO listed mountain grasslands sites for their distinctive landscapes and historical people-nature connections, such as "Pyrénées - Mont Perdu" site (France and Spain) or the "Qinghai Hoh Xil" site (Qinghai-Tibetan Plateau; China). An emblematic cultural practice of mountain grassland is transhumance, where herds are relocated to different grazing areas at varying altitudes, taking advantage of seasonal cycles (Liechti and Bieber, 2016). In addition to providing food and related products, it offers a range of social benefits such as cultural diversity and a strong sense of regional identity among people (Nori and Gemini, 2011).

Mountain grasslands are increasingly facing degradation due to a range of factors. Climate change, especially weather extremes (Dong et al., 2022; Easterling et al., 2000), and unsustainable practices such as overgrazing (Torresani et al., 2019), are primary drivers of land degradation (Montenegro-Díaz et al., 2022). The abandonment of farmland can lead to an increase in negative environmental effects, such as a higher risk of wildfires, landscape homogenization, and a reduction in biodiversity over the medium and long term, also deeply affecting soil physico-chemical properties (Lasanta et al., 2015; Nadal-Romero et al., 2023). Altered climatic conditions can result in shifts in vegetation distribution, modifying the composition and structure of grassland communities (Dong et al., 2022; Easterling et al., 2000; Jentsch and Beierkuhnlein, 2008; Y. Liu et al., 2014). Additionally, these changes can lead to alterations in water availability, plant growth, nutrient cycling, and overall productivity, including impairments in the rate of nitrogen mineralization in the soil (Bell et al., 2005; Piao et al., 2009; Wilcox et al., 2017).

An increase in the frequency of extreme rainfall events is one of the most concerning consequences of climate change for mountain grasslands. This can lead to higher rainfall erosivity (Gayen et al., 2020), posing these landscapes at risk of soil erosion (Turnbull et al., 2009). This is documented in several studies, for instance in Central Asia (Wiesmair et al., 2016), China

(Liu et al., 2008) and Europe (Durán et al., 2020). Intense precipitation events could also trigger surface landslides (Zweifel et al., 2021). A primary reason is the low tensile strength of the root system (Löbmann et al., 2020). Nevertheless, plant diversity, vegetation composition, and the frequency of key species play a significant role in influencing such forces, either exacerbating or mitigating the issue (Krautzer et al., 2011). Drought is another significant issue linked to climate change, and 2022 stands out as a notable example, marked by numerous hotspots worldwide. Europe faced one of the most severe events in 500 years, exacerbated by heatwaves (Toreti et al., 2022). This led to devastating wildfires, reduced river levels with saltwater intrusion in some deltas, and significant challenges for the environment and human sectors due to water shortages, especially agriculture (ECMWF, 2022; Hall et al., 2022). Mountain grasslands were also exposed to such extreme event. This is a worrying fact, especially since similar occurrences are only at beginning due to climate change (Bonaldo et al., 2023; Corona Lozada et al., 2019). Prolonged water scarcity can lead to significant alterations in soil moisture, thereby affecting the microbial community structure, reducing extracellular enzyme activity, and decreasing litter decomposition rates, resulting in changes in soil nutrient cycling (Wang et al., 2014). Moreover, drought can severely affect plant productivity, altering biomass and impacting livestock, as observed for example in China (Zhou et al., 2018) and the USA (Carroll et al., 2021). The climate change-related risk to mountain grasslands extends beyond ecosystem damages, impacting the cultural ecosystem services they provide. It is therefore strategic to assess the extent of these ecosystems globally and investigate critical degradation factors driven by opposing climate change-related processes. Therefore, the primary objective of this study was to generate an unprecedented global map of mountain grasslands using high-resolution remote sensing satellite data. Moreover, the research aimed to explore two critical phenomena impacting these ecosystems: soil erosion and extreme drought events. The first analysis was based on data provided by Borrelli et al. (2020) covering the current conditions (baseline; 2015) and future projections (2070; RCP8.5 scenario) at a global scale using the Revised Universal Soil Loss Equation (RUSLE). Then, the study focused on evaluating drought severity in European mountain grasslands during the extreme drought and high-temperature event of summer 2022, utilizing the Vegetation Health Index (VHI). Understanding these risks holds significant value in developing measures such as nature-based solutions (NbS) to safeguard the cultural ecosystem services provided by mountain landscapes.

6.2. Material and Methods

6.2.1. Mapping global mountain grasslands

The first goal of the paper was to provide a map of mountain grasslands worldwide. Mapping grasslands has been a topic of debate for decades due to their wide distribution, diverse types, and dynamic nature influenced by natural factors and human activities (Hobbs et al., 2007; Latham et al., 2014). However, remote sensing technology for Earth Observation (EO) has made significant advancements in understanding the land covers, successfully tackling challenges related to dynamic biomes and large-scale analyses, even if with some inherent limitations (Ali et al., 2016). In this research, we employed the Google Earth Engine platform to address the issue of handling extensive datasets. Land cover data were collected from the Copernicus Global Land Service (CGLS) product called "Dynamic Land Cover map (CGLS-LC100)". It stands as one of the most accurate global land cover datasets, presenting 100-meter resolution geospatial information that includes discrete land cover classes and continuous layers for vegetation/ground cover (Tsendbazar et al., 2021). Data were collected from 2015 to 2019 and are derived from the PROBA-V 100 m time-series, a high-quality repository of land cover training sites and ancillary datasets. This iteration demonstrates an accuracy level of 80% at Level 1 throughout all included years (Buchhorn et al., 2020). From this dataset, we firstly selected the class "Herbaceous vegetation", which contains areas dominated by herbaceous species, with less than 10% of tree and shrub cover, and without a defined forest structure, aligning with the grassland definition proposed by Dixon et al. (2014). Next, this data was filtered for only those areas located at an elevation above 600 m, a threshold commonly used to define mountainous landscapes (such as Körner et al. (2017)). The topographic data used for this operation was obtained from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), a U.S. Geological Survey dataset with a resolution of 7.5 arc-seconds. The distribution of mountain grasslands was investigated across various continents (data based on ESRI ArcGIS HUB; World Continents; https://hub.arcgis.com/datasets/esri::world-continents/exploreis). We finally evaluated the accuracy of the mountain grasslands map using Copernicus' classification quality index, a validation measure utilized for assessing the accuracy of the CGLS dataset. This process entailed comparing more than 20,000 classified points against an independent reference dataset (Buchhorn et al., 2020). Higher index values indicate greater confidence in the accuracy of pixel classification.

6.2.2. Global pattern of soil erosion in mountain grasslands under climate change

We applied the RUSLE to assess the potential soil loss by water of mountain grasslands worldwide. We integrated the localization of global grasslands (see section 2.1) with erosion data published by Borrelli et al., (2020). While accompanied by a degree of uncertainty, these data offer quantification of annual water erosion (expressed ad Mg/ha/yr) for approximately 96% of the Earth's surface in an open-access format. Additionally, they provide insights into the current erosion status (baseline: 2015) and projected erosion rates for the future (2070) under various climate scenarios (RCP2.6, RCP2.4, and RCP8.5) and socio-economic scenarios (SSP1, SSP2, SSP5), adhering to the Intergovernmental Panel on Climate Change (IPCC) guidelines. We investigated the influence of climate change on soil erosion in global mountain grasslands with a specific focus on the most critical climate scenario (RCP8.5). To specifically emphasize the role of climate in the analysis, land use conditions were maintained unchanged. The quantification process involved two stages. First, we intersected the mountain grasslands mosaic with the potential erosion of 2015 to describe the current erosion rates; second, the same positions were cross-referenced with projected soil erosion for 2070. The comparison in percentage terms was made by taking advantage of the computational capability of Google Earth Engine, comparing the total erosion estimations for mountain grasslands in 2015 and 2070 globally, and for each continent.

6.2.3. The extreme drought of 2022 on European mountain grasslands

Mapping drought severity on mountain grasslands during extreme events and identify hotspots are vital for understanding potential ecological impacts, aiding in crop health assessment, yield loss anticipation, and promote water management strategies. This research concentrates on the extreme drought that affected European mountain grasslands during the extreme event of summer 2022, particularly during July, marked by low precipitation and high temperatures. We employed the VHI exploiting MODIS satellite data in Google Earth Engine, following Straffelini and Tarolli (2023). It is a well-established index for investigating agricultural drought recommended by the United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER). It measures the severity of drought and high temperature on vegetation by combining two factors. The first is the Normalized Different Vegetation Index (NDVI) anomaly of the month of observation compared to a long-term average; the second is the land surface temperature anomaly (LST), again compared to the long-term average (in both cases about 20 years, according to MODIS availability). The index has already been successfully tested in extensive grassland regions in Mongolia (Chang et al., 2017), where authors have identified it as the most effective one among a set of nine indices for evaluating drought impacts in grassland environments.

6.3. Results and Discussion

6.3.1. Global distribution of mountain grasslands

Figure 6.1a presents the global map of mountain grasslands developed by implementing satellite-based data on land cover and elevation, while Figure 6.1b their spatial distribution across the different continents. Results show that over half of the entire mountain grasslands are concentrated in Asia (53.9%), spanning from Central Asia to China, Mongolia, and northward into Russia. Following, North America ranks second in terms of mountain grasslands coverage (20.8%), primarily concentrated in the western regions. In Africa (12.9%), mountain grasslands are predominantly found in the central and southern regions, with a significant presence in South Africa. In South America (7.4%), they are mainly located along the Andes Mountain range, but also in the eastern countries, particularly in Brazil. In Europe (3.6%), the highest concentration was found in Spain (including the Pyrenees shared with France), the Alps, the Balkans, and Norway. Australia and Oceania host the smallest fraction of mountain grasslands (1.5%), mainly situated in the central and eastern parts of Australia and New Zealand. A summary of results is reported in Table 6.1. The pixel classification quality related to mountain grasslands is presented in the form of a quality index in Figure 6.1c. Higher performance could be observed in the great plain of Northen America, South Africa, and China.

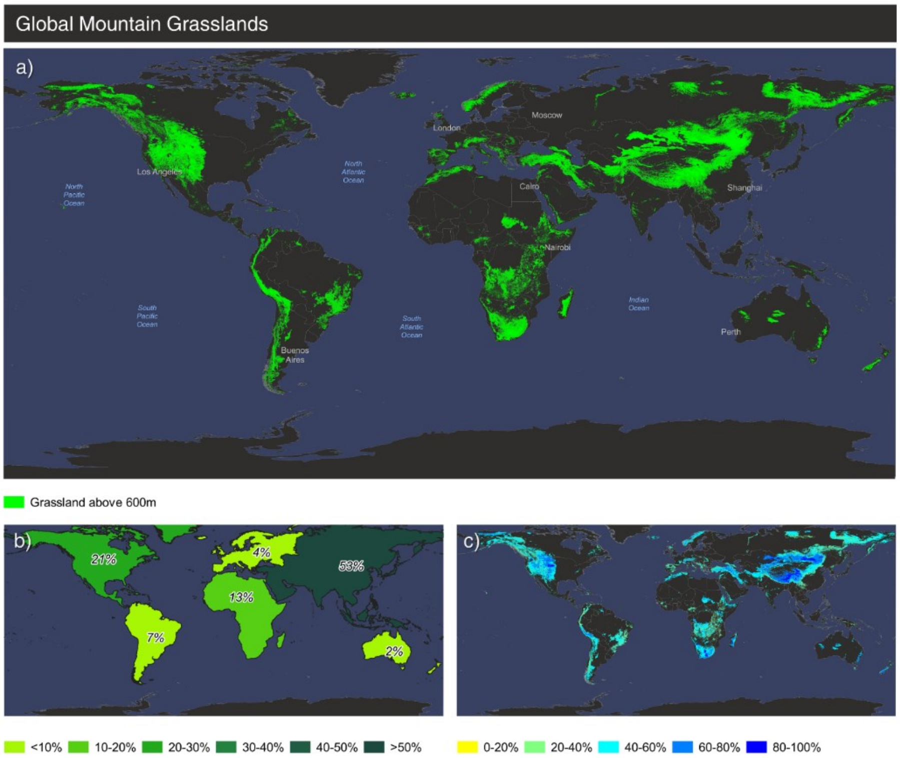

Figure 6.1 - a) Global distribution of mountain grasslands (elevation greater than 600 m) derived from Copernicus Global Land Service (CGLS) data for the year 2019; b) Mountain grasslands distribution in different continents; c) quality index which

6.3.2 *Soil erosion in global mountain grasslands: present scenario*

Figure 6.2a shows the map depicting water-induced soil erosion in mountain grasslands worldwide under the current scenario (2015). 14.5% of such landscapes globally experienced high erosion rates (greater than 10 Mg/ha/yr; from the orange-coloured class in Figure 6.2). The main hotspots could be found in South America, particularly along the Andes Mountain range and in Brazil. The continent stands out for having the higher erosion values in mountain grasslands. 53.2% of them are characterized by rates exceeding 10 Mg/ha/yr. A reason can be attributed to a vigorous hydrogeological cycle. Most of the continent (approximately north of 33° degrees south) has high rainfall erosivity values (R-factor parameter of RUSLE equation), often exceeding 1800 (MJ mm)/(ha h yr) (Borrelli et al., 2020; Riquetti et al., 2020). This is a critical problem for example in Brazil, where several mountain grasslands are severely affected by the erosion process. Here, the R-factor can exceed 6000 (MJ mm)/(ha h yr), especially in the central-eastern regions (Oliveira et al., 2013). Grazing practices also contribute to soil erosion, as highlighted in more specific studies, not only in Brazil (Antoneli et al., 2018; Sobral et al., 2015), but also in Chile (Bonilla et al., 2010) and Venezuela (Sánchez et al., 2002). In Africa, 17.0% of the mountain grasslands are classified as severe potential soil erosion. Major hotspots are in the eastern regions, including Ethiopia, the borderland of Congo, Uganda, Rwanda, Burundi, and Tanzania, as well as in South Africa and Madagascar. Few studies have been conducted at a more local scale in Africa, for instance about the controlling factors of sheet erosion in steep slope degraded grasslands (Dlamini et al., 2011) or on the impact of land-use change in Ethiopian grassy landscapes (Negese, 2021). In Asia, 14.0% of the total mountain grasslands are at risk due to severe potential soil loss. A significant portion of Central Asia hosts some of the most severely affected mountain grasslands globally. The area extends from Kyrgyzstan, Tajikistan, Afghanistan, and Pakistan southwards to India and Nepal. A study on the hydrology and soil erosion of the Central Asian grasslands was proposed by Spaeth et al. (2020). In China, some of the largest mountain grasslands could be found in the Qinghai-Tibet Plateau, where water-induced soil erosion is a known and well-recognized problem. Zhou et al. (2023) recently published a review on the degradation status of these ecosystems, analyzing the factors contributing to degradation and the techniques adopted for their restoration. Another hotspot is the semi-arid grasslands of the Loess Plateau in central China. The region has some of the highest erosion rates on the planet and for this reason massive reforestation campaigns are underway, such as the "Grain-for-Green" project (Chen et al., 2015). Here grassland cover plays a crucial role, particularly in the initial soil conservation phase, where it could outperform forests (Wei et al., 2007). High erosion patterns are also in eastern Eurasia and in the southern regions of the Asian continent, such as in Indonesia. In Europe, 9.6% of the mountain grasslands exceeds 10 Mg/ha/yr of potential soil loss. Main hotspots could be found in the Alps, Apennines, Pyrenees, and Balkans. Multiple studies have been carried out on this continent, such as on grasslands' vulnerability to land degradation in the Alps or their contribution to mitigating erosion and flood dynamics. Finally, lower erosion magnitude could be observed for

North America (2.6% classified as experiencing more than 10 Mg/ha/yr of potential soil loss), Australia, and Oceania (less than 1.0%, primarily on the east coast mainly concentrated in the East coast of Australia and New Zealand; (Kirschbaum et al., 2012)).

6.3.3. Soil erosion in global mountain grasslands: future scenario

Figure 6.2b presents the map of water-induced soil erosion in global mountain grasslands under a future climate scenario (2070; RCP8.5). Our analysis indicates a projected global increase of +2.3% in potential annual water-induced soil erosion compared to the current scenario. Figure 6.2c highlights the disparities between the baseline (2015) and the future scenario (2070). Figure 6.2d illustrates the frequency distribution of soil erosion values (on a logarithmic scale) for both simulations. Up to approximately 30 Mg/ha/yr, the two distributions exhibit similar trends, but more pronounced distinctions become evident for higher values, with the future scenario projecting higher estimates of soil loss. South America could face an increase (+19.4%) in the future due to climate. The most critical area is located towards the east, mainly in Brazil. One of the main contributing factors could be the projected rise in rainfall erosivity for much of the areas occupied by mountain grasslands (R-factor potentially increasing up to 1500 (MJ mm)/(ha h yr), as observed in Borrelli et al. (2020)). Other studies have also reported an increase in the R-factor for South America; projections suggested an up to 109% rise in the period 2007-2040 for Brazil (Almagro et al., 2017) and for the eastern part of the continent along the Andes (Riquetti et al., 2020). The second continent facing significant risk is Africa, with results indicating a 10.0% increase in potential erosion. The areas most impacted could primarily be the central-eastern states, South Africa, and Madagascar. The role of rainfall erosivity will be crucial in this context as well, particularly in Ethiopia (Nyssen et al., 2005), South Africa and Madagascar (Vrieling et al., 2010). For Asian mountain grasslands, the outcomes indicated a slight decrease in the potential soil loss (-2.6%). Worsening conditions may be observed along the Himalayas and the Loess Plateau; however, such variations could be compensated by expected lower values in the southern Qinghai-Tibet Plateau, where rainfall erosivity could decrease by over 20% in the

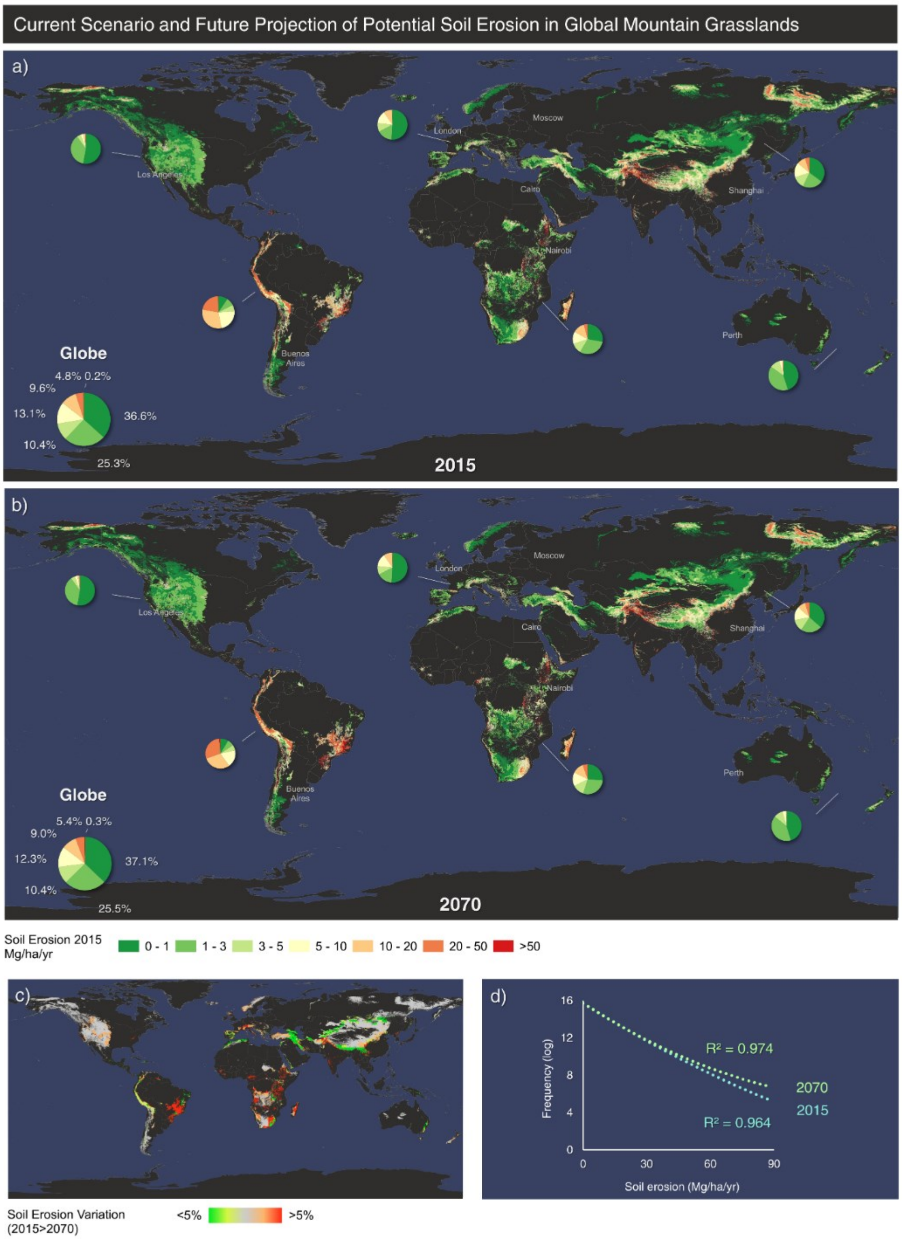

Figure 6.2 - a) and b) Potential annual soil loss for global mountain grasslands estimated using the RUSLE equation for 2015 (baseline) and 2070 (scenario RCP8.5), respectively. Pie charts investigate a single class of soil loss for each continent and globally; c) Map of the soil loss variation between present and future scenarios; d) graph comparing 2015 and 2070 soil loss data (log-scale). Note the higher frequency of higher soil loss values in the 2070 scenario. All soil loss data were based on Borrelli et al. (2020)

Table 5.1 - Summary results of mountain grasslands spatial distribution (%; in different regions) and total/severe projected change in soil erosion by water (%; baseline: 2015; future scenario: 2070 - RCP8.5)

Region	**Mountain grasslands distribution**	**Change in mountain grasslands soil erosion** (2015>2070; RCP8.5)	**Change in severe mountain grasslands soil erosion** (> 10 Mg/ha/yr) (2015>2070; RCP8.5)
Globe	100.0%	+2.3%	+0.2%
Africa	12.9%	+10.0%	+0.7%
Asia	53.9%	-2.6%	-0.8%
Australia/ Oceania	1.5%	-1.2%	0.0%
Europe	3.6%	-0.6%	-0.1%
North America	20.8%	-0.1%	0.0%
South America	7.4%	+19.4%	+6.6%

future (2010-2050; Scenario 2.6; (Panagos et al., 2022)). More moderate variations (< 2.0%) could be observed in other continents, although it is important to stress the presence of localized hotspots with potential increases in soil erosion. In North America, the mountain grasslands that could experience worsening erosion values are those in the central States, from Colorado to southwards. In Europe, the areas at greater risk could be the mountain grasslands of the western Alps, the Apennines, and the Pyrenees. For example, in Italy, there is an estimated increase of about +1.5% in severe erosion, especially in the hotspots of Pre Alps of Veneto and Lombardy (about +4.5%), values similar to the Apennines of central Italy and northeastern Sicily. The grassland of the Swiss Alps is another critical area of soil erosion, a fact already investigated by other authors (Schmidt et al., 2019; Zweifel et al., 2019). Here, we estimated an increase of about +3.8% in 2070, with peaks above +5.0%. Instead, a major change is not expected for much of the grasslands in Spain and the southern Balkans (a pattern consistent with the observation of Borrelli et al., (2020)). For Australia and Oceania, major variations are not predicted as in other parts of the World, but there is still a hotspot in the mountain grasslands of New Zealand. A summary of results is reported in Table 6.1. By gaining insights into erosion dynamics and identifying high-risk areas worldwide, our research contributes to promoting land management and conservation strategies, safeguarding mountain grasslands amid the challenges posed by climate change.

6.3.4. The extreme drought of 2022 on European mountain grasslands

This section investigates the impact of extreme drought and high temperature in European mountain grasslands during the event of July 2022. Figure 6.3 presents the results of the VHI index calculation as an indicator of agricultural drought severity. On average, nearly a quarter of the entire system was affected by drought, with 5.7% classified as severe or extreme. Southern Europe experienced the most difficult conditions, with France and Spain being among the hardest-hit countries, with almost 80.0% of their mountain grasslands affected by drought. Other hotspots were visible in the Balkan region, particularly in Bosnia and Herzegovina (72.9%) and Montenegro (66.2%), as well as in Italy (48.3%) and Romania (32.5%). Spain faced the most worrying conditions, with 14.3% experiencing extreme drought and 22.2% severe drought. Areas severely affected included the western and southern regions of Salamanca, the mountainous area north of León extending eastward to Bilbao, the Pyrenees Mountain range, and several central areas of Aragon. A critical zone was also identified in the south, although to a smaller extent, such as in the Sierra Nevada National Park. France ranked second in terms of drought severity in mountain grasslands during the summer of 2022, with 10.0% experiencing extreme drought and 17.6% severe drought. Many of those areas were situated along the Pyrenees and the Alps, with a smaller portion in the region of national parks between the cities of Clermont-Ferrand and Montpellier and on the island of Corsica. Italy, relatively less affected (2.7% extreme drought and 6.6% severe drought), saw the northern regions of the Alps and Pre-Alps affected, with a critical point being the Lessinia Regional Park. The severe drought of 2022 is already driving scientific research efforts to help protect alpine grasslands in Italy, also involving local consortia. An example is reported by Castelli et al. (2023), which proposed a satellite-based approach to estimate yield losses attributed to drought events in the mountain grasslands of northeastern Italy. In the central regions, the Apennines, particularly the Monti Sibillini National Park and the Sirente-Velino Regional Natural Park, also experienced severe drought. The severity was lower in the southern regions and on the islands, with the northern part of Sardinia being a hotspot. In eastern European areas, severe drought conditions were observed in Bosnia and Herzegovina (south of the city of Sarajevo) to Montenegro and in Romania (north of Brașov and west of Cluj-Napoca).

A growing body of evidence indicates that drought, often in combination with high temperatures, can cause a range of different effects on mountain grassland ecosystems, encompassing alterations in community composition, functioning, and the upward migration of species (Beniston et al., 2018; Sloat et al., 2015; Steinbauer et al., 2018). Drought can significantly reduce soil microbial carbon (C) while increasing nitrogen (N), compromising the carbon sink role attributed to global mountain grasslands (Fuchslueger et al., 2019; Hasibeder et al., 2015), a phenomenon also described by Zhang et al. (2023). Furthermore, it can have serious consequences on vegetation response in such landscapes. Hoover et al. (2014) found that extreme drought affected both aboveground and belowground net productivity of plants, with a more pronounced impact observed when the drought persisted for two consecutive years throughout the growing season. This observation was also confirmed by recent research conducted in northern Italy (Lessinia Regional Park, Veneto Region; (Chen et al., 2023). The authors investigated two successive dry periods in 2012 and 2013, which resulted in a decrease in soil water content, subsequently leading to a reduced capacity of vegetation to recover in the following year. Therefore, in light of the challenges posed to mountain grasslands by climate change impacts such as intense rainfall and extreme drought, it is important to promote sustainable solutions for the conservation of ecosystems and associated ecosystem services.

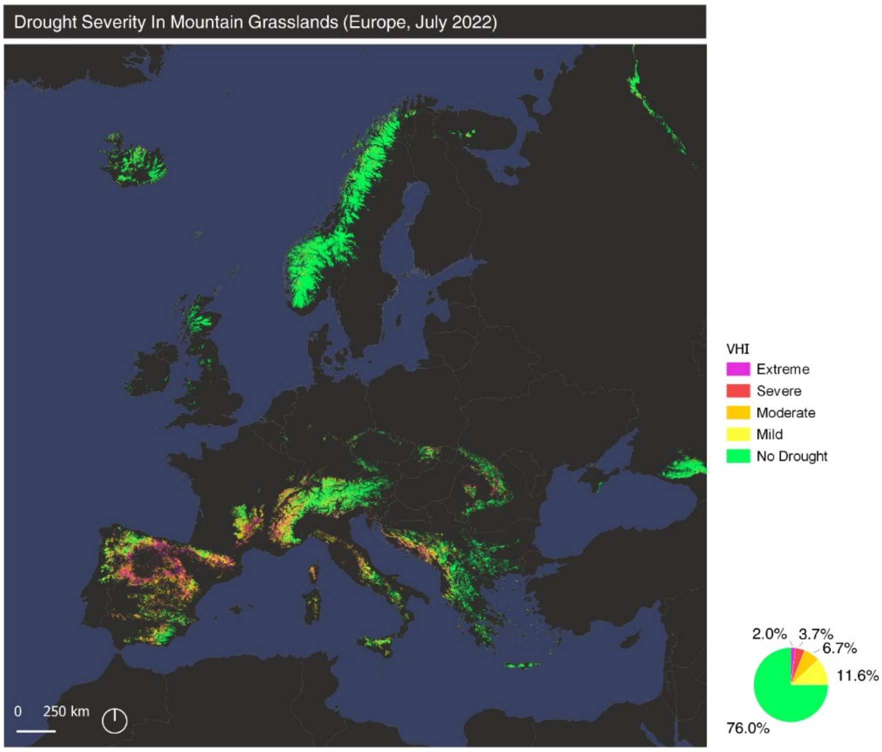

Figure 5.3 - Agricultural drought severity map and pie-chart for mountain grasslands in Europe during July 2022, calculated using the MODIS-based VHI.

6.3.5. Preserving ecosystem services

Preserving the ecosystem services provided by mountain grasslands requires effective conservation strategies to address the challenges posed by climate change. Such interventions could be implemented where human activity persists and serve various purposes. On one hand, they aim to ensure the protection of biodiversity and ecological functionality; on the other hand, they contribute to maintaining traditional mountain activities such as pastoralism or transhumance. Firstly, it is important to promote protected areas, conservation corridors and wetlands to safeguard the integrity and connections of grassland ecosystems (Samways et al., 2010; Żmihorski et al., 2016). They can provide refuges for different species, enabling natural processes to continue, and allowing for the long-term monitoring and research necessary for conservation efforts (Zhou and Song, 2021). Secondly, it is vital to incorporate nature-based solutions (NbS), which are increasingly recognized techniques for preserving ecosystem services (Cohen-Shacham et al., 2019). They can be used for protecting ecological function and mitigating land degradation processes, becoming valuable tools against climate change impacts. An example is rotational grazing, which implies moving animals in different pastures following a regular schedule, avoiding overgrazing (Eagle and Olander, 2012). Li et al. (2023) reported a positive and progressive long-term ecological benefit for pasture managed with this solution. NbS could also be adopted to for the restoration of degraded and abandoned grasslands. For instance, they are crucial interventions for mitigating soil erosion and shallow landslides, as these problems tend to be more common in bare hillslopes compared to those with healthy grass (Apollonio et al., 2021). Török et al. (2011) provide a comprehensive technical overview of a number of NbS restoration techniques for this purpose. Sowing seed mixtures is the most common practice, where different target species are selected according to the aim of the restoration and the site characteristics. It is then recommended to promote the use of native/regional species (Prach et al., 2014). Indeed, species-rich grass is more resilient in facing various environmental changes or disturbances, including land degradation drivers (Lavorel et al., 2019; Muller et al., 1998; Zhu et al., 2015). Other solutions are proposed by Cervasio et al. (2016), which conducted a five-year observation in the grasslands of the northern Apennines under different managements (such as soil tillage, adjustments to forage mixtures, and bracken removal). Their conclusions emphasized the significance of bracken cutting to improve native species colonization and the sowing of forage mixtures to preserve pasture quality, strategies also confirmed by previous research (Prach et al., 2014; Stewart et al., 2007). Continuous maintenance is then a crucial activity to ensure the long-term sustainability and functionality of interventions (Carbutt and Kirkman, 2022; Schermer et al., 2016). Finally, in the case of steep slope grasslands, an excellent example of more structural solutions for mitigating surface processes and soil erosion is agricultural terracing. These are traditional soil and water conservation practices found in various parts of the world and are recognized for their cultural significance. For example, in the Swiss Alps, terraced grassland primarily served as meadows and pastures for goats, sheep, and donkeys for centuries (Rusterholz et al., 2020). Many articles investigated terrace performance in protecting soil; for instance, in a Brazilian case study, researchers observed that well-managed terraced pastures could achieve a remarkable reduction of over 700% in soil erosion rates caused by rainfall when compared to non-terraced landscapes (Galdino et al., 2016).

NbS are valuable interventions also in mitigating drought impacts. Multiple droughts tolerated grass species were found in previous studies, such as *D. glomerate*, *viciifolia* Scop. and *M. sativa* (Dumont et al., 2015; Kallida et al., 2016). The use of a grass-legume mix, which may include subclovers and medics, can also be employed; legumes, in particular, serve as a crucial protein source that helps mitigate the adverse effects of low soil moisture and rising temperatures on forage yield (Dumont et al., 2015). In addition, mountain grasslands resilience can be improved including water ponds, or topographic depressions that serve as water reservoirs (Jooste et al., 2020). Traditional mountain communities have historically relied on these systems to increase water availability for agricultural, livestock and sometimes fish farming purposes (Henderson et al., 2012; Verga et al., 2012). Firstly, they play a key role in preserving biodiversity within grasslands by providing habitat for numerous species (Knutson et al., 2004). Then, during times of drought, they can become valuable emergency water sources. However, they are close systems, primarily dependent on rainfall, and sensitive to evaporation; as a result, their number and distribution significantly affect the amount of water available and, consequently, their effectiveness in mitigating drought impacts. A recent study conducted by Chen et al. (2023) in northern Italy delves into these issues. They highlighted the pivotal role of ponds in supporting mountain grasslands' functionality and the importance of maintaining these traditional solutions in a changing climate. Finally, it is important to mention that increasing the resilience of mountain grasslands against new climate challenges requires promoting collaborative research, involving a variety of regional experts, data sharing, and policy exchange. This can facilitate innovation, improve understanding of climate change effects, and support the development of conservation strategies at a large scale.

6.3.6. Limitations and future perspective

While this study attempts to offer a comprehensive analysis of the global mountain grasslands and related threats, it is important to recognize the presence of limitations. For instance, the use of satellite data, despite its extensive coverage, may present constraints due to spatial resolution and potential inaccuracies in interpreting specific ecosystem features. Additionally, projections of future scenarios such as those related to soil erosion by water are intrinsically susceptible to uncertainties arising from climate models and long-term forecasting. Future research efforts could enhance mapping techniques by integrating higher resolution data, such as Sentinel 2, Landsat 8/9, or Unmanned Aerial Vehicles (UAV) and in-field surveys in selected sites. Then, the implementation of advanced machine learning algorithms could allow improved accuracy in the identification of areas vulnerable to challenges such as soil erosion and drought in mountain grasslands. Finally, integrating in the analysis specific socio-economic factors and engaging local communities would enrich discussions on sustainable practices, preserving the cultural significance of these landscapes.

6.4. Conclusion

This study analyzes mountain grasslands and their associated ecosystem services in the context of climate change. They are areas of high landscape and social value, often more vulnerable due to unsustainable management practices or from traditional pastures abandonment. We first employed satellite-based remote sensing to shed light on the global distribution of mountain grasslands. Then, we delved into two significant climate change impacts: water-induced soil erosion and drought. For soil erosion analysis, we relied on open-access data and focused on climate condition changes (2015 vs. 2070-RCP8.5) while maintaining consistent land use. Despite possible limitations, our findings reveal that, in the current scenario, 14.5% of global mountain grasslands face a high risk of erosion (> 10 Mg/ha/yr). South America stands as the most affected continent (53.2%), followed by Africa (17.0%), Asia (14.0%), and Europe (9.6%). In the future scenario, a projected +2.3% in water-induced erosion is estimated for global mountain grasslands. South America (+19.4%) and Africa (+10.0%) are expected to experience the most increases, while Asia may see a slight decrease (-2.6%). Furthermore, we assessed the severity of drought in European mountain grasslands during the extreme event of summer 2022 using a satellite-based Vegetation Health Index. A quarter of the area suffered from drought, with 5.7% experiencing severe or extreme severity. Southern Europe was the most affected zone, particularly Spain (80.0% of mountain grasslands affected), Bosnia and Herzegovina (72.9%), Montenegro (66.2%), Italy (48.3%), and Romania (32.5%). Finally, we explored strategies to enhance the resilience of mountain grasslands while preserving their critical ecosystem services. Our focus centered on NbS, including effective grassland management to mitigate erosion and the implementation of water ponding systems to address droughts. Recognizing mountain grasslands' importance in mitigating climate change is the first step to securing them for future generations. Crucial solutions involve targeted interventions addressing various climate change challenges, restoring degraded or abandoned valuable areas, and preserving the traditions that have maintained the balance between humans and nature for centuries.

7. A Remote Sensing-Based Monitoring Workflow to Enhance Resilience of Traditional Agricultural Terraces during Extreme Rainfall

Context

Terracing in agriculture is emblematic of cultural agricultural Landscapes in steep regions. This section examines how increasingly frequent extreme precipitation events, driven by climate change, exacerbate the management challenges of the UNESCO World Heritage site "*Portovenere, Cinque Terre, and the islands*". Traditional agricultural slope management often results in inadequate water management measures during and after intense precipitation events. The design of new solutions is further complicated by the complex geomorphological characteristics of the slopes. To address these challenges, this section proposes an operational monitoring workflow utilizing multi-temporal remote sensing data (ranging from LiDAR to drones) to identify areas in need of stabilization or remediation. This methodology also overcomes the limitations of outdated remote sensing datasets. The proposed approach establishes a hierarchical prioritization of interventions, focusing on the most degraded areas, thereby providing support for Cultural Landscape managers in making informed decisions.

The article

This section is based on the conference paper presented in 2024 at "*Biosystems Engineering Promoting Resilience to Climate Change*," titled “*Multitemporal Remote Sensing for Monitoring Hydro-Erosive Process Dynamics in Terraced Cultural Landscapes*”. It is currently under review for the book series “*Lecture Notes in Civil Engineering*” (Springer).

> This paper mainly addresses SO-B by developing a remote sensing-based workflow to monitor and mitigate hydro-erosive processes in terraced Cultural Landscapes. It also touches on SO-C by suggesting resilient management strategies for these areas, particularly in the context of extreme rainfall events. The study provides a practical tool for Cultural Landscape preservation amidst climate change.

CONFERENCE PAPER (UNDER REVIEW)

Multitemporal remote sensing for monitoring hydro-erosive process dynamics in terraced Cultural Landscapes

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CRediT authorship contribution statement:
Eugenio Straffelini: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing.

Abstract

Cultural Landscapes embody the evolving relationship between humans and nature, often reflecting strong rural influences. Agricultural terraces are repositories of traditional knowledge, supporting local sustenance through food production and economic development, including tourism. However, challenges such as field abandonment, inadequate maintenance, and extreme rainfall events significantly affect terrace systems. These issues lead to instabilities, wall collapses, landslides, floods, and debris flows, posing an imminent threat to their distinct identity. The increased frequency of heavy rainfall due to climate change exacerbates these problems. Therefore, monitoring hydro-erosive processes is crucial to mitigate these risks and protect the associated social and cultural values. Remote sensing technologies, especially multi-temporal Digital Elevation Models (DEM) within High-Resolution Topography (HRT) datasets, offer effective tools for this purpose. This research introduces a preliminary workflow for monitoring instabilities in terraced Cultural Landscapes, focusing on Italy's UNESCO World Heritage site "Portovenere, Cinque Terre, and the islands". The area is prone to such issues as evidenced by a dramatic flash-flood event in 2011. The method integrates data collected over different years and platforms (i.e., LiDAR and SfM), overcoming challenges associated with "old legacy" datasets. These data facilitated investigations into hydro-erosive processes over time, using hydrological modeling and geomorphometric indices to identify critical areas for rapid and targeted mitigation. Monitoring, planning, and preventive measures are crucial for enhancing resilience in terraced Cultural Landscapes, and remote sensing technologies are key in reshaping protective strategies and preserving these invaluable landscapes.

Keywords: Cultural Landscapes, Agricultural terraces, Remote sensing, Hydro-erosive processes, Monitoring workflow

7.1. Introduction

Cultural Landscapes represent a close relationship between the natural environment and human practices carried out over the centuries. Traditional agriculture, including cultivation methods and specific water and soil management, plays a key role in shaping these territories (Salvati et al., 2017). In hilly and mountainous areas, agricultural terraces are common practices to ensure agriculture and food production. These terraces provide a wide range of ecosystem services, such as soil conservation, water regulation, increased biodiversity, and carbon sequestration (Brown et al., 2021). Additionally, they offer significant cultural and landscape value, making terraced landscapes important from both historical and touristic perspectives. However, terraced Cultural Landscapes are also inherently fragile and at risk, especially during intense precipitation (Tarolli and Straffelini, 2020). These events can cause soil erosion and trigger serious issues, such as the collapse of terrace walls, landslides, floods, and, in extreme cases, debris flows. These phenomena are exacerbated if fields are not regularly and properly maintained, as is the case with abandoned land, a widespread phenomenon in some parts of Europe. Furthermore, climate change and the increasing frequency of intense precipitation are worsening this critical condition. The problem is serious in Cultural Landscapes, which must implement initiatives to ensure the functionality of terraces in the future and thus preserve their value.

Monitoring hydrological processes in terraces, as well as identifying the most at-risk areas, is crucial for optimizing mitigation interventions (Preti et al., 2018a). Remote sensing (RS) and high-resolution topography (HRT) can offer valuable insights by creating high-resolution, multi-temporal Digital Elevation Models (DEMs). These models are essential for hydrological and geomorphological analyses needed to understand surface processes. Various technologies are available for agricultural surveys, including airborne (ALS) or terrestrial (TLS) LiDAR, as well as the more cost-effective drone photogrammetry (UAV-SfM). Despite technological innovation bringing increasingly modern and efficient tools to the market for topographic surveying, some of these techniques have been in use for over a decade. They often employed different approaches, coordinate systems, and sometimes historical data could be incomplete. Therefore, in a multi-temporal analysis aimed at understanding the evolution of terraced surfaces, challenges could arise to harmonize new topographic surveys with "old-legacy" datasets.

In this research, we propose a preliminary workflow for monitoring hydro-erosive process dynamics in terraced Cultural Landscapes based on such multi-temporal topographic products. The study area is the UNESCO Cultural Landscape "Portovenere, Cinque Terre, and the islands (Italy)," an area dramatically prone to such issues, as evidenced by the flash-flood event recorded in October 2011, which caused significant damage to the terraces and the town, and resulted in human casualties. Specifically, the workflow identifies three levels of priority: L1, which aims to identify areas requiring urgent interventions such as landslide stabilization; L2, which involves intermediate urgency, such as identifying areas needing the implementation of drainage systems; and L3, which considers long-term actions, such as large-scale identification of zones requiring slope consolidation.

The goals of this work are to monitor hydro-erosive processes in terraced landscapes, prioritize areas needing intervention, enhance resilience against extreme weather, and therefore contribute to preserving the cultural value of terraced Cultural Landscapes.

7.2. Materials and Methods

7.2.1. Study Area

The study area (Figure 7.1a) is located in the Liguria region, northern Italy (44º6'31.522"N, 9º43'45.502"E). It is within the UNESCO Cultural Landscape “Portovenere, Cinque Terre, and the Islands (Palmaria, Tino, and Tinetto)”. The site covers an area of 10.9 ha and has a slope of 64%. It is situated above the village of Manarola, in the municipality of Riomaggiore (SP) (Figure 7.1b). The area is characterized by a complex system of agricultural terraces supported by dry-stone walls, mostly built from the 12th century. The main cultivations are olive trees, vineyards, and vegetable gardens and managed by local people. Some terraces are currently not cultivated and are covered by grass, while others are abandoned and overgrown with natural vegetation. Terrace restoration projects are underway, especially in the upper part of the site (https://www.stonewalls4life.eu/?lang=it, last accessed 2024/05/28). The aim is the recovery and maintenance of terraces and hydraulic regulation works to protect the territory and inhabitants from extreme weather events, aligning safety with landscape and cultural value. The area also includes damaged terraces (example in Figure 7.1c) due to slope instabilities and severe rainfall.

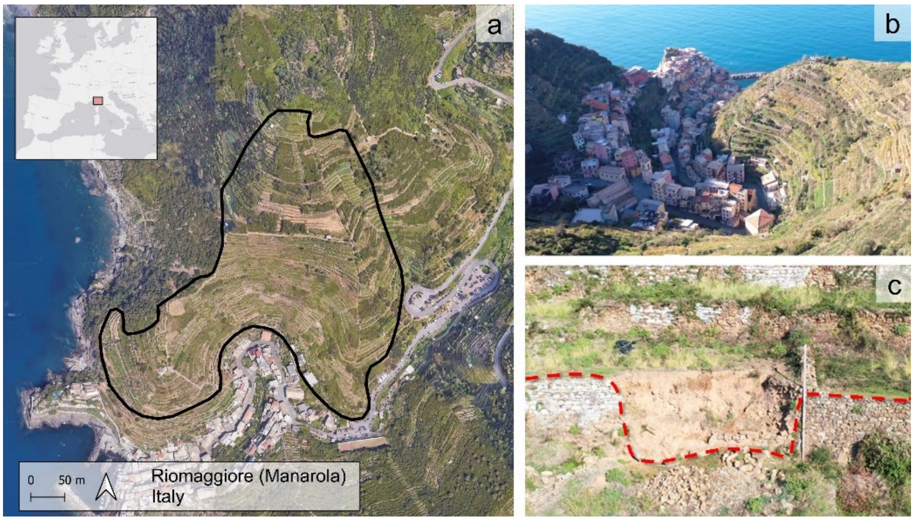

Figure 1 - (a) Study area; (b) A view of site and the village of Manarola (Italy) (photo: Eugenio Straffelini); (c) A collapsed dry-stone wall.

7.2.2. Topographic Surveys and Data Homogenization

Three different topographic surveys were conducted at different times by different operators using different techniques. Specifically: in 2011, an ALS survey; in 2019, a TLS survey for the DEM and SfM for the orthomosaic; and in 2022, SfM for both DEM and orthomosaic. The authors of this research conducted only the 2022 survey using a professional quadcopter (DJI Matrice 210 v2 with DJI Zenmuse X4S camera) and measuring Ground Control Points (GCPs) and Check Points (CPs) with a Geomax Zenith40 GNSS (x,y,z accuracy: 0.02 – 0.03 m). Point cloud filtering was performed in CloudCompare v2 12.4 software, applying distance filtering and subsequently decimated at 1 m and 0.2 m using the geostatistical Topography Point Cloud Analysis Toolkit (TopCAT) in the Geomorphic Change Detection software (Wheaton et al., 2010). The final products obtained are DEMs (1 m cell size; UAV-SfM originally 0.20 m) and orthomosaics (0.15 m cell size for the 2011 survey; 0.05 m cell size for the 2019 and 2022 surveys). The coordinates of the products were transformed using ConveRgo software into RDN2008/UTM/zone32N. Since no point clouds were available for the 2011 and 2019 surveys, the co-registration was performed directly on DEMs using the CO-REG tool on stable areas (Cucchiaro et al., 2020). This solution, despite including an intrinsic error due to conversion and co-registration, allowed the use of historical datasets for monitoring processes in the study area.

7.2.3. Monitoring Workflow

The homogenized multi-temporal topographic data obtained through the procedure described in Section 2.2 form the basis of a monitoring workflow for hydro-erosive processes (Figure 7.1). This data is valuable for guiding maintenance interventions in terraced areas, providing useful insights for Cultural Landscape managers. The workflow is structured into three priority levels, addressing short-term (L1), medium-term (L2), and long-term (L3) implications.

L1 involves the analysis of high-resolution orthophotos to create a detailed punctual inventory of damages, primarily focusing on dry-stone wall collapses that are unstable and potentially areas of rapid slope deterioration. L2 aims to map potentially critical areas connected to the unstable

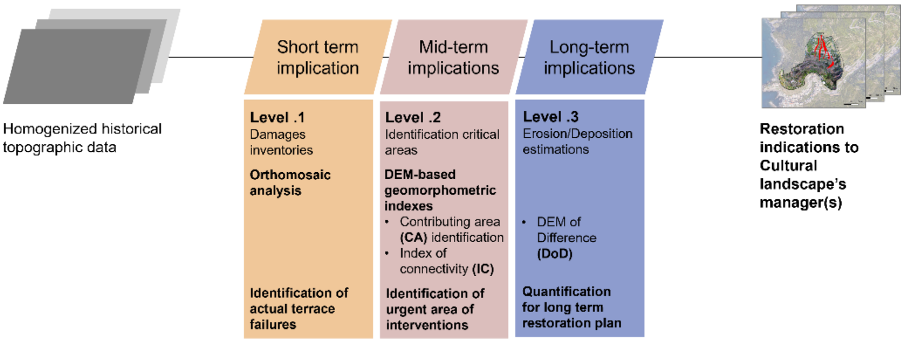

Figure 7.2 - Conceptualization of the monitoring workflow proposed in this research.

zones identified in L1. This is achieved through the analysis of geomorphometric indicators based on DEMs. In this preliminary research, the well-known contributing area algorithms (D8 and Dinf) were applied to map potential surface runoff following intense precipitation and to identify micro-watersheds that channel water and sediment into the collapse zones. These are areas that require urgent soil and water conservation (SWC) interventions to prevent further instability. Additionally, an index of connectivity (IC) was calculated to identify potential sediment source areas to better guide interventions (Cavalli et al., 2013). Finally, a DEM of Difference (DoD) approach was performed to estimate the volumes of material moved on a mask that includes only non-vegetated areas, to reduce errors due to vegetation cover, using a probabilistic threshold of 95% (considering the propagation of the error of GNSS and DEM co-registration) [7]. Although this approach is characterized by possible bias due to data co-registration, it can provide indications of areas that have experienced significant erosion or sedimentation, aiding in the planning of long-term interventions such as the reconstruction of new terraces. The L1, L2, and L3 analyses were conducted by comparing the 2011-2019 and 2019-2022 surveys.

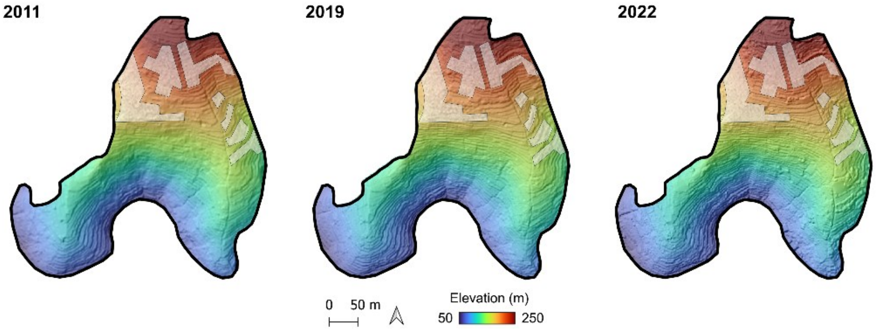

Figure 7.3 - The three DEMs; White polygons indicate areas with major changes in elevation due to dense vegetation or maintenance interventions for terrace restoration.

7.3. Results and Discussions

7.3.1. Multitemporal DEMs

The final DEMs used in this research are shown in Figure 7.3. For the UAV-SfM survey conducted by the authors in 2022, the RMSE error calculated on the point cloud compared to the ground points was 0.05 m, while it was 0.08 m compared to the DEM with a resolution of 0.20 m. Regarding the comparison of the three multi-temporal DEMs reclassified to a 1 m resolution (the best resolution for 2011 and 2019) with ground points in stable areas only (such as agricultural roads), the RMSE error was 0.23 m for 2011, 0.15 m for 2019, and 0.10 m for 2022. The whitish zones indicate areas that experienced the most significant changes in land cover due to vegetation growth in some areas and clearing for the restoration of agricultural terraces in others. These areas were excluded from some analyses, such as DoD, as they could not be representative of the ground elevation due to vegetation cover, particularly in UAV-SfM surveys.

7.3.2. Guiding Terraces Restoration

The analysis of multi-temporal remote sensing data in this research allowed for three levels of understanding regarding the issues in the analyzed Cultural Landscape. Figure 7.4 illustrates some exemplary results mainly related to the latest topographic survey conducted in 2022.

At the first level, the analysis of high-resolution orthomosaics led to the identification of five terrace failures. These are primarily located in the central part of the site, both in terms of area and elevation. These areas require immediate consolidation or reconstruction of the dry-stone walls to prevent further degradation during intense precipitation (Figures 7.4a and 4b), especially to safeguard the people living in the village downstream.

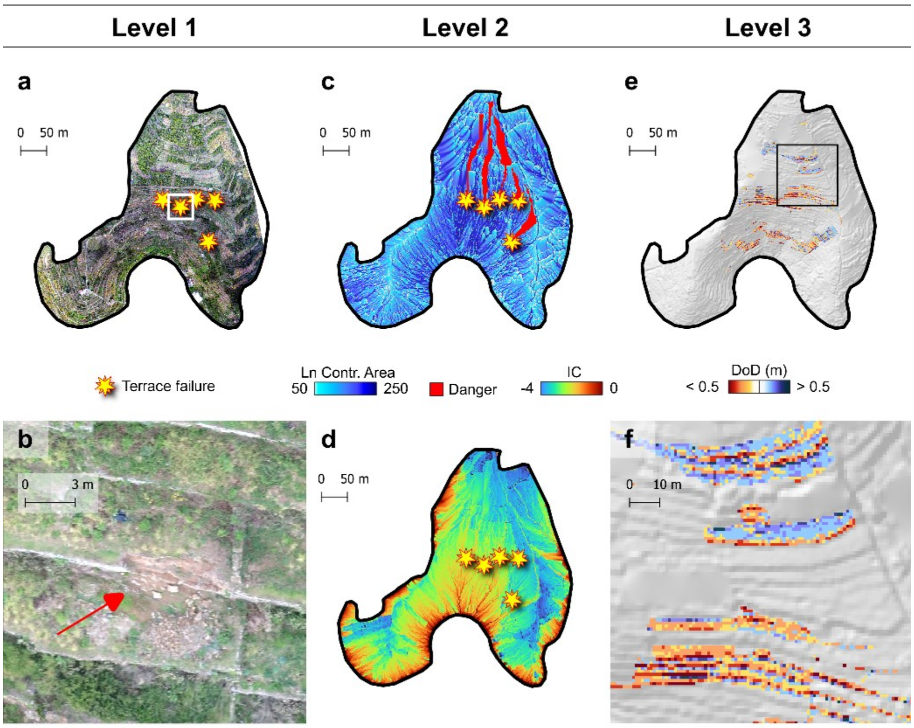

Figure 7.4 - How the proposed workflow can guide terrace restorations. Level 1 (based on 2022 survey): a) Identification of criticalities on high-resolution orthomosaic; b) A collapsed wall. Level 2 (2022): a) Flow accumulation (Ln) and critical areas that need rapid intervention; b) IC to identify sediment sources. Level 3 (2019 and 2022): e) DoD for identification of erosion/deposition areas; f) Zoom on some critical areas.

At the second level, areas needing immediate intervention for the implementation of drainage systems and soil conservation practices were identified. Figure 7.4c shows the natural logarithm of the geomorphological indicator 'contributing area'. This index is useful for showing and mapping the potential surface runoff that could occur during extreme precipitation events. It is shown alongside the mapping of the sub-catchment that uses the collapse points of the walls identified at level 1 as closure sections. Proper water management and the introduction of micro-water storages in these areas could help to attenuate runoff, collect reusable rainwater during drought periods, and prevent excessive runoff from further damaging the most critical zones. An in-depth study on this topic was conducted for a terraced vineyard in northern Italy using a physically-based hydrological model (Wang et al., 2023). The application of the drained area can be supported by the IC indicator, as shown in Figure 7.4d. Highly connected areas (i.e., greater IC values) are potentially critical sediment sources, information that site managers can use to identify and prioritize maintenance areas. Finally, the information from level 3 can be used for long-term site management. Figures 7.4e and 7.4f provide an example of DoD between 2019 and 2022. In the higher zones, linear zones with negative differences (such as areas with erosion due to wall collapses) and widespread low-positive DoD values (< 0.2 m) in deposition areas can be observed. However, the most critical areas are in the central zone, where elevation differences of more than 1 m are observed due to severe structural collapses of the terraces. There, the average net thickness difference for the area of interest (net of uncertainty) is -0.40 m. Although the DoD results in this preliminary research should be considered carefully due to errors in historical DEMs, the proposed methodology could be useful for identifying areas experiencing erosion and/or deposition on a large scale. If calculated on topographic products updated consistently over time (e.g., every 2-5 years), this information could be valuable for describing potential slope movement, identifying terraces undergoing significant deformations, and effectively identifying areas needing immediate structural interventions.

7.4. Conclusions

This study highlights how remote sensing technologies and multitemporal digital elevation models (DEMs) can be valuable tools for monitoring hydro-erosive processes in terraced Cultural Landscapes and supporting their mitigation by prioritizing intervention areas. The research focused on the UNESCO World Heritage site "Portovenere, Cinque Terre, and the Islands," presenting a preliminary workflow to identify areas that require urgent intervention, drainage systems, and long-term management. The integration of data from different years and platforms, despite the challenges posed by "old legacy" datasets, proved to be effective in identifying critical areas. The methodology provided valuable insights for Cultural Landscape managers, enabling targeted maintenance and restoration interventions to increase the resilience of these fragile landscapes in climate change scenario. Regular future updates of topographic surveys can further help in understanding slope movements and preserving the cultural value of terraced landscapes.

8. Remote Sensing Data and Sustainable Solutions for Adapting Agricultural Terraces to Climate Change

Context

This chapter emphasizes the importance of steep-slope terraces as Cultural Landscapes with significant cultural values, focusing on water harvesting methods to address climate change challenges. Steep-slope agricultural terraces are not only critical for food production but also embody traditional practices and heritage. The unique topography and access constraints of these areas make conventional agricultural water harvesting infrastructure costly and complex. Consequently, deploying small-scale water harvesting facilities is advantageous. These facilities are less expensive to construct, easier for farmers to manage, and more adaptable to the specific needs of steep-slope agriculture. By leveraging such sustainable methods, we can enhance the resilience of these culturally valuable landscapes against the impacts of climate change.

The article

The section is based on the research article "*Enhancing Resilience to Weather Extremes through Micro-Water Storage in Steep Slope Viticulture*," published in 2023 in the journal *Agricultural Water Management* (*Q1, covering Agronomy and Crop Science; Earth-Surface Processes; Soil Science; Water Science and Technology; IF 2023: 5.9*), highlights the efficacy of cost-effective water harvesting in mitigating the impacts of extreme weather events. This chapter employs a high-resolution overflow simulation model that integrates comprehensive selection criteria to identify an optimal network of water harvesting facilities, blending traditional knowledge with contemporary practices. Additionally, the study quantifies potential water storage capacities under varying intense rainfall conditions, demonstrating the significant role of micro-water storage in enhancing the resilience of steep-slope viticulture to climate change.

> This paper primarily addresses SO-B by evaluating the effectiveness of micro-water storage systems in enhancing the resilience of steep-slope viticulture against extreme weather events. It also addresses SO-A by demonstrating how these water storage facilities can mitigate drought impacts, and SO-C by integrating traditional knowledge with modern techniques to propose sustainable water management solutions.

PEER-REVIEWED & PUBLISHED RESEARCH ARTICLE

Steep slope viticulture: the effectiveness of micro-water storage in improving the resilience to weather extremes

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Eugenio Straffelini: E.S. wrote the first draft and edited the manuscript and figures; E.S. validated the dataset and the method.

Abstract

Steep slope viticultural systems are widely distributed in the Mediterranean region and have a pivotal role in wine production, economic development as well as diverse cultural heritage. Such landscapes face serious environmental criticalities due to more frequent weather extremes such as intense rainstorms and long-time droughts. These issues give rise to the need for further economic development and pressure on the available water resources. In response, rainwater harvesting has been a standout among all the water resource management strategies in controlling water shortage problems. Due to the shortcomings of the systemic framework, the selection of the most suitable water harvesting sites represents a relevant act for optimal water management in such high-steep slope landscapes. In this study, a high-resolution overflow simulation model was utilized, combining an elaborate set of selection criteria in identifying the optimal network of water harvesting facilities (also taking inspiration from traditional knowledge) and quantifying potential water storage under different intense rainfalls. The study area considered is the Soave vineyard (located in the north of Italy), a globally important agricultural heritage system recognized by FAO. The surface overflow was simulated considering two key rainstorms that occurred in the last few years at different time intervals. 53 potential sites for water harvesting were selected according to field survey, runoff simulation, and topographic analysis. The results indicate that the water potentially collected from designed sites could have a double function: (1) mitigate the surface overflow that can potentially cause downslope terrace collapse or even flooding villages; (2) provide irrigation water for vineyards during water scarcity scenarios. The spatial distribution of the amount of water collected could undoubtedly guide sustainable decisions in steep slope viticultural systems under climate change forcing.

Keywords. steep slope viticulture; micro-water storages; high-resolution topography; weather extremes; rainfall; runoff.

8.1. Introduction

The steep slopes accommodate some of the most important vineyards in Italy. Examples are the rural landscapes of the Veneto region (such as the hills of Soave and Conegliano Valdobbiadene), the Valtellina (Lombardy region), the Langhe (Piedmont region), the Gran Sasso National Park (Abruzzo region) as well as Trentino Alto Adige etc. (Eynard and Dalmasso, 1990). Soave vineyards (Veneto region, Italy) is a traditional terrace agricultural Landscape that economically supports more than 3000 families in the past 200 years (GIAHS, 2018). The GIAHS (Globally Important Agricultural Heritage Systems) programme safeguards the social, cultural, economic, and environmental goods and services these rural areas provide. Soave is one of only 57 agricultural heritage sites worldwide and the first Italian wine region to meet the organization's stringent criteria (GIAHS, 2018). Another specific example is the Conegliano Valdobbiadene Prosecco steep slope viticulture (215 km^2) (Veneto region, Italy), now part of the UNESCO World Heritage sites. Another example is coming from the south of Italy: the ingenious techniques of cultivating head-trained bush vines called "alberello", which can successfully protect vineyards from the wind and it is transmitted for centuries by vine growers and farmers of the Mediterranean island of Pantelleria (Chironi et al., 2020). However, these precious landscapes are experiencing quite often extreme weather events now and are predicted to continue in the future (Bai et al., 2013; Pijl et al., 2019a; Tarolli et al., 2014; Yin et al., 2018).

The challenge of growing intense rainfall is paralleled by the increasing prolonged aridity (Tarolli and Straffelini, 2020). On the one hand, climate change tends to have a more dramatic impact on steep-slope agriculture than in other agriculture landscapes since the fraction distributed in the arid climate class will double in the future (Wang et al., 2022a). One of the worst examples is the drought that occurred in the north of Italy in 2022, where 40% of the crop for the whole country and water levels have reached the lowest in the last 70 years (Stella Levantesi, 2022). On the other hand, the increasing intensive rainfall led to landslides and even flooding in steep slope areas (Chen et al., 2018; Tarolli and Straffelini, 2020). One of the most recent and intense storms recorded in Soave vineyard (North of Italy) was 182 mm/h occurred on 29th of August 2020 (ARPAV, 2020), which caused devastating consequences for the vines and huge economic losses for the local farmers. In addition, steep slopes agricultural areas tend to be more susceptible to water deficits if control measures lack (Kimaro, 2019). Considering that water source management will be more complex due to future climatic conditions, mitigating climate-induced effects like localized extreme rainfall and prolonged droughts is very urgent for the suitable development of steep slope viticulture. Unlike other kinds of farmlands, the physical transport of water is difficult and expensive in steep-slope agriculture due to its complex topography. In this case, rainwater harvests are indispensable water supplies in the irrigation and groundwater recharge (Wu et al., 2018). Water storage and harvest facilities are the best solutions for making each drop of water useful and decreasing surface overflow at the same

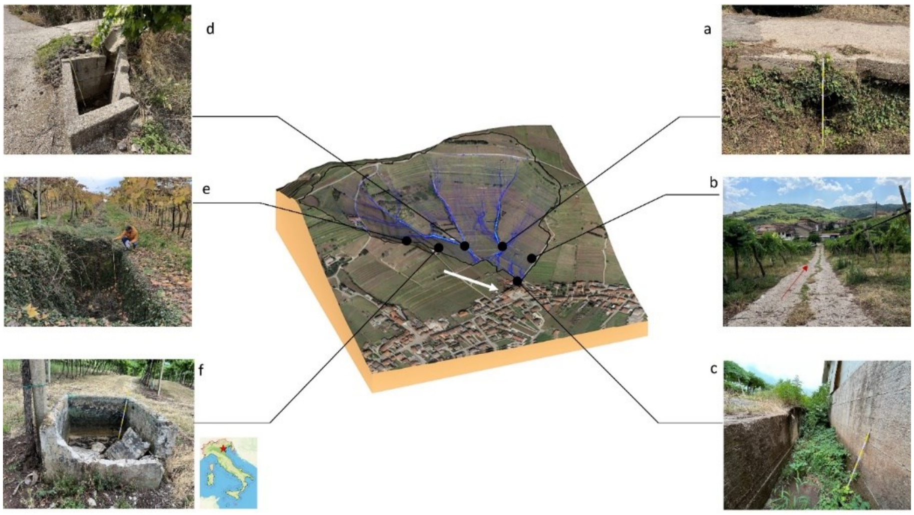

Figure 8.1 - The location of the study area (middle); The 3D overflow simulation in the study is made by SIMWE model to illustrate the potential hydrological risk; the Outline of the study area is labeled in black color; Runoff simulation is labeled by blue color; a: The drainage system under the road; b: Runoff enters the village along the steep slope road; c: The main drainage system in the study area; d: Water storages in the road; e: Water storages in the vineyard; f: Abandoned water storage (photos by Wendi Wang). The location of the village downstream is indicated by the white arrow.

time (Adham et al., 2018). Rainfall water can be collected in different approaches like run-off interception, infiltration improvement in soil, and integrated watershed management (Rockström and Falkenmark, 2015). Water harvesting technique such as dams, ditches, tank and ponds etc. combined with crop management has been proven as a plausible approach to address the water shortage issues and have been widely applied in many countries for years (Deora and Nanore, 2019; Morgado et al., 2022; Munyasya et al., 2022; Odhiambo et al., 2021; Zhang et al., 2021). For instance, Kumar et al (2008) derived suitable sites for different types of water conservation structures like check dams, contour bunding, recharge pits, wells, and contour trenching on the regional scale (Kumar et al., 2008). Furthermore, successful water conservation measures have multiple interacting implications in biophysical, economic, and ecological systems (Wordofa et al., 2020).

Although the grapevines are experiencing previously unseen conditions due to extreme weather (Helder and João A., 2018; Naulleau et al., 2022), there have been few studies working on the more resilient sustainable water management in steep slope vineyards. Identifying the optimal position for water storage facilities is the key step to maximizing the amount of water collected and crop production, especially under extreme weather in areas with complex topographic conditions. The main objective of this paper is to present a prototype of a water harvesting system consisting by low-impact micro storages. In detail, the goals are: (1) to simulate hydrological processes in steep slope viticulture for different rainfall events; (2) to design a water reservoir system in optimal sites for both alleviating the runoff and harvesting rainwater with minimal disturbance to the local site, giving the value of landscapes protected by FAO; (3) to quantify the water collected (therefore also the runoff reduction) of the designed water management system, to be potentially re-used then for irrigation. This study provides new insights for farmers and decision-makers in exploring rational and economic-feasible water resource management, which is meant for developing sustainable steep slope vinicultural systems, particularly in the context of climate change and intense water pressure.

8.2. Materials and Methods

8.2.1. Study area

The study area is situated in the north-eastern part of the Soave vineyard (North of Italy), a valley called Brognoligo (Figure 8.1, 45°27’12.07” N; 11°16’41.98” E), covering 20 hectares. Brognoligo is one of the most historic areas for wine production in the area of Soave. It is famous for producing full-bodied and structured wine manually in a dry system. The study area is located on the steep slope with an average gradient of 17 degrees. The elevation ranged from 98 to 217 meters. Annual precipitation is around 1200 mm. The dominant soil type in this area is clay. The main land use is vineyard (Figure 8.1). Figure 8.1 (middle) is a 3D map of overflow simulation to illustrate the potentially critical points in terms of flow accumulation in the study area. As Figure 8.1 shows that all the runoff during the rainfall flow towards the downslope village (white arrow in the figure). The only drainage system in the village is a 1-meter-deep and 0.5-meter-wide ditch (Figure 8.1, picture c).

8.2.2. The surface runoff simulation

To quantify the efficiency of the water reservoirs, we applied the SIMulated Water Erosion (SIMWE) model to simulate overland flow in different rainfall scenarios with and without designed water reservoirs. SIMulated Water Erosion (SIMWE) was developed by Mitas and Mitasova (1998), a physically distributed model well recognized for real-time overflow

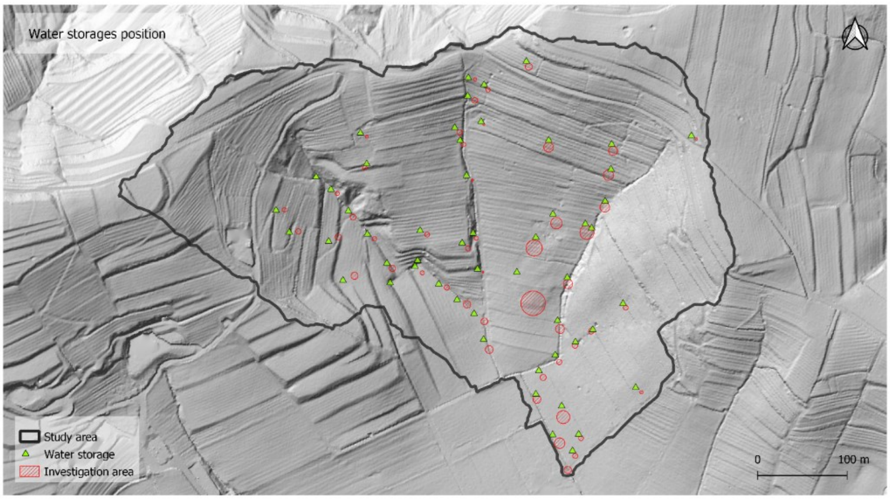

Figure 8.2 - The position of designed water storages (green triangle) and investigation area (red circle) for runoff decrease analysis.

simulation, which is widely used in flood risks estimation, surface runoff analysis, and accumulation as well as drainage systems design in recent years (Pijl et al., 2019; Li et al., 2020). With only a few input data, the SIMWE model can quantitatively describe the spatial-temporal water distribution in the complex agro-hydrological process. The input of SIMWE includes an elevation raster map, Manning's roughness values (-), and rainfall excess (mm h^{-1}); the output includes a water depth raster map (m) and a water discharge raster map (m^3/s). Considering the SIMWE has a higher estimation for hydraulic risk with a high-resolution elevation input map (Li et al., 2020), 1-meter high-resolution digital elevation model was applied in this study. The topographic dataset was produced by LiDAR data (Pijl et al., 2020). Runoff simulation is based on two real rainfall intense events occurred in the Veneto region on September 1st 2018 (82.4 mm h^{-1}) and August 29th 2020 (182.4 mm h^{-1}), respectively. In the first scenario (82.4 mm h^{-1}), Manning's roughness values (-) for vineyard and designed water storage facilities are 0.1, 0.013, and rainfall excess (mm h^{-1}) for vineyard and designed water storage facilities are 45.1, 82.4 respectively. In the second scenario (182.4 mm h^{-1}), the Manning's roughness values (-) for vineyard and designed water storage facilities are 0.1, 0.013. The rainfall excess (mm h^{-1}) for vineyard and designed water storage facilities are 145.1, 182.4, respectively. The Manning's roughness coefficient (-) and rainfall excess (mm h^{-1}) are already validated and based on previous research in Soave (Pijl et al., 2020; Straffelini et al., 2022).

8.2.3. Water storage locations and design

53 potential sites were identified for water harvesting systems based on field survey and runoff simulation (Figure 8.2). Different size of water reservoirs was developed according to the traditional knowledge of local farmers (farmers were interviewed; they also showed to us some abandoned examples of micro-storages) that two generations ago were used to deal with these kinds of water storage solutions, now not anymore proposed. The volume of water storage designed according to the amount of simulated runoff (water depth) and surrounding environment ranges from 4 m^3 to 30 m^3. All the designed sites are generated by "digging the hole" on the ground with locally available materials, similar to the picture e in Figure 8.1. The operation of the water collection facilities in the study area is achieved by modifying the elevation of DTM. The site of water storages facilities meets four conditions as follows: (1) in the position where have potential runoff; (2) in a direction perpendicular to the simulated overflow to intercept runoff more effectively; (3) parallel to the contour lines to reduce the practical difficulties; (4) between rows of vines where without interfere vineyard cultivation. Considering the increasing climate change influence on steep slope agriculture landscapes, the runoff simulation based on two rainfall scenarios (82.4 mm/h, 182.4 mm/h) in 5 minutes and 10 minutes, separately, to identify the runoff intercepting and water saving function of designed water reservoir under extreme rainfall events. We chose the maximum 10-minute interval for two reasons: (1) the peak rainfall recorded in this area, 182.4 mm/h, lasted for 5 minutes (Pijl et al., 2022). (2) The model reaches a "steady state" after 10 minutes as the input and output values are in equilibrium. The investigation area highlighted by the red circle (Figure 8.2) is where to detect runoff reduction. This area is chosen in the position below the designed water storage and perpendicular to the direction of the simulated runoff simultaneously.

8.2.4. statistical analysis

The significance of mitigation of surface runoff by designed water management systems was statistically analyzed in different hydrological simulations. Specifically, water depth values for each simulated rainfall intensity (82.4 and 182.4 mm/h) and at the two event times (5-minutes and 10-minutes) were compared. The gridded values of model outputs were imported and analyzed in R software. The comparison was made using the one-way ANOVA test to determine the differences between the simulations and the post-hoc Tukey-Kramer test to perform the pairwise comparison between the scenario without (before) and with (after) the implementation of the storages.

8.3. Result

8.3.1. The simulation of runoff

Figure 8.3 shows the simulated water depth (blue label) value before and after putting designed water reservoirs based on two real rainfall events in 5 minutes and 10 minutes intervals. In the same time interval, the water depth and surface overflow at 182.4 mm/h are much higher than at 82.4 mm/h. Similarly, in the same rainfall scenario, the water depth in 10 minutes is higher than in 5 minutes. Simulated water fluxes showed that water from the upslope mainly followed the ditches located in the center of the study area, accumulated in the downslope, and finally converged at the outlet of the terraces, which is the only drainages system mentioned before (Figure 8.1, picture c). In the 82.4 mm/h (5-minutes) rainfall scenario, the average water depth and water discharges are 0.07 m and 0.04 m^3/s. In the 82.4 mm/h (10-minutes) the average water depth and water discharges are 0.09 m and 0.07 m^3/s. In the 182.4 mm/h (5-minutes) rainfall scenario, the average water depth and discharge are 0.016 m and 0.013 m^3/s. In the 182.4 mm/h (10-minutes) simulation, the average water depth and discharge are 0.019 m and 0.02 m^3/s.

Figure 8.4 shows the magnification of the runoff path before and after putting water storage in several critical areas.

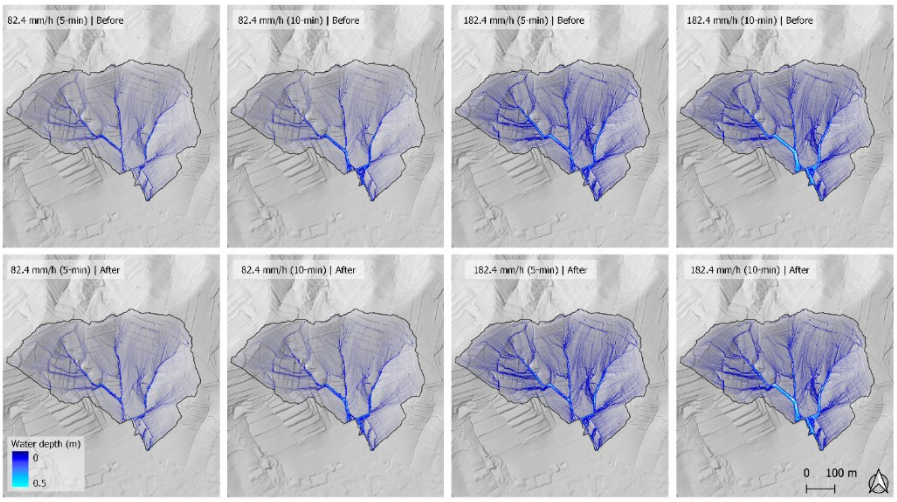

Figure 8.3 - simulated runoff distribution before and after putting water reservoirs under 82.4 mm/h (5-minutes), 82.4 mm/h (10-minutes), 182.4 mm/h (5-minutes), 182.4 mm/h (10-minutes) rainfall scenarios.

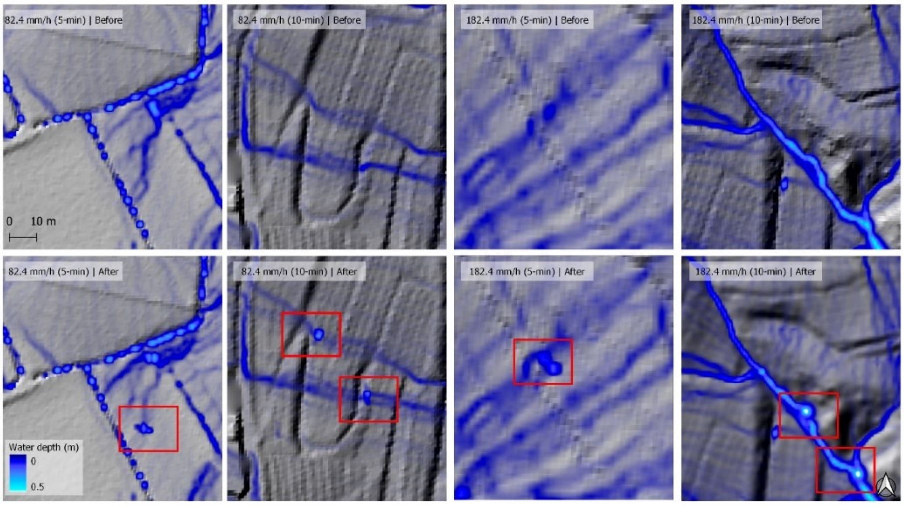

Figure 8.4 - Detailed map of comparison of simulated runoff in several positions before and after placed water reservoirs. Red rectangular highlighted the water accumulation in the position of putting designed water storage by SIMWE.

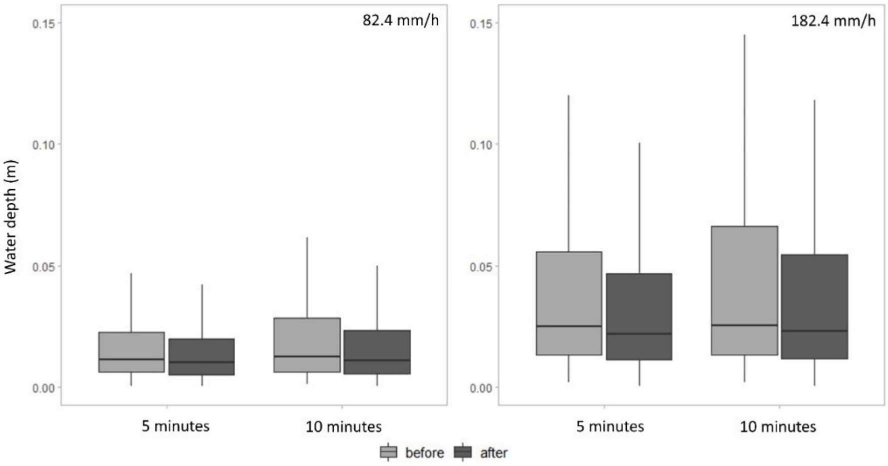

Figure 8.5 - The runoff comparison before and after implementing water storage in the investigation area (Investigation area highlighted by the red circle in Figure 8.2).

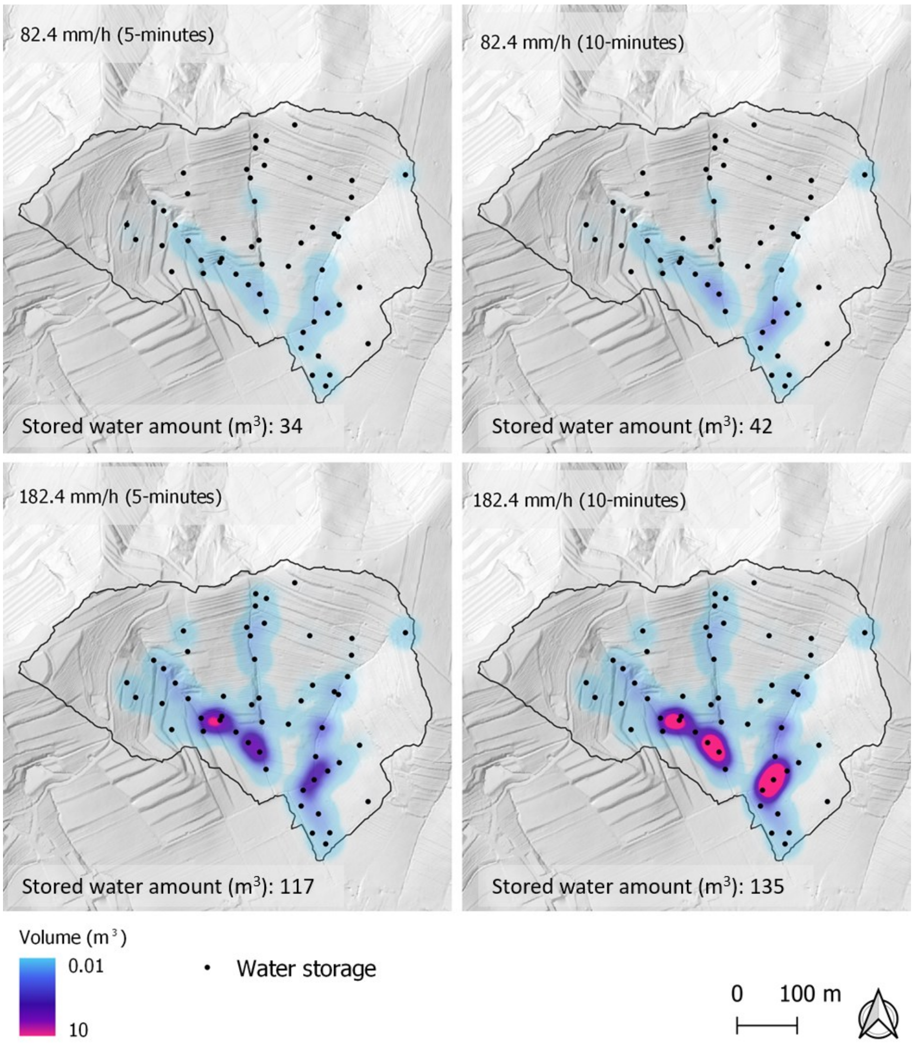

Figure 8.6 - The map of the spatial distribution of water amount saved by designed water storage in four different scenarios.

Water accumulation in designed water storage facilities was highlighted by red rectangular. The average water depth harvested by designed water storages facilities are 0.07 m, 0.09 m, 0.26 m, 0.30 m in the 82.4 mm/h (5-minutes), 82.4 mm/h (10-minutes), 182.4 mm/h (5-minutes), 182.4 mm/h (10-minutes) rainfall scenarios, respectively. Our result showed that low-tech and simple water resource management facilities could collect water effectively in steep slope agricultural Landscapes, which is especially important for areas that are difficult to access by machinery due to poor traffic conditions.

8.3.2. The effect of water resource management on runoff mitigation

Our result indicated that a water reservoir can decrease runoff significantly in 82mm/h (5 minutes) scenario, 82mm/h (10 minutes) scenario, 182mm/h (5 minutes) scenario, 182mm/h (10 minutes) scenario with the p-value less than 0.000001, 0.000001, 0.001, 0.001 separately. It is interesting to note that in both 5 minutes simulations in 82mm/h and 182mm/h rainfall events, the effect of water decreased is much more significant in 10 minutes simulation, which can be reflected by P-value tests returned <0.000001. The water depth data in investigation area before put water storages in 82 mm/h (5 minutes) scenario, 82 mm/h (10 minutes) scenario, 182 mm/h (5minutes), 182 mm/h (10minutes) scenario is 0.026 m, 0.040 m, 0.058 m, 0.078 m. The water depth data after put water storages in 82 mm/h (5 minutes) scenario, 82 mm/h (10 minutes) scenario, 182 mm/h (5minutes), 182 mm/h (10minutes) scenario is 0.024 m, 0.033 m, 0.053 m, 0.069 m.

8.3.3. Assessment of water amount saved by designed water storage

Figure 8.6 shows the amount of water saved in the designed water reservoir in different scenarios. The most efficient water storages were highlighted in Figure 8.6. It is worth mentioning that the more effective water storage facilities are mainly located in the middle and lower reaches of the study area. The overall location remains the same, although it changes slightly under different climatic conditions. According to the calculation, 33.67 m^3 of water was saved in the 82.4 mm/h (5 minutes) scenario, 41.92 m^3 in the 82.4 mm/h (10 minutes), 116.74 m^3 in the 182.4 mm/h (5 minutes), and 134.7 m^3 in the 182.4 mm/h (10 minutes) scenario. If we assume that all the water storage facilities are filled with water, a total of 500 m^3 of water can be potentially collected.

8.4. Discussion

8.4.1. The importance of designing site-specific water storages facilities for the steep slope viticulture landscapes

Our study concludes that the micro water storage systems have a large potential for water saving in steep slope agriculture. In this study, the micro water storages network was designed for four reasons: (1) As one of only 57 agricultural heritage sites worldwide recognized by FAO in the GIAHS list, Soave traditional agricultural systems were not allowed to make a big land use shift such as the construction of big dams or large farm ponds, since it had already maintained by locally adapted management (GIAHS (Globally Important Agricultural Heritage Systems), 2018); (2) To avoid larger and complex infrastructure that can be unstable on a high-steep slope, all the designed water storages in this study are at a maximum depth of 1 meter for safety reason; (3) for a site-specific reason. Several studies have documented the critical role of ponds and pans, check dams, terracing, percolation tanks etc., in water harvesting (Ammar et al., 2016). However, different water harvesting structures have their own particularities and purpose and require specific construction conditions (Vema et al., 2019). For example, check dams have been well recognized in China and India for alleviating the problem of water scarcity and preventing floods (Balooni et al., 2008; Shuilong Yuan et al., 2022). However, check dams are only suitable in the catchment area ≥ 25 (ha), and agriculture ponds are available for small flat areas with slopes ≤ 5% (Ammar et al., 2016). The Percolation Ponds are suitable on moderate slopes of 5–10% also more tend to recharge groundwater instead of irrigation water use (Christy and Lakshmanan, 2017); research has consistently shown that above-water harvesting facilities are not plausible in the steep slopes viticulture with low runoff potential and high permeability (Vema et al., 2019); (4) The difficulty in transporting water in steep slope vineyards; (5) Economic acceptable by local farmers. The introduction of complicated new water storages systems can largely decrease water stress and risk of crop failures in different scales of farming systems (household, community, catchment). However, the investment cost is also expensive, in this case, an economically feasible system with locally available material approaches is advisable in steep slope agriculture for multipurpose use (Rockström, 2000). Tiwari et al. (2018) also emphasized the importance of time-saving and cost-effectiveness in water resource management (Tiwari et al., 2018). Our research highlighted the significance of the revival of traditional agricultural water harvesting facilities, which is also well recognized by some other countries like India (Balooni et al., 2008).

8.4.2. Improve water productivity by combining the smart irrigation systems for dry spell mitigation

In our study, a total of 500 m^3 of water can be potentially collected. Based on the previous research, the minimum water consumption in the vineyard is 300 mm ha^{-1} yr^{-1}, and approximately 20 hectares of the vineyard could be irrigated by collected water for one day (Medrano et al., 2015). In the Mediterranean areas, rain usually comes in sporadic, unpredictable storms and is mostly lost in evaporation and runoff, leaving frequent dry periods during the crop-growing season (Oweis and Hachum, 2006). Many researches about smart irrigation systems, such as pressurized irrigation systems and Automation of Farm Irrigation are applied for optimal irrigation scheduling (Bwambale et al., 2022; Kamienski et al., 2019; Ommani, 2011; Oweis and Hachum, 2006; Vij et al., 2020), but few studies focus on the water source for irrigation in mountainous areas. One of the ideas from Precision Agriculture is to combine intelligent agricultural irrigation systems with designed water harvesting systems, where funding allows, to solve the problem of over-irrigation in steep-slope viticulture and thereby improve water productivity. Optimal distribution of limited water resources can also be coupled with improved irrigation management options and technologies such as Supplemental irrigation, Deficit irrigation, Sprinkler irrigation as well as Drip irrigation, in this way, tangible water productivity can be achieved on a sustainable basis (Baig et al., 2013; Geerts and Raes, 2009; Man et al., 2017). The collection of rural water can also be used to develop livestock farming and ecosystem diversity (Rockström, 2000). Maximum water productivity should be highlighted by water management guidelines rather than land productivity (Geerts and Raes, 2009; Oweis and Hachum, 2006).

8.4.3. Runoff reduction via utilization of micro water harvesting systems

Our study concluded that micro water reservoir systems could both significantly intercept runoff and harvest water in intense rainfall events to be potentially used for irrigation during drought periods. These dual benefits are not necessarily coincident in all types of water harvesting techniques (Sample and Liu, 2014). Most studies of water harvest techniques have focused on water supply exclusively or large water harvesting facilities (Kaushal K. Garg et al., 2022; Landicho et al., 2022). In this study, we aim to identify the influence of a micro water harvesting system with minimum land modifications, but to maximum mitigate the hydrologic risk of extreme rainfall events, more water harvesting facilities are strongly recommended, especially considering that all runoff eventually drains downstream in the village.

8.5. Limitations and future challenges

The accuracy of the rainfall-runoff relationship simulated is highly dependent on the input data, model complexity, users (Adham et al., 2018), and data availability for model calibration and validation in complex morphology areas are usually lacking. The spatial design and organization of the vineyard can considerably affect surface runoff pathway and accumulation patterns (Pijl et al., 2020); thus, the same initiative should be repeated in other steep slope viticulture to avoid site-specific biases. This study clearly illustrates the water amount harvested by the designed method for irrigation use, but this stands in stark contrast with the actual amount of irrigation in the study area. Further exploration of the micro water harvesting systems is thus encouraged for maximum water amount collection. We strongly recommend the application of advanced technologies like GIS, RS, and hydrological models in the delineation of potential sites for water harvesting structures and water leakages detection, which is also confirmed by previous studies (Abdulla Umar Naseef and Thomas, 2016; Chartzoulakis and Bertaki, 2015; Engman, 1991; Hammer et al., 2011; Waseem Ghani et al., 2013). In addition, real-time monitoring systems provide a shoulder to the farming industries in monitoring and tracking agricultural water use and improving the effectiveness of water retention measures at multiple scales (Foster et al., 2020). There is a need for further research on the hydrological model development involving both surface and sub-surface parameters such as groundwater discharge and evapotranspiration. A novel way of estimating the trends of global irrigation dynamics based on multiple satellite products was reported recently (Zhang et al., 2022). The development of finer spatiotemporal resolution satellite-based products will greatly increase the effectiveness of water resource management in the future (Zhang et al., 2022).

8.6. Conclusion

As one of only 57 agricultural heritage sites worldwide recognized by the FAO as GIAHS, Soave traditional viticulture system (Italy) has provided social, cultural, economic, and environmental goods and services for more than 200 years for local people (Vigotti, 2021). Improving water resource management is important for designing sustainable and climate-change-resilient agricultural systems. In this study, a potential water harvesting network including 53 sites was designed for collecting rainwater based on indigenous knowledge, field survey, runoff simulation, and topographic analysis. The results show that these simple, micro-harvesting systems can considerably reduce the surface overflow (with P values tests returned <0.001) and effectively collect rainwater in different rainfall conditions. According to the calculation, 33.67 m^3 of water was saved in the 82.4 mm/h (5 minutes) scenario, 41.92 m^3 saved in the 82.4 mm/h (10 minutes), 116.74 m^3 saved in the 182.4 mm/h (5 minutes), and 134.7 m^3 saved in the 182.4 mm/h (10 minutes) scenario. A total of 500 m^3 of water can be potentially collected, which can be used for approximately 10 days of drip irrigation water amount during the drought period. The maximum drop in water depth at the outlet of the study area was 2 cm at 82.4 mm/h (5 minutes) scenario and 182.4 mm/h (5 minutes) scenario. Our work illustrated the urgent need revival of traditional and cost-effective water resource management in steep slope viticulture. Furthermore, we discussed that combining new irrigation technologies with designed water harvesting facilities will have a multiplier effect on improving water use. Given the specificities of steep-slope agriculture, there is a need to promote diverse indigenous water harvesting facilities and improve water productivity rather than designing more complex and expensive water management methods that are difficult for farmers to accept, except when funding is available. Sustainable development can only be achieved when the water resource management systems is adapted to the local natural, economic and social environment in steep slope viticulture.

PART C – Human Management Affects the Resilience of Cultural Landscapes to Global Environmental Change

The resilience of representative Cultural Landscapes to global environmental changes is significantly influenced by human management practices. The **Part C** of this PhD thesis (sections 9-10-11) investigates the dual role of human management: while certain practices can mitigate environmental impacts, others may exacerbate vulnerabilities. Effective adaptation strategies are therefore essential for preserving the resilience and cultural value of these landscapes under changing global conditions.

The section is based on the following case studies:

- **In Argentinian Vineyards**, the article *"Viticulture in Argentina under Extreme Weather Scenarios: Actual Challenges, Future Perspectives"* explores how vineyard management is evolving in response to climate change. To mitigate the impacts of increasing heatwaves, vineyards are being relocated to higher elevations. While this shift addresses heat-related issues, it introduces new risks such as soil erosion and flooding from extreme rainfall. The study underscores the complexity of adapting viticultural practices and the role of human decisions in managing these risks, emphasizing the need for strategies that balance both heat and rainfall challenges.
- **In Traditional Viticulture**, the article *"Viticulture and Cultural Landscapes: Remote Sensing and Earth Surface Processes Modelling to Promote Sustainable Agricultural Practices"* focuses on the impact of heavy mechanization on Cultural Landscapes. The transition from traditional methods to mechanized operations has increased soil compaction and surface runoff, exacerbating erosion during heavy rainfall. This shift highlights how modern practices can challenge the resilience of traditional viticultural Landscapes. The study calls for sustainable management practices that preserve the cultural heritage while improving resilience to extreme weather.
- **In Steep-Slope Agriculture**, the article *"Sustainable Water Resource Management in Steep-Slope Agriculture"* discusses the integration of traditional knowledge with modern technology for water management in steep-slope landscapes. Effective water management is crucial for maintaining productivity and resilience in these culturally significant areas. The study demonstrates how sustainable practices, informed by both indigenous knowledge and contemporary technology, can mitigate the adverse effects of climate change, thereby enhancing the resilience of these landscapes.

9. Argentinian Vineyards are Shifting to Face Climate Change. A Wise Move?

Context

In Argentina, viticulture is a major industry that blends wine production with eno-gastronomic tourism. The Cuyo region, particularly Mendoza, is famous for its wine-growing areas rich in cultural heritage. This tradition has developed over centuries, starting with sophisticated irrigation systems started from the pre-Hispanic era. Climate change, however, poses significant threats to viticulture. Increasing heatwaves have caused severe damage to vineyards and have intensified the need for water in irrigation. To counter these challenges, many wine-growers are relocating vineyards from the vulnerable plains to higher elevations towards the Andes, where the sloped terrain offers a cooler climate. This strategic shift is aimed at mitigating the impact of extreme heat, but it also introduces new risks. Specifically, these elevated areas are now facing challenges related to extreme rainfall events, which can lead to soil erosion and flooding, destroying entire vineyards (phenomena previously uncommon in for winemakers). This chapter provides a detailed overview of Argentinian viticulture, highlighting its Cultural Landscapes and the emerging risks associated with climate change. It emphasizes the role of human intervention in adapting to these changes, focusing on strategies like shifting vineyard locations to enhance resilience, but also facing new risks. Through this lens, the chapter explores how the sector is evolving to address the complex interplay between climate dynamics and viticultural practices.

The article

This chapter focuses on the perspective paper (open access) titled: *"Viticulture in Argentina under extreme weather scenarios: Actual challenges, future perspectives"*. It was published in 2023 in the peer-reviewed journal *"Geography and Sustainability"* (*Q1 in Geography, Physical, and Green & Sustainable Science & Technology; IF 2022: 8.0*).

> This paper primarily focuses on SO-C, examining the adaptation strategies of relocating vineyards to higher elevations in response to climate change. It also partially addresses SO-A by investigating how heatwaves and droughts affect vineyard productivity, and SO-B by considering the new risks associated with extreme rainfall in these relocated areas.

PEER-REVIEWED & PUBLISHED PERSPECTIVE ARTICLE

Viticulture in Argentina under extreme weather scenarios: Actual challenges, future perspectives

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CRediT authorship contribution statement:
Eugenio Straffelini: conceived and designed the research; wrote the first draft, and edited the manuscript and figures.

Abstract

Viticulture in Argentina is an important socioeconomic sector, reflected in a significant wine market and tourism. However, climate change and related extreme events are serious concerns. The main issues are heatwaves, hailstorms, and heavy rainfall, resulting in damage to vineyards. While climate change impacts have already been discussed for regions such as the Mediterranean, the literature lacks an up-to-date overview of Argentine viticulture and potential mitigation solutions. In a country culturally and economically connected to the world of wine, it is strategic to bridge this gap to be prepared for a climatically adverse future. This perspective paper presents an overview of Argentine viticulture and its relationship to climate change. We focus on the Mendoza region, one of the most productive areas and home to Cultural Landscapes where internationally recognized wines are produced. Climate change is already occurring, a fact we observed by analyzing data from the past decades. We discussed how heatwaves in the lowlands drive farmers to move to the Andes slopes looking for more favorable conditions. But new threats arise, such as extreme rainfall. Due to surface hydrological processes, they can cause land degradation and compromise vineyards. We investigate these phenomena in detail, highlighting how they represent a growing challenge that must be addressed for the sustainable development of future viticulture in the area. Therefore, we propose mitigation strategies for more resilient production, drawing inspiration from the Sustainable Development Goals and suggesting a framework that can be extended to broader contexts worldwide.

Keywords. Viticulture; Wine; Climate change; Adaptation; Argentina; South America

9.1. Introduction

Since the first domestication of the vine (*Vitis vinifera L.*), viticulture has become a widespread agricultural practice worldwide. In several cases, winegrowing areas are important Cultural Landscapes that integrate ecosystem services with social needs. Viticulture faces serious difficulties due to climate change, which could alter the terroir of unique cultivations. The consequences can be dramatic. Heatwaves have a strong impact on vine plants, causing leaf loss and grape damage, such as in the case of an extreme event in France in 2021 (Lopez-Fornieles et al., 2022). Another problem is the variation in the precipitation regime, which often leads to dry periods alternating with extreme rainfall. Drought is one of the most alarming agricultural hazards posed by climate change. Although controlled conditions of vine water stress can positively affect wine quality, prolonged lack of water causes irreparable damage (Chaves et al., 2010). Therefore, especially in drier areas, irrigation is a key practice. When rainfall is concentrated in short periods, serious surface processes such as soil erosion, flash floods, landslides, and other severe processes can be triggered. They can significantly compromise the functionality of vineyards (Maetens et al., 2012). Numerous researches have been conducted on this issue, for example, in Spain (Rodrigo Comino et al., 2017) or Italy (Pijl et al., 2020). Hailstorms are also major concerns, especially during grape ripening or before harvest (Vinet, 2002).

In the Northern Hemisphere, European soils accommodate the largest area devoted to viticulture. In 2021, Spain, France, and Italy alone were responsible for roughly half of the global wine production (OIV, 2022). Vineyards are also in Portugal, Germany, and the Eastern European states. Other examples worldwide are China, the United States, and Turkey. The scientific literature is rich in research conducted on the impact of climate change on vineyards in these areas. Interesting recent examples include the effects of heatwaves in Europe (Fraga et al., 2019), the importance of climate risk management in the United States (Babin et al., 2022) or the potential loss of vineyard areas in China (Bai et al., 2022). Viticulture is also widespread in the Southern Hemisphere. The vineyards are planted in Australia, Africa, and South America, where it is an important economic activity. Examples are Chile, Brazil, and Argentina. The latter is a key producing country and seventh in the world regarding area under vines. Viticulture is a leading economic sector, integrating wine production and eno-gastronomic tourism. The Cuyo region and, specifically, the province of Mendoza host outstanding wine-growing areas. The landscape also has strong cultural attributes. It has been shaped over centuries, starting from a complex traditional irrigation system that began in the prehispanic era. Thus, climate change may affect production and the cultural values that characterize some related areas.

Compared to the Northern Hemisphere, less research on the interaction between climate change and viticulture can be found in the Southern one. Examples include the adaptability of viticulture in Chile (Mills-Novoa et al., 2016) and the impacts of spring frosts in Brazil (Campos et al., 2017). Few studies focus on Argentina. For instance, Cabré and Nuñez (2020) simulated future climate changes in Argentine winegrowing areas by describing potentially critical scenarios. However, the literature lacks a general overview of the topic, in which potential damages are deeply investigated and effective solutions sought. In a country deeply rooted in the wine industry, filling this gap would open the door to more specific research, contributing to the safety of viticulture that cannot be compromised. In addition, it could address policymakers toward an improved landscape planning and natural resource management strategy. Therefore, in this perspective article, we summarized these concepts by proposing an overview of viticulture in Argentina and focusing on the Mendoza area. We explore the current and future challenges related to climate change in vineyards, also discussing possible mitigation strategies in line with the United Nations (UN) Sustainable Development Goals (SDGs).

9.2. Viticulture in Argentina and Mendoza

Argentinian viticulture extends from 22° to 45° South latitude, mainly located along the piedmont of the Andes Mountains. 92% of the country's vineyard area corresponds to varieties suitable for wine and must production, and 8% for fresh consumption and sultanas. The most cultivated wine varieties are Malbec, Bonarda, Cabernet Sauvignon, Torrontés riojano, and Chardonnay. Four main winegrowing regions can be distinguished: the North, the Cuyo, the Atlantic, and the Patagonian (Figure 9.1a). Except for the Atlantic one, many vineyards are located at altitude. The Cuyo region is among the most important in South America. A significant portion is located in Mendoza province (Figure 9.1b). Despite the dry climate (rainfall regime is in Figure 9.1c), viticulture is a major socio-economic activity. This is possible thanks to oases supported by a complex system of reservoirs and irrigation canals. The province is characterized by the largest area under vines in the country (71% of the total cultivated surface) and is recognized as one of the Great Wine Capitals. Five winegrowing regions are located here: North, East, Center, South, and Uco Valley. The Center and Uco Valley (Figure 9.2) are remarkable regarding the production and exportation of qualitative wines. Soils vary from loam to clay loam (based on USDA classification) and are characterized by the presence of coarse material (gravel and boulders), poor organic matter, and good permeability (INV, 2022). Over the past 20 years, the vineyards in these areas have steadily increased their surface through modern and technological systems. Some of the most interesting cultivations are located in the foothills of the Andes, in the Department of Luján de Cuyo. Favorable ecological and climatic conditions lead to a strong viticulture expansion here, even on steep slopes at high altitudes.

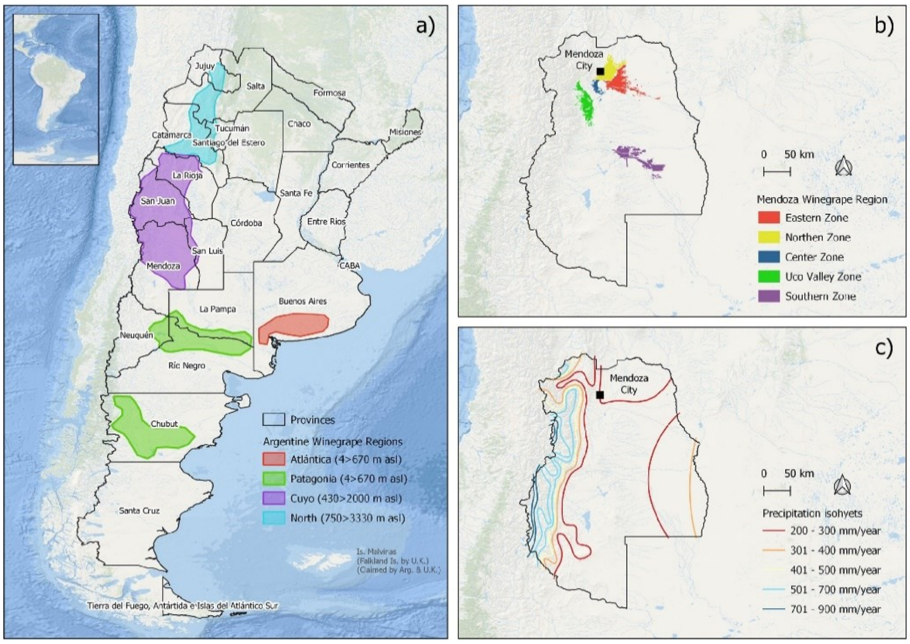

Figure 9.1 - a) The Argentine provinces and the main winegrowing regions; b) Focus on the province of Mendoza related to the viticultural areas; c) Precipitation isohyets of the province of Mendoza.

Figure 9.2 - Vineyards located at 1,300 m asl near Andes mountains (Uco Valley, Mendoza province; photo by Paolo Tarolli).

Winters are harsh, summers are hot, with temperate days and cold nights, resulting in an annual mean temperature of approximately 12–15 °C (Cabré et al., 2016). Milder temperatures and fewer climate change-related heatwaves are the main reasons for this territorial expansion.

9.3. Climatic threats in Argentine vineyards

9.3.1. Water, storm, hail

Most Argentinean viticulture takes place in the valleys of the Andes mountains, where the climate is highly influenced by topography. The annual precipitation mostly occurs during spring and summer. However, rainfall is insufficient in some key viticultural areas to cover the vine plant cycle, requiring irrigation. The snowmelt is the primary water source, reaching the cultivation areas by flowing from three main rivers to a dense channel network. A primary climatic threat is a drought. From 2010 to the present, the central-west of Argentina has experienced severe periods of hydrological drought. Reduced snowfall at high altitudes decreases the river flow downstream, leading to restrictions on water consumption for agriculture and domestic use (J.A. Rivera and Arnould, 2020). In case of water scarcity, exploitation of groundwater resources increased, an unsustainable solution in the long run (Rivera et al., 2021). One critical aspect is the regime with which rainfall occurs, often concentrated in heavy, localized storms in recent years (Castex et al., 2015). The consequences are severe, such as landslides on slopes and flash floods in lowlands, sometimes involving urban areas. Argentina is prone to intense hailstorms (Bechis et al., 2022), mainly during spring and summer. They damage plants at delicate phenological stages, such as flowering and ripening (Mezher et al., 2012). Topography influences diurnal winds, resulting in convection initiation (CI) hotspots that trigger hailstorms (de la Torre et al., 2015; Hierro et al., 2013). Impacts on agriculture are considerable, with annual production losses estimated at 10%, mainly caused by large hail (diameter greater than 2 cm) concentrated in 2-3 events per year. Over the past 60 years, several attempts have been made to prevent hail damage in Mendoza province through cloud seeding. However, no scientific evidence demonstrates a statistically significant reduction in the frequency with which these events occur and a reduction in hail size (J.A. Rivera and Arnould, 2020). For this reason, it is crucial to focus on forecasting and prevention, studying the mechanisms that generate severe convective phenomena in the region, and testing the activation of warning systems. Also, there is a need to invest resources in improving real-time observations, such as radar, radiosondes, and ground measurement stations.

9.3.2. Rising temperatures and heatwaves

Rising temperatures are a problem for viticulture in Argentina. The first concern is the loss in the mass balance of glaciers, resulting in earlier snowmelt that affects irrigation management (Hock et al., 2019; Zazulie et al., 2018). High pre-sprouting temperatures advance the date of bud break and increase the rate of bud growth. Excessive heat can disturb the developing berries, affecting wine quantity and quality. Moreover, the influence of the water deficit producing colorful and flavourful wines rich in phenolic substances cannot be achieved at elevated temperatures (Bonada et al., 2015). Mendoza is an area where a gradual increase in temperatures is occurring. Figure 9.3 shows an original analysis of two representative meteorological stations located north and south of Mendoza. The dataset consists of daily temperature and precipitation measurements from 1961 to 2020 (courtesy of the Servicio Meteorológico Nacional; SMN). The data were used for temperature (in this section) and precipitation analysis (section 4.1). Figures 9.3a and 9.3b show the trends of minimum, average and maximum measures. There is a general increase in temperature and a positive slope of the linear regression fit curve. We tested the significance of the trend through the modified non-parametric Mann-Kendall test, which is widely used for time series (Hu et al., 2020). Outcomes show a statistically significant trend ($p\text{-value} < 0.05$) for mean and minimum temperatures in the southern zone and for maximum temperatures in the northern. The latter is increasing in the last decade. Decomposing the dataset into two periods, we observed that the maximum temperature increased by an average of +0.7°C in the period 2010–2020 compared to 1961–2009 (statistically different according to the t-student test; $p\text{-value} < 0.05$). High maximum temperature events can evolve into heatwaves, a serious threat to viticulture (Barros et al., 2015). They can damage the flowers during spring flowering, resulting in reduced fruit production and increased berries' temperature and wilting. These events are becoming more frequent in Argentina, especially in the lowland areas of Mendoza. We analyzed the frequency with which hot days occurred (Figures 9.3c and 9.3d). The results show that days where the maximum temperature exceeds threshold values (percentiles of the entire time series: 0.75, 0.85, and 0.90) are intensifying due to climate change ($p\text{-value} < 0.05$). Increasingly difficult growing conditions are leading wine growers to expand farmland elsewhere, mainly on the slopes of the Andes in Mendoza province. However, new hazards, such as extreme rainfall events, are arising.

9.4. New threats due to climate change

9.4.1. Intense and localized rainfall events

In Mendoza province, the average annual rainfall in the plain is ordinarily low (around 200 mm/year), with high inter-annual variability/heterogeneity in space and time. Climate models indicate that rainfall and snowfall in the Andes may decrease in the future. At the same time, an increase in precipitation, especially in summer, is projected in the lowlands east of the mountain range. Cabré and Nuñez (2020) estimated the precipitation anomalies for two climate scenarios (RCP4.5, RCP8.5). For the province of Mendoza, a decrease in precipitation at high elevations (-60 mm) and an increase at lower elevations (+60 mm) is projected for the worst-case scenario (comparison of 1960–2010 and 2075–2099). The latter is already observable in the historical data series. We analyze the average annual precipitation for the period 1961–2020 (Figures 9.3e and 9.3f), observing a significant positive trend (p-value < 0.05) both in the northern (+16.0 mm/decade) and southern (+23.3 mm/decade) areas. The greater water availability led to an expansion of the rural territory and a progressive increase in production. But to understand the benefits of agriculture in detail, it is important to analyze the spatiotemporal regime with which rainfall happens. On the one hand, extreme weather events in Argentina occur with high spatial and temporal variability, a process analyzed by several studies (Castino et al., 2017). This is also accentuated by periodic phenomena such as the effect of "El Niño/Southern Oscillation" or "La Niña" events

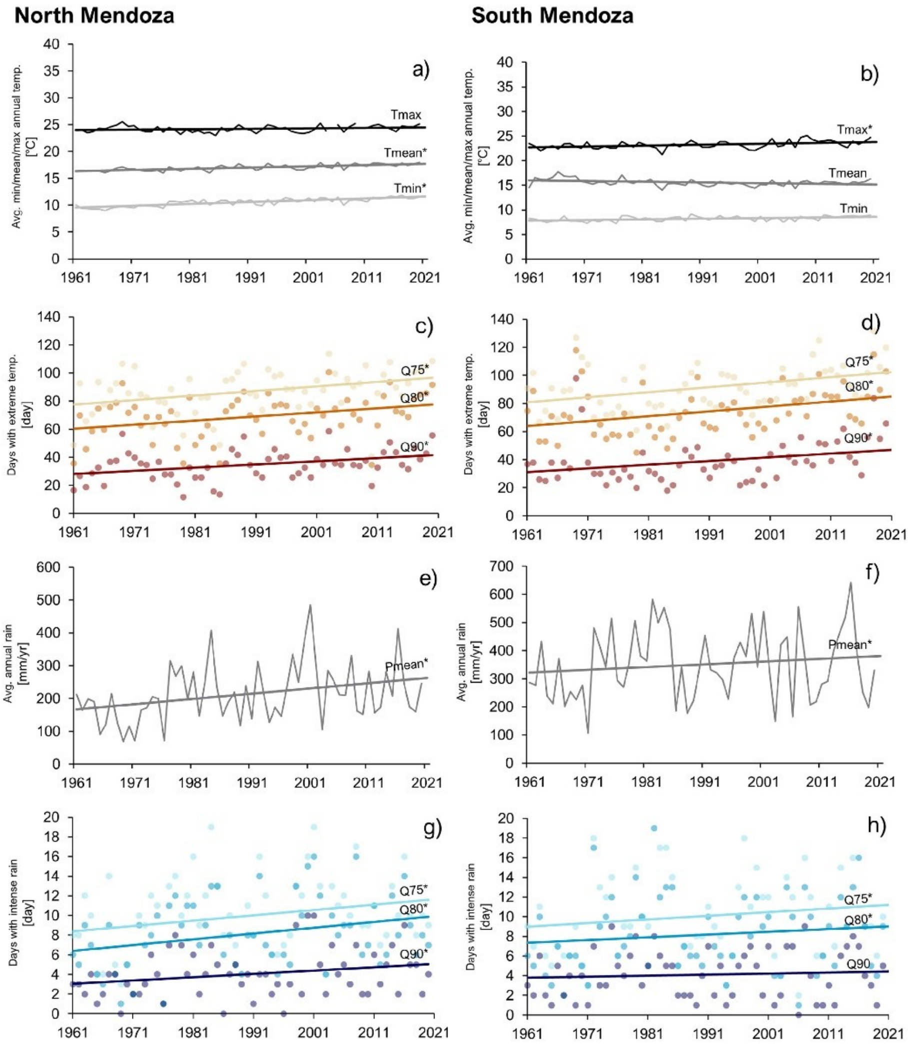

Figure 9.3 - Analysis of temperature and precipitation at two representative weather stations in Mendoza's north (left column) and south (right column). The data refer to the period 1961–2020 and are recorded daily. a) and b) analyze the trends of minimum, average, and maximum temperature over the period; c) and d) are the number of hot days according to three thresholds (percentiles 0.75, 0.85, 0.90); e) and f) are the average annual precipitation; g) and h) analyze the days with heavy rainfall (percentiles 0.75, 0.85, 0.90). Statistical significance of the linear regressions is indicated by *, calculated by the modified Mann-Kendall test.

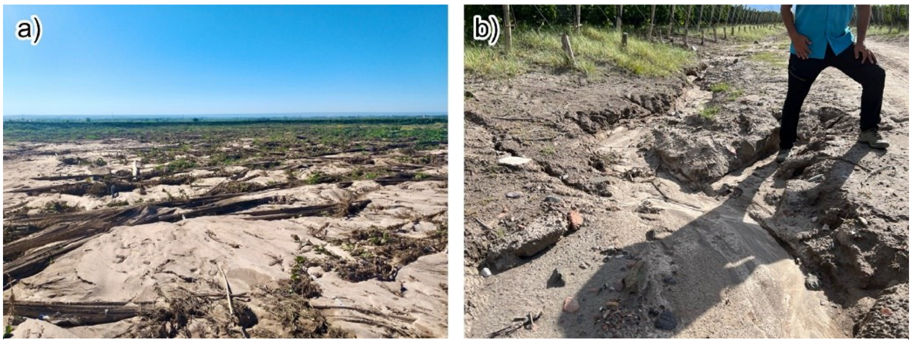

Figure 9.4 – a) Flash flood damages in a low-slope vineyard in the valley floor of the Andes mountain range (event of February 27, 2021; Uco Valley, Mendoza province photo by Carlos Schilardi); b) Soil erosion in a vineyard located on a slope. Soil eroded from the vineyard inter-rows was transported and deposited along an unpaved road, which is itself deeply damaged by surface runoff after heavy rainfall (event of February 9, 2022; Mendoza River Basin, Mendoza province; photo by Paolo Tarolli).

(Trenberth et al., 2014). On the other hand, it was observed that in key Argentine wine regions, an increasing fraction of rainfall occurs in the form of short, intense, and localized events. This was also recorded in Mendoza province (Castex et al., 2015). Our analysis support previews research, indicating that in the period 2010–2020, the total annual precipitation increased compared to 1961–2009 (p-value < 0.5). At the same time, the number of rainy days (> 0.1 mm/day) decreased by 12%. Consequently, the average precipitation during rainy days increased by 17%, including more heavy precipitation episodes. We also analyzed the frequency with which daily rainfalls exceeded certain thresholds (percentiles of the entire time series: 0.75, 0.85, and 0.90). The results show a significant increase (p-value < 0.05) for both stations and for almost all percentiles (Figures 9.3g and 9.3h). Extreme events worry local authorities, farmers, and communities, causing considerable damage to people, vineyards, and their productivity. Among the most severe processes are flash floods, which cause soil erosion, landslides, and flooding (examples are reported in Figures 9.4). Water stagnation is another related problem. The soil tends to become saturated and anaerobic, leading to a reduction in the quantity and quality of the grapes to the possible death of plants. Organic matter is easily washed away by excess water, making support measures necessary to maintain optimal fertility conditions. Another indirect effect of heavy rainfall and hyper-humid conditions is the development of vine diseases. Some significant examples involve root rot (such as *Rosellinia necatrix* or *Armillaria mellea*), leaf wilt, and possible plant death. As the climate change-related risks increase, farmers need to take the problem seriously, especially if the trend is to move vineyards to higher and steeper areas to mitigate the impact of climate change, such as heatwaves.

9.4.2. New threats due to vineyards shifting up to the Andes?

Extreme weather events cause severe yield reductions with potential consequences on price fluctuations in grapes and wine markets. Priorities include obtaining heat- and drought-tolerant varieties, modifying traditional agronomic and winemaking practices, promoting efficient water management, and finding new growing areas among the many challenges facing the wine sector. New vineyards are increasingly located at higher altitudes, where average temperatures during the grape ripening period are lower, and heatwaves are rarer. In contrast, the traditional lower flat regions will gradually become less optimal for production. This is due to climate change-induced aridification, making it increasingly difficult to grow vines in the Argentine lowlands. The rainfall deficit turns into a lack of available water for human activities. It causes problems for the vineyards (concept exemplified in Figure 9.5 as warm-colored rows representing water-stressed conditions). Therefore, moving the vine frontier towards regions further south or advancing towards higher areas (up to 2,000-3,000 m above sea level) are increasingly considered strategies. The development of higher terroirs represents an excellent alternative to compensate for warmer temperatures and is in line with the global trend of consuming fresher wines with good natural acidity. In addition, as the vineyards increase in height and are closer to the mountains, the UV-B radiation generates thicker and darker skins, which represent an advantage for obtaining higher concentrations of color and aromas (Alonso et al., 2016).

On the contrary, in high-altitude areas, the climate becomes more extreme (hail, heavy rains), and the occurrence of intense runoff phenomena cannot be underestimated. The construction of new vineyards on slopes requires the alteration of the original soil and surface morphology. As a consequence, there could be problems related to water regulation, with repercussions on hydrogeological processes. While excess water can be potentially exploited in agriculture,

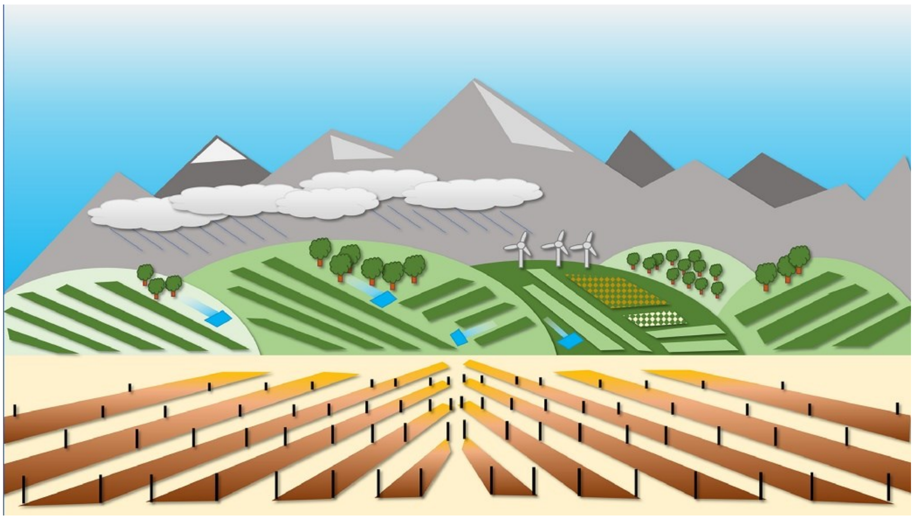

Figure 9.5 – Conceptual illustration describing vineyards' shift to Argentina's mountains. Lowland plantations suffer increasingly severe drought conditions and heatwaves due to climate change and are represented with a warm brown color. The new vineyards built at higher altitudes benefit from better climatic conditions. A green color, therefore, characterizes rows to describe excellent vegetative conditions. Appropriate water and soil management measures can help mitigate related issues.

it also causes soil erosion. In addition to a progressive loss of fertility, it can evolve into a more severe issue of land degradation (Lal, 2001). Without an appropriate soil and water management plan, extreme phenomena such as landslides, flash floods, and mudslides can occur (Wang et al., 2018). These can compromise the functionality of vineyards and threaten the safety of people living downstream. Farmers will likely face these challenges when they plant vineyards on the slopes. The management of the new challenges that viticulture faces worldwide can only be overcome with adequate research and local development that integrates private companies and public institutions linked to the industry and natural resources. The challenges are enormous, but the key to success will be to propose integrated solutions toward a more sustainable management model, focusing on research and innovation as a driver for adaptation.

9.5. Sustainable solutions for mitigating climate change impacts

9.5.1. Impact on the socioeconomic sector

For Argentina, the wine industry accounts for almost 0.4% of the national GDP based on nearly 0.1% of its surface. The activity in 18 provinces depicts an industry with broad territorial distribution, reduced surface, and high added value. For 2017, the wine industry generated an overall value of $1.4 thousand million meaning $6.5 thousand per hectare. These values include the different business units such as table grapes, bottled wine, bulk wine, raisings, and tourism. In terms of employment, more than 385 thousand persons directly or indirectly contribute to the activity. Under a climate change scenario, this industry is threatened in terms of added value and social impact. When defining adaptation or mitigation measures, it is essential to have a comprehensive vision of the industry and to understand the different business units and their productive and social constraints. Suppose viticulture in Mendoza must move upward to reduce the vine's exposure to high temperatures. In that case, it is essential to understand where wineries and suppliers should be located and how to connect them. The carbon footprint of increased transport can then endanger an intelligent decision from a climate change perspective. For instance, all workers dedicated to grape cultivation (82% of all wine industry) will require transportation and services, defining associated economic and social costs. Grape transportation to the winery should also be assessed in terms of financial costs and also quality issues that could arise. It is necessary to understand the return on investment to employ other strategies, such as drip irrigation or anti-hail systems. If only 5% of the world market of wine is composed of one-liter bottles over $30 retail price (ultra-premium), the possibility of assuming such costs is reduced. Thus, sustainability requires a comprehensive approach, balancing environmental, social, and economic issues. Consumers look forward to this approach and are willing to pay for these differentiation attributes (Valenzuela et al., 2022). An adequate communication strategy must be designed to increase consumers' awareness and willingness to pay, allowing wineries to invest in climate change mitigation strategies. These communication strategies can include the use of eco-certifications and generic promotion for regional or national agencies can be of significant contribution. In all, management practices need to have sustainability issued from a broad perspective, assessing profit, people, and the planet in a harmonic way.

9.5.2. Mitigation strategies: monitoring, structural and non-structural solutions

Making viticulture more sustainable can contribute to climate change mitigation, and examples of carbon-neutral production are already realities (Chiriacò et al., 2019). Sustainable viticulture management can lead to more resilient rural landscapes. Primarily, it is important to promote monitoring campaigns to investigate threats. The use of field/remote sensors can lead to detailed mapping and guide mitigation strategies. Among the most interesting measures are the conservation agriculture (CA) guidelines. They are proposed by the FAO to promote biodiversity and natural soil processes, thereby improving resource efficiency. It is based on three principles: minimal mechanical soil disturbance, permanent organic soil cover and crop diversification. More resilient viticulture should gradually include these practices in the cultivation process and adopt nature-based solutions. For steep-slope vineyards, the cover crop is a crucial practice. Grass can help mitigate erosion by protecting the soil from drops, erosivity, and surface runoff. An alternative solution may be mulching, which can be carried out using crop residues such as leaves or chipped branches (Keesstra et al., 2018). In the case of slope instability, an interesting solution is the installation of wooden reinforcement structures. They can be paired with live plants to increase the stabilizing effect through the root system (Sonnenberg et al., 2012). However, on steep slopes, agricultural terraces are still the optimal solutions as they include a wide range of ecosystem services (Xiong et al., 2018). For lowland vineyards, water stagnation is a major issue. The process can be mitigated by adopting specific solutions, such as surface drainage systems. To be functional, they must be constantly monitored through a maintenance programme. Alternative solutions involve sub-surface processes systems, useful to remove deep water by mechanical pumps in wells or by deep tillage. Mitigation strategies for climate change impacts must also consider biodiversity to ensure maximum soil functionality. The selection of indigenous grass mixed with polliniferous species can promote biodiversity and support the vineyard agroecosystem (Straffelini et al., 2022). Other solutions can be adopted to optimize water resources. In this case, water availability during severe drought increases, and biodiversity in agricultural areas is promoted, ensuring habitat development in the rural landscape. An example is the implementation of a network of wetlands, often recognized as among the most effective nature-based work.

9.5.3. Sustainable Development Goals and future challenges

Global climate change is affecting wine producers in different areas worldwide. To guarantee the survival of this activity, especially in Cultural Landscapes with a long winegrowing tradition, it is essential to plan for resilient rural management right now. Adapting human activity to a more sustainable future must be a globally shared pathway inspired by solid principles. Among the most ambitious benchmarks are the SDGs. They identify critical social and environmental issues on human and natural themes, indicating resolution strategies and tools to measure progresses. The SDGs can inspire new solutions to make viticulture in Argentina more resilient to global changes (Figure 9.6). SDG-2 is established to improve food security and promote sustainable agriculture. The scientific community must promote the transformation of intensive viticulture towards more sustainable production processes. For example, to limit soil erosion while ensuring its fertility and integrity in a vineyard on the slope, it is recommended to implement a soil cover in the inter-row, avoiding bare terrain. Sustainability means efficiency. SDG-6 aims to improve water use efficiency in human activity, including agriculture. With the aridification of large agricultural areas worldwide (Wang et al., 2022a), this issue must be central to long-term wine sector planning. The sparing use of water should be preferred both in lowland areas, most affected by increasingly frequent droughts and on the slopes of the Andes. Vineyards must become hi-tech by implementing systems that indicate to farmers when and where to irrigate. Remote sensing and sensor technology offer new opportunities compared to the past. Argentinian growers can exploit new technologies to implement precision farming systems, such as using high-resolution cartography for surface process mapping and monitoring vine health. Innovation and the use of renewable forms of energy must be at the heart of future viticulture, as indicated by SDG-7 and SDG-9. Solutions can come from the intelligent exploitation of slope microtopography to locate water deposits that can act as emergency reservoirs in extreme drought and as biodiversity incubators, as promoted by SDG-15. It will also be important to avoid monoculture, favoring landscape mosaicisation through implementing other secondary crops and careful design of ecological corridors. Especially for new plantations on Andes slopes, it is advisable to cultivate vines in a complex landscape, where vineyards are integrated with forest areas and rich in water and soil conservation measures. These recommendations could be helpful in making viticulture more sustainable and in laying the foundation for more hydrogeological safe land.

9.6. Conclusions

Climate change alters the environmental conditions that make some areas of the planet particularly

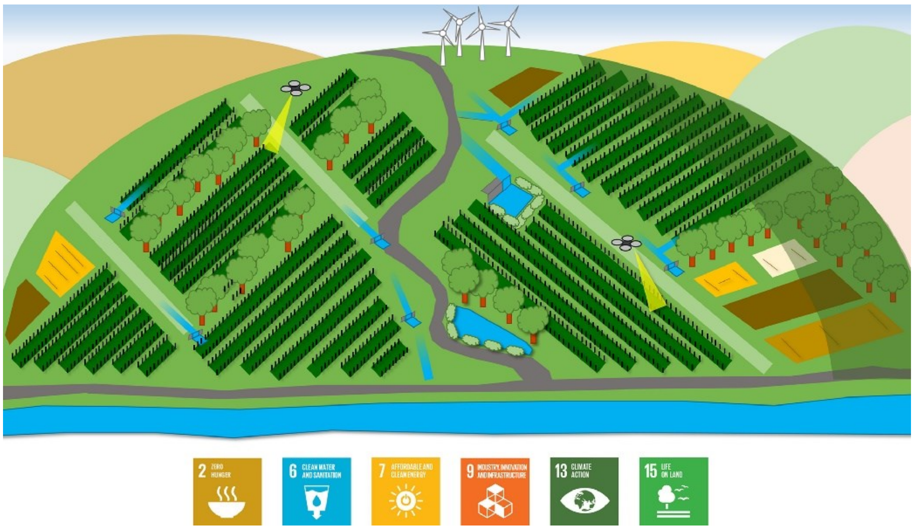

Figure 9.6 – Illustration of a vineyard landscape in which production needs are combined with the guidelines of SDGs. The vine plants (dark green rows) are integrated with the cultivation of other crops (in brown) and natural areas (represented with trees) to ensure biodiversity and ecological corridors. Sustainable water resource management allows to collect water to face drought periods using micro reservoirs while ensuring the survival of aquatic habitats in a pond system. Finally, cultivation must embrace innovation, such as monitoring with remote sensors and preferring energy from renewable sources.

suitable for cultivating vine plants and producing quality wines. This is the case for viticulture in Argentina, especially in Mendoza, home of internationally recognized wines. Increasingly arid climatic conditions, characterized by periods of drought and intense heat waves, are driving farmers to create new vineyards uphill to the slopes of the Andes. A more favorable climate and rainfall regime help preserve production rates, which are increasingly difficult to achieve in the lowlands. However, new threats arise. Among the most worrying phenomena is the increase in extreme rainfall observed in the last few years. Especially on steep slopes, they can cause runoff and subsequent soil erosion, with severe consequences for the integrity of the vineyards. It is worthwhile to understand the new challenges to enable optimal adaptation to the new conditions and ensure the resilience of local viticulture. Sustainable management of water resources, including using new technologies for high-resolution monitoring combined with precision irrigation, can help meet the challenge of climate change adaptation in these important wine-growing areas, both in severe rainfall and lack of water.

10. Remote Sensing & Hydrological Modelling for a Sustainable Management of Traditional Vineyards

Context

While humans are developing solutions to address global environmental changes, unsustainable practices are increasingly threatening agricultural Cultural Landscapes. This section focuses on traditional viticulture, which is becoming increasingly vulnerable due to climatic changes and evolving agricultural techniques. Traditional viticultural practices, such as terracing and manual labor, are being replaced by mechanized operations intended to enhance efficiency. Although mechanization boosts productivity, it can also lead to soil compaction, increased surface runoff, and erosion, factors that pose challenges to both the environment and the cultural heritage of these landscapes. Understanding the impact of these management practices on the resilience of viticultural Landscapes to extreme weather events, like heavy rainfall, is crucial for assessing their ability to adapt to climate change. This chapter explores how different management strategies affect the resilience of these landscapes in the face of global environmental changes. By comparing the effects of conventional versus lightweight machinery on soil processes and landscape stability, the study aims to offer insights into how human interventions can either mitigate or exacerbate vulnerabilities in culturally significant areas. Such understanding is essential for developing sustainable practices that enhance the resilience of these landscapes to ongoing environmental changes.

The article

This section is based on the conference paper published in 2022 in the *IEEE Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)* titled "*Viticulture and Cultural Landscapes: remote sensing and Earth surface processes modelling to promote sustainable agricultural practices*".

> This paper primarily addresses SO-C by exploring how unsustainable practices, such as heavy mechanization, exacerbate soil erosion in traditional vineyards during extreme rainfall events. The study uses remote sensing and hydrological modeling to suggest more sustainable management practices, highlighting the impact of human interventions on the resilience of these Cultural Landscapes. In doing so, it also partially contributes to the broader understanding of SO-B due to extreme rainfall events.

PEER-REVIEWED & PUBLISHED CONFERENCE PAPER

Viticulture and Cultural Landscapes: remote sensing and Earth surface processes modelling to promote sustainable agricultural practices

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CRediT authorship contribution statement:
Eugenio Straffelini: conceived and designed the research; wrote the first draft, and edited the manuscript and figures

Abstract

Viticulture, when practised in its traditional form, can contribute to creating unique Cultural Landscapes. Several examples exist worldwide, often included in specific protection lists that aim to protect and promote them (such as UNESCO and GIAHS). The complex morphological characteristics of these territories, resulting from centuries of human-nature interaction, make them fragile and susceptible to external disturbances. Among the responsible for serious impacts are the surface processes triggered by heavy rainfall. It causes direct effects on the landscape, from soil erosion to collapses of rural structures to vast areas of land degradation. This phenomenon is accelerated by two factors. The first is climate change, with an increase in the frequency of extreme rainfall events; the second is unsustainable human development, which is reflected in agricultural practices. Of considerable interest is the issue of soil compaction caused by the transit of agricultural machinery. In addition to purely agronomic problems, this is associated with increased surface runoff and resulting issues. Therefore, it is necessary to promote lighter machinery, at least for small agricultural duties. Although innovation is making great strides in the mechanical sector, there is still much to be done in understanding what the benefits in terms of surface processes of using light machinery in viticulture might be. This investigation encourages research in this direction, proposing a remote sensing and modelling approach based on data collected in the field and surveyed using UAV-SfM. The goal of the paper is to evaluate the advantages of using a lightweight prototype for vineyard cultivation compared to a traditional competitor. Firstly, the work attempts to assess the critical precipitation thresholds that activate surface runoff for two rows of an experimental vineyard, one operated with a light prototype and the other with a traditional tractor. In addition, the work simulates a recent critical rainfall event that occurred in the vineyard and diagnostically compares the two study rows. Research outcomes aim to stimulate technological innovation toward more sustainable light mechanisation, as well as to raise farmers' awareness of their primary role in preserving cultural agricultural Landscapes.

Keywords. Cultural Landscape, Climate change; Anthropogenic impact, Remote sensing, Hydrological modelling

10.1. Introduction

Viticulture is a worldwide popular agricultural cultivation. When it is practised in its traditional form and is deeply rooted in the culture of an area, it creates a Cultural Landscape. The term describes a broad and complex concept, first developed in 1925 and subsequently adopted by UNESCO in 1992. They are defined as the combined work of man and nature that describes a long relationship between peoples and their natural environment (UNESCO, 1992). Besides being witnesses of ancient traditions, they are also economically interesting thanks to the direct marketing of their products and high potential tourist attractions. Often, Cultural Landscapes are included in special protection lists, designed to preserve their authenticity, and promote them internationally. The main ones are the UNESCO list and the GIAHS (Globally Important Agricultural Heritage Systems) sites. Some vineyard landscapes perfectly fit into this definition, such as the Alto Douro region in Portugal, Palestinian areas south of Jerusalem, the French Champagne hills, or the Italian Soave wine regions. Vines are often cultivated on steep slopes, mainly for better climatic conditions. Indeed, the plants receive more effective sunlight, increasing their growth rate (Greer and Weedon, 2012). In traditional viticulture ("*heroic viticulture*" when it takes place on very steep slopes), agricultural terraces are often used. Numerous authors have emphasised the benefits of this practice, widespread worldwide for different cultivation purposes. Terraces are providers of ecosystem services and promote biodiversity in the agroecosystem. They provide optimal water resource management in sloping conditions, regulating surface runoff, and favouring water utilisation (Wang et al., 2022b) . This fact is of considerable interest to Cultural Landscapes. Indeed, in their morphological complexity (the result of centuries of history) terraced slopes are in a delicate balance with their surroundings and climatic conditions, making them susceptible to external disturbances (Tarolli and Straffelini, 2020). Climate change and unsustainable anthropogenic development may impact Cultural Landscapes. Numerous studies indicate that global climatic conditions are significantly changing due to human activity, from rising temperatures to precipitation disturbances (IPCC - Intergovernmental Panel on Climate Change, 2021). On the one hand, droughts and heat waves threaten viticulture worldwide, such as in 2022 for European vineyards. On the other hand, there are extreme rainfalls. Global climate models predict a future with less precipitation (more dry periods) but stronger rainfall events (Padilla et al., 2019). They are critical disturbances to wine-growing Cultural Landscapes due to the severity of surface processes. Of significant importance are the impacts caused by runoff and the subsequent occurrence of soil erosion. Among the most significant impacts in such landscapes is dry-stone wall collapses, slope failures/instabilities and reduced fertility (Novara et al., 2018). This

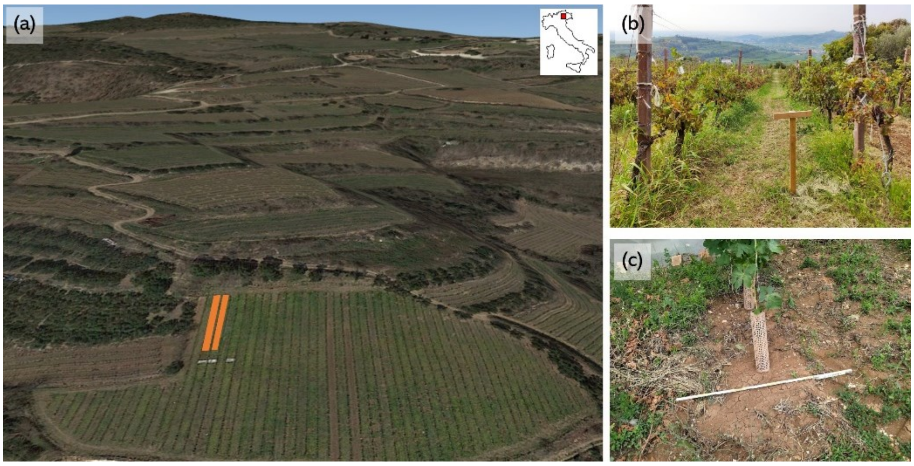

Figure 10.1 – (a) Location of the two study rows in their geographical context. Source: Google Earth Pro. (b) The vineyard where the experiment was carried out. Photo by Eugenio Straffelini; (c) Soil sediment deposited within an inter-row due to heavy rainfall. Photo by Eugenio Straffelini.

condition is worsened by unsustainable human activity. In traditional vineyards, field management operations have been performed manually for centuries. Nowadays, these techniques are often replaced by mechanisation. The technological revolution that occurred in 50' asked farmers to adapt their vineyards to welcome innovation. The first problem is the alteration of the vineyard layout. In fact, to make the fields more suitable for mechanized operations, terraces are sometimes flattened in favour of cultivation along the steepest slope. This practice can be problematic when extreme rainfall occurs. Firstly, higher magnitudes of hydro-erosive processes have been documented in such vineyards (Pijl et al., 2022); secondly, if morphological alteration occurs in areas where traditional viticulture survives, the cultural heritage may be compromised. Notable are damages caused by inefficient agricultural road networks, which can lead to critical overland flow concentration, soil erosion and shallow landslides. Also, tyre pressure on the ground can cause significant soil compaction. This is a serious problem in agriculture, as it compromises the root system and influences soil hydrology. Several studies focus on this aspect in viticulture, emphasising the increased generation of surface runoff (Capello et al., 2019). Therefore, there is a need to promote soil compaction mitigation strategies, including using light machinery that can limit tyre pressure. For example, some studies focus on using innovative prototypes using batteries for light agricultural duties (Redpath et al., 2011). Although scientific literature and technological innovation have advanced in the study of sustainable solutions for mechanical processing in agriculture, there is still much to be done in understanding the benefits of light machinery in viticulture regarding Earth surface process mitigation. Innovative solutions could be found in hydrological modelling. In fact, some physical models allow the simulation of the hydrological response of agricultural soils to an input of intense precipitation. In this way, it is possible to estimate surface runoff and soil erosion/deposition, according to specific soil characteristics. Among the most popular models, we can mention the Watershed Erosion Prediction Project (WEPP) (Laflen et al., 1991), Kinematic Runoff and Erosion Model (KINEROS) (Smith et al., 1995) and Simulation Water Erosion (SIMWE) (Mitasova et al., 2004). However, detailed microtopography information is essential to obtain realistic results and offer reliable data for decision-making. Photogrammetry combined with drones (UAV-SfM) can be a suitable solution. The technique is widely used to survey agricultural soils and allows for rapid and cost-effective mapping of surface processes.

In this paper, we propose the application of the SIMWE hydrological model to quantify the mitigation of hydroerosive processes achievable by using a prototype light tractor that avoids excessive soil compaction compared to a conventional tractor. The benefits are estimated in two ways. The first, by analysing the critical threshold of precipitation intensity that triggers surface runoff and erosion; the second, by assessing the surface processes mitigation simulating an intense precipitation recorded in the vineyard in 2020. The objective is to quantify the hydrogeological benefits that can be obtained from this solution and to stimulate a technological innovation capable of protecting the soils of agricultural Cultural Landscapes.

10.2. Material and Methods

9.2.1. Study area

The vineyard where the research was carried out is located in northern Italy, in the Veneto region. It is part of the GIAHS 'Soave Traditional Vineyards' site, a Cultural Landscape where heroic viticulture has survived for centuries (FAO, 2021). The vines are planted along the slope line on a hill managed with different vineyard layouts, mainly terraces (Figure 10.1). For the experiment, two homogeneous inter-row plots of 35 m length, 2.5 m width, 28% slope and grass cover (high-percentage Medicago sativa) were identified.

9.2.2. Comparison of operating machinery

The experiment involves modelling runoff and soil erosion in two inter-rows cultivated with two different machines. The first, used regularly on the farm, is an orchard tractor with a width of approximately 140 cm, a gross weight of 2040 kg and 360/70 R24 tyres. The second is a lightweight (450 kg) tracked prototype designed for small agricultural tasks. It has a width of 1.3 m and is equipped with two 30 cm wide crawler tracks. The average pressure exerted on the soil by the conventional tractor is 0.98 kg/cm^2, while that of the prototype is reduced to 0.07 kg/cm^2. This feature allows it to significantly limit the pressure exerted on the soil, preventing excessive compaction (Erbach, 1994). In each of the inter-rows, one of the two machines was tested, thus allowing a diagnostic comparison. To avoid bias, both plots were mechanically weeded using roto-tillers at the start of the experiment.

9.2.3. Field Surveys

Field surveys were carried out to acquire model input data. Precipitation was measured with a rain gauge installed on the farm, which provides data at a 1-5-60 minute interval. The saturated hydraulic conductivity was investigated for both plots using the double-ring infiltrometer for WTT (wheel tracks - conventional tractor), WTP (wheel tracks – prototype), IR (inter-row) and VI (vines). The method, which has already been applied by other research in this area, offers values in a cost-effective and efficient manner (Lai and Ren, 2007; Straffelini et al., 2022). The infiltration test was repeated several times during the course of the experiment, averaging the values obtained (Table 10.1).

Table 10.1. Infiltration rate values measured using double-ring infiltrometer in the experimental vineyard.

	WTT	WTP	VI
Infiltration rate (mm h^{-1})	3.6	12.4	18.3

A Digital Elevation Model (DEM) was constructed using the UAV-SfM technique. The survey was carried out with a DJI Matrice210v2 drone equipped with the DJI Zenmuse X4S camera (20 M pixels, focal length 8.8 mm, 1-inch CMOS sensor) and a Geomax Zenith40 GNSS (XY-accuracy: 0.02 m; Z-accuracy: 0.03 m). A total of 290 images were taken over an area of approximately 0.10 ha. The data were subsequently processed with Agisoft PhotoScan Pro® 1.4.5 software to create a DEM (resolution 0.10 m) and orthomosaic (resolution 0.05 m). UAV-SfM performances are calculated according to (Remondino et al., 2017) (Cucchiaro et al., 2019) and indicated in Table 10.2. The error analysis shows that the digital model used is sufficiently accurate for hydrological and soil erosion modelling. In fact, understanding the micro-topography of the vineyard makes it possible to further investigate the generation of surface processes, providing information appealing to farm management improvement.

Table 10.2. Errors estimation on the (a) point cloud and on the (b) DEM.

(a)

Accuracy CPs				Precision CPs			Registration on GCPs
MAE (m)			RMSE$_{3D}$ (m)	SDE (m)			RMSE$_{3D}$ (m)
X	Y	Z		X	Y	Z	
0.007	0.013	0.009	0.032	0.007	0.008	0.014	0.028

(b)

MAE (m)	ME (m)	SDE (m)	RMSE (m)	Median (m)	NMAD (m)
0.036	0.003	0.008	0.019	-0.001	0.005

9.2.4. Model application and critical threshold assessment

In this research, the physically based model SIMWE was used to evaluate surface processes of runoff and soil erosion following (Straffelini et al., 2022). It is based on two components integrated into the GRASS-GIS software. The first component simulates the hydrological component, while the second simulates soil erosion (r.sim.water and r.sim.sediment, respectively). SIMWE works using a single rainfall event as input, together with other descriptive parameters of soil characteristics. The main ones are the DEM (m), soil water infiltration (mm h^{-1}), Manning's roughness coefficient (-; literature value), soil detachment capacity (s m^{-1}; literature value), transport capacity (s; literature value) and critical shear stress (Pa; literature value). The outputs used in this work are overland flow discharge (m^{3}s^{-1}) for the liquid component, and sediment concentration (particles per m^3) for the solid component. Two rainfall events were simulated. The first was the minimum rainfall value for which the model generated runoff and erosion, obtained by iterative model execution via code scripting. The second referred to the precipitation intensity of 102 mm h^{-1} (1-minute step) which caused serious damage to the vineyard in 2020 (for more information regarding the events please refer to: https://blogs.egu.eu/divisions/nh/2020/12/21/climate-change-is-viticulture-under-threat/).

Statistical comparison of the results was made using a one-way ANOVA test to capture significant differences between managements and post-hoc Tukey-Kramer test to perform the comparison. Outputs allow to (1) quantify the differences in terms of critical rainfall intensity between the row managed with a conventional tractor and one with a light prototype (identification of rainfall intensity threshold); (2) measure the benefits of using a light prototype in the event of intense rainfall in terms of runoff and erosion. Model results were evaluated by field observation. However, the methodology has been applied several times in other recent research in the study area (Pijl et al., 2022; Straffelini et al., 2022). Since the aim of the study is a diagnostic evaluation of two different practices, any possible bias caused by a modelling approach is therefore negligible, as it affects both analysed inter-rows.

10.3. Results and Discussion

The first result of the SIMWE model is the identification of critical thresholds for the activation of processes occurring on the surface for the two study inter-rows. The model shows that in the inter-row managed with the prototype, a higher critical rainfall intensity is required to activate the runoff and soil erosion, compared to the conventional tractor. Specifically, 29 mm h^{-1} (1-minute step) are required to activate runoff in the inter-row operated with a conventional tractor, compared to 36 mm h^{-1} (1-minute step) for the one operated with the prototype (24% of difference; p-value < 0.05). Similar results were observed for the erosion process, described by the model as sediment concentration (particles per m^3). The simulations indicate that a 94% (p-value < 0.05) higher rainfall intensity is required for the movement of soil particles in the inter-row managed with the prototype (66 mm h^{-1} 1-minute step) than in the one managed with a conventional tractor (34 mm h^{-1} 1-minute step). Figure 10.2 offers a graphic visualisation of the results. To appreciate the processes mitigation, the left-hand side of the figure shows simulations for critical rainfall thresholds that activated surface runoff (36 mm h^{-1} 1-minute step) and erosion (66 mm h^{-1} 1-minute step) in the inter-row processed with the prototype. As can be seen from the colour scales, with rainfall intensity triggering processes in the row worked with the prototype, runoff and erosion are higher in the inter-row worked with the tractor. Similarly, the left part of the figure simulates the extreme rainfall that occurred in the vineyard in 2020, with an intensity of 102 mm h-1 (1-minute step). Again, more severe processes can be observed in the row managed with a conventional tractor. In addition, evident is the role of machinery footprints in the formation of surface processes (note the example in the figure 10.2). Results are mainly determined by better water infiltration performance in the soil in the row managed with light prototype. It is also remarkable that a considerable reduction in soil pressure between the two machines is reflected in a not so marked increase in water infiltration. Therefore, it is advisable to couple light mechanisation with sustainable soil management, such as specific tillage and the use of suitable herbaceous species (Straffelini et al., 2022). Although the approach has already been used successfully in the same wine-growing area, the method could be affected

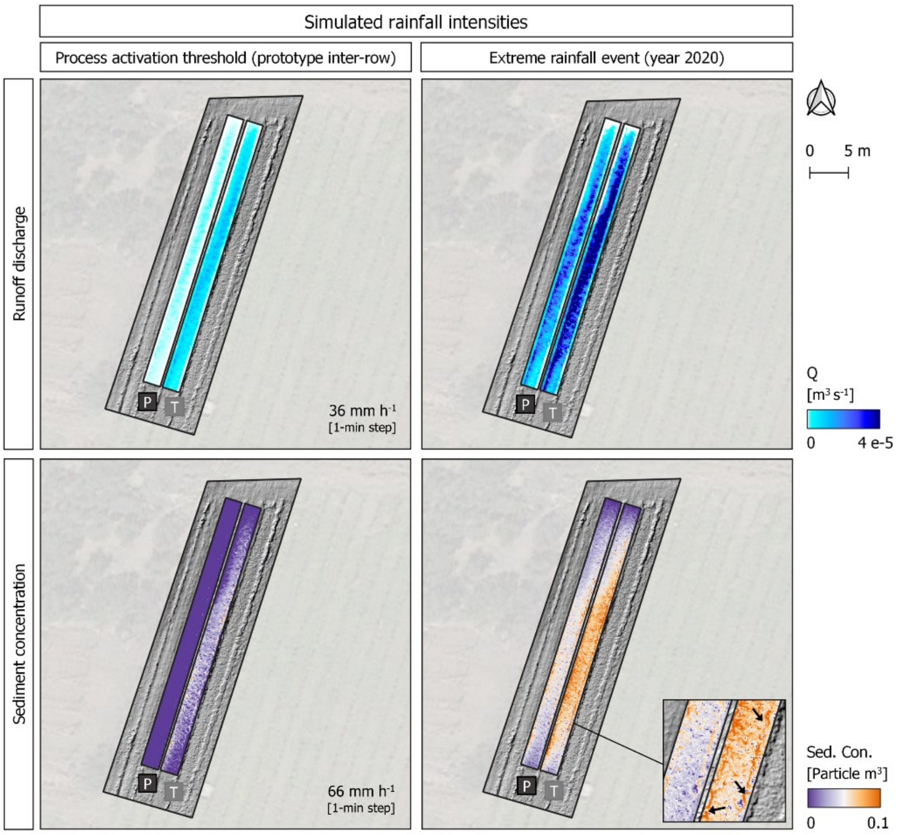

Figure 10.2 – SIMWE model results for runoff and sediment concentration, for the row processed with the prototype (P) and with the conventional tractor (T). The left-hand side shows the simulation results with the critical rainfall intensity required to activate the processes in the P row (note that at this rainfall intensity the processes are more severe in the T row). The right-hand side shows the simulation of the extreme weather event affecting the vineyard in 2020. The bottom right box shows an enlargement of the sediment concentration simulation. Notice the higher values at the tractor tracks (black arrows).

by certain biases. The first is determined by the use of a physical model, which despite efforts can incorporate inaccuracies. However, the purpose of the work is to understand the benefits of one processing rather than the other for diagnostic purposes, so any error is repeated in both scenarios, making it acceptable. In addition, the determination of precipitation thresholds is valid for standard environmental conditions, i.e. dry soil and heavy rainfall. As these conditions change, there may be consecutive threshold variations. Interesting future research could investigate this variation to study even more detailed solutions for other study areas.

10.4. Conclusion

The research aims to investigate the mitigation of surface runoff and soil erosion processes in two different inter-row of an experimental vineyard, one managed by a conventional tractor, the other by a light prototype. The work is based on results simulated using the SIMWE hydrological model, which uses as input a high-resolution DEM from UAV-SfM and infiltration measurements determined by means of a double-ring infiltrometer. The results show that the use of light agricultural machinery leads to an increase in the critical rainfall intensity required to activate processes in the vineyard compared to the use of a conventional tractor. Adopting lightweight solutions contributes significantly to making these vineyards more resilient to extreme weather phenomena. This fact is very important in view of climate change and the increased frequency of such events. This research attempts to stimulate scientific exploration for the promotion of new lightweight and sustainable machinery and to raise farmers' awareness of their central role in protecting agricultural Cultural Landscapes.

11. Sustainable Water Resource Management in Steep Slope Agricultural Cultural Landscapes

Context

This chapter focuses on the critical role of cultural steep-slope agricultural Landscapes, which are not only vital for food production and biodiversity but also serve as living testaments to human ingenuity and adaptation. Central to this chapter is the exploration of how human intervention in water management can either exacerbate or mitigate these climate-related challenges. The sustainable management of water resources in these steep-slope environments is essential for maintaining their productivity and resilience. By integrating traditional knowledge with modern technological advances, such as high-resolution remote sensing and GIS-based modeling, this chapter offers strategies for optimizing water use in such Cultural Landscapes. These approaches are strategically designed to counteract the impacts of climate change, which are increasingly manifesting in this agricultural domain. Integral to the management strategies is the incorporation of indigenous knowledge, which uniquely contributes to water conservation efforts, thereby enhancing the overall resilience of these landscapes. This chapter highlights the dual potential of human actions in these landscapes: to either worsen or alleviate the impacts of climate change, thus ensuring their sustainability for future generations.

The article

This chapter focuses on the perspective paper (open access) titled: *"Sustainable water resource management in steep-slope agriculture"*. It was published in 2022 in the peer-reviewed journal *"Geography and Sustainability"* (*Q1 in Geography, Physical, and Green & Sustainable Science & Technology; IF 2022: 9.7*). Within the scope of this chapter, the primary focus lies on delineating sustainable approaches to managing water resources specifically within the context of steep-slope agriculture, including Cultural Landscapes.

> The article primarily addresses SO-C regarding the role of human practices in worsening and/or mitigating the impact of climate change on agricultural Cultural Landscapes. It also partially addresses SO-A and SO-B by examining how traditional knowledge, combined with modern technological advances, can mitigate the impacts of climate change, including drought and extreme rainfall, on these culturally significant landscapes.

PEER-REVIEWED & PUBLISHED PERSPECTIVE ARTICLE

Sustainable water resource management in steep-slope agriculture

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Eugenio Straffelini: W.W. and E.S. equally wrote the first draft, and edited the manuscript and figures.

Abstract

Steep-slope agricultural Landscapes are under threat due to climate change. On the one hand, the growing frequency of extreme high-intensity rainfall events concentrated in both temporal and spatial scales are causing flash floods or slope failure risk scenarios. On the other hand, future climate projections indicate a significant expansion of arid zones in the steep slope agricultural system. There is evidence that these landscapes face a high risk of growing water scarcity. Considering their unique role in crop production, ecosystem diversity, and crop production, ecosystem diversity, and cultural heritages, understanding sustainable water resource management for mitigating climate change-induced drought has never been more urgent than today. In these landscapes, unique indigenous knowledge of water conservation is adopted to manage water resources improving their resilience optimally. It is, therefore, necessary to promote water storage to mitigate floods or increase the resilience to prolonged drought (creating at the same time favourable conditions for biodiversity). Modern technological advances (e.g. high-resolution remote sensing and GIS-based modelling) are crucial in supporting these activities and understanding earth's surface processes.

Keywords: Steep slope agriculture; Water; Climate change; SDG

11.1. Steep-slope agriculture: food-producing systems, historical heritage and ecosystem services under threat

Steep-slope agriculture landscapes refer to the cultivated agricultural area with slope values above 7° (Wang et al., 2022a). Agricultural landscapes cultivated in hilly and mountainous regions represent intensive food-producing systems, historical heritage and cultural ecosystem services recognised by society. For example, agriculture on the steep slopes of tropical America can produce more than 30% of the crop, supporting more than 40% of the farmers' life (Posner and McPherson, 1982). In Italy, terraces are one of the most important factors affecting crop production and economic development (Pijl et al., 2020). Farmers in Nepal have cultivated maize and potato on steep slope agriculture as the primary source or supplement of staple food for generations (Joshi and Shrestha, 2020).

FAO initiated the Globally Important Agricultural Heritage Systems (GIAHS) programme to protect, preserve and manage traditional agricultural knowledge and the landscapes they developed. An example is the GIAHS site of Soave's traditional vineyards (North of Italy), where agriculture has been practised through a sustainable management system that contributed to the uniqueness of the landscape (Figure 11.1). Here, the so-called 'heroic agriculture' system survives on steep terraced slopes designed and constructed according to historical techniques. On the one hand, this traditional management practice is very fragile as terraces are intrinsically fragile and susceptible to hydrogeological risk. On the other hand, unsustainable management (land abandonment, heavy mechanization etc.) and climate change have exacerbated land degradation in steep-slope agriCultural Landscapes (Tarolli and Straffelini, 2020). Water scarcity is a common issue associated with the cultivation of steep hillslopes due to agricultural and domestic water withdrawals and climate change (Figure 11.2, left-hand side (Alcamo et al., 2007; Tarolli and Straffelini, 2020)). Projected future spatial-temporal rainfall variations are widely confronting farmers with the risk of drought, as increased seasonality and meteorological unpredictability challenge the sustainability of water resources management (Arnell et al., 2019; Easterling

Figure 11.1 – Soave's traditional vineyards cultivated on steep-slope landscapes (FAO-GIAHS site, North of Italy; photographs by P. Tarolli).

et al., 2000; Iglesias et al., 2011; Rosenzweig et al., 2004). A widespread agricultural impact of climate change is the reduction of water availability in irrigation systems. Climate change-induced drought causes a global average loss of at least 60 billion dollars annually (Ma et al., 2017). For example, in 2009, the Yunnan Province of China experienced the worst drought in 50 years, and 4.9 million hectares of agricultural land and drinking water for about 9.65 million people were severely affected (Ma et al., 2017; Wu et al., 2017). In addition, it is reported that central America, China, Mediterranean area, where the steep slope agriculture systems are widely distributed, were largely affected by flash droughts (phenomena characterized by a period of rapid drought intensification with impacts on agriculture) from 1980-2015 (Christian et al., 2021). Jiao et al. (2021) documented that global vegetation water deficit areas significantly increased from 1982 to 2015. Extreme climatic conditions also impact substantially soil moisture and groundwater that are closely related to food production and ecosystem services (Joshi and Shrestha, 2020; Qiu et al., 2019). Aside from water scarcity, drought can also result in a loss of soil resources (Figure 11.2, red labels) due to the reduced cohesion by vegetation (Gyssels et al., 2005) and crusting of the topsoil layer (Arnáez et al., 2015).

The challenge of growing aridity is paralleled by the increasing likelihood of extreme rainfall (Figure 11., right-hand side) due to a widespread increase in frequency and intensity of precipitation in the 21st century (IPCC, 2019). Consequently, growing runoff rates are expected to challenge the sustainability of soil and water management in agriculture (Tarolli and Straffelini, 2020), e.g. by causing soil erosion, mass movement, and flood risk (Figure 11.2, red labels). Furthermore, rainfall distribution in steep-slope areas varies dramatically within short distances due to the interaction between climate and topography. In some coastal areas, the precipitation on the windward slope exceeds 10,000 mm a year, while the rainfall on the leeward slope is sometimes only 50 mm. Due to the combination of a changing climate interaction and the local topographic setting, steep cultivation systems tend to be largely affected by drought or excessive rain more than other land uses.

11.2. Towards sustainable water management practices

11.2.1 Improved water storage and other structural solutions

Resilient water management systems play an important role to maintain agricultural productivity and mitigate the detrimental on-site and off-site environmental impacts, e.g. by harvesting and storage (Figure 11.2, light-blue labels; Figure 11.3). Sustainable structural solutions can improve water availability over extensive drought periods and effectively reduce the loss of on-site soil resources by soil erosion, landslides, debris flow, and other forms of land degradation (Tarolli et al., 2014). During extreme rainfall events, water resource management such as ponds, hillslope terracing, drainage systems (e.g. roadside drainage, terrace drainage, etc.) and dams are essential to flood and soil erosion control measures (Rockström and Falkenmark, 2015). A relevant example can be found in the steep agricultural Landscapes of the Loess Plateau (P.R. China), where more than 58,446 check dams have been constructed for water and soil conservation and sustainable agriculture (Wang et al., 2018). Moreover, the buffering of water flow has off-site benefits, e.g., reducing flood risk or sediment deposition in mountainous river systems (Mohammed et al., 2022; S. Yuan et al., 2022). It is clear that suitable water

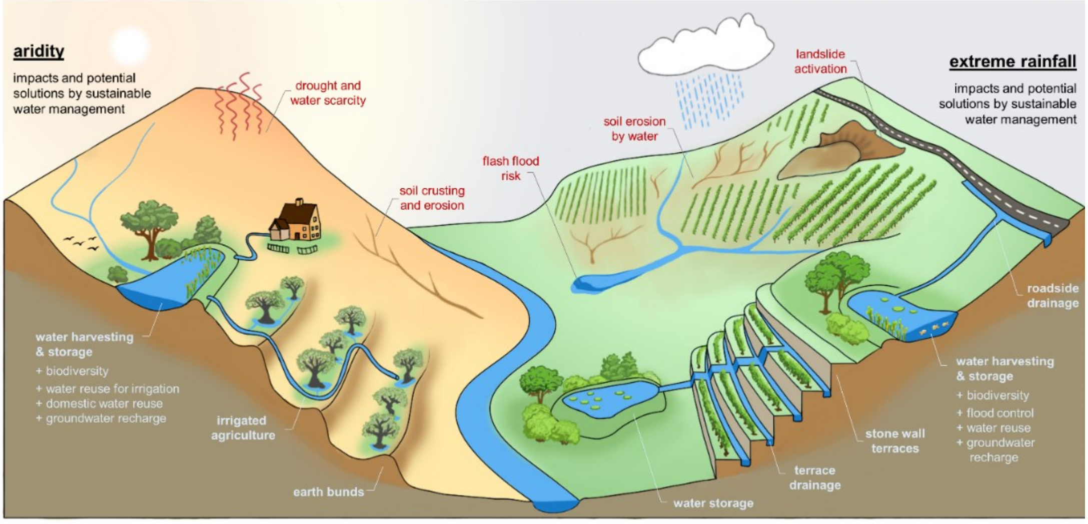


Figure 11.2 – This illustration depicts two key climatic challenges in steep-slope agriculture: increasing aridity (left) and extreme rainfall (right). Red labels highlight impacts such as drought or flood risk, while light blue labels showcase sustainable water management solutions, like water harvesting and storage, to mitigate these climate effects.

(a)

(b)

Figure 11.3 – Water reservoir infrastructure in the vineyards of Soave FAO-GIAHS site, Italy (photographs by Wendi Wang).

storage and management effectively saves water resources and provide multiple goods and services (e.g. fish production, water supply, groundwater recharge and biodiversity) in sustainable agricultural development and ecosystem services (Aeschbach-Hertig and Gleeson, 2012; K.K. Garg et al., 2022; Hu et al., 2016). In drylands, engineered soil and water conservation structures (e.g. earth bunds) and water storage benefit to biodiversity, irrigation water reuse, and groundwater recharge (K.K. Garg et al., 2022).

Some engineering fortified settlements (e.g. stone wall terraces) are significant in water resources management for supporting a more resilient agrarian society. For instance, Konso Cultural Landscape represents an outstanding example of adaptation to a dry hostile environment of more than 400 years with ancient stone wall terraces. The 5-meter-wide dry-stone wall built of locally available rock plays a considerable role in maintaining water and soil, collecting rainwater, draining excess water, and creating agricultural areas. In the South-West of Jerusalem, the Battir cultural terrace system with dry-stone architecture constitutes a spectacular example of how engineering practices have enabled to change of the deep valley system into the land for agriculture. The effective water distribution system is the main feature of the Battir agricultural systems and led to a good water supply (Wessels, 2015). Creating these dry walls terraces in the Battir cultural agrarian system is the basis for the perfect irrigation systems with good water supply (UNESCO, 2014). It is attested that this intact irrigation and drainage system (e.g. collection pool, channels, etc.), based on a simple mathematical analysis, would continue to benefit local people at least a millennium in the future (UNESCO, 2014). Another important example is the wide distribution of various indigenous water harvesting techniques (WHT), locally known as jessr are commonly distributed in Tunisia for water-saving and have been recognised as a helpful supplementary water resource during drought periods, such as drought and low soil fertility are the main causes of low land productivity in steep agriculture areas in Africa (Schiettecatte et al., 2005; Wolka et al., 2021).

Sustainable water management should also consider nature and ecosystem functions while focusing on agricultural diversification and landscape preservation. Ecological systems in steep areas face threats and challenges from many aspects due to human activities, natural disasters and industrial development. Dong's Rice Fish Duck System (P.R. China) is a spectacular representation of an agro-ecosystem that shows how local people respect the environment during their interaction with nature (FAO-GIAHS, 2022a). It is famous for being rich in bio-diversity and well managed by Dong minority through traditional practice for thousands of years. It produces more than 40 types of rice for the local area to meet the needs of daily life while also serving as a habitat provider for more than 100 kinds of animals and 200 kinds of wild plants (FAO-GIAHS, 2022a). Elsewhere, Pu'er Tea agricultural Landscape (P.R. China) is considered a complete, compact and self-sufficient agro-ecosystem of the largest tea tree communities. The landscape is the composition of economic crops, vegetables and free-range livestock with a multi-functional role for local agriculture, forestry, animal husbandry (FAO-GIAHS, 2022b). In addition, to protect this landscape and ensure the flavor of the tea, the local farmers avoid using artificial fertilizers and chemical interventions (FAO-GIAHS, 2022b).

Though several studies have shown the potential solution for agricultural systems, most of them are focused on how to improve the crop production by water harvesting technique (Piemontese et al., 2020), little is known about the role of water resource management (e.g. water storages, water harvest, drainage systems, etc.) in the mitigation of the effects

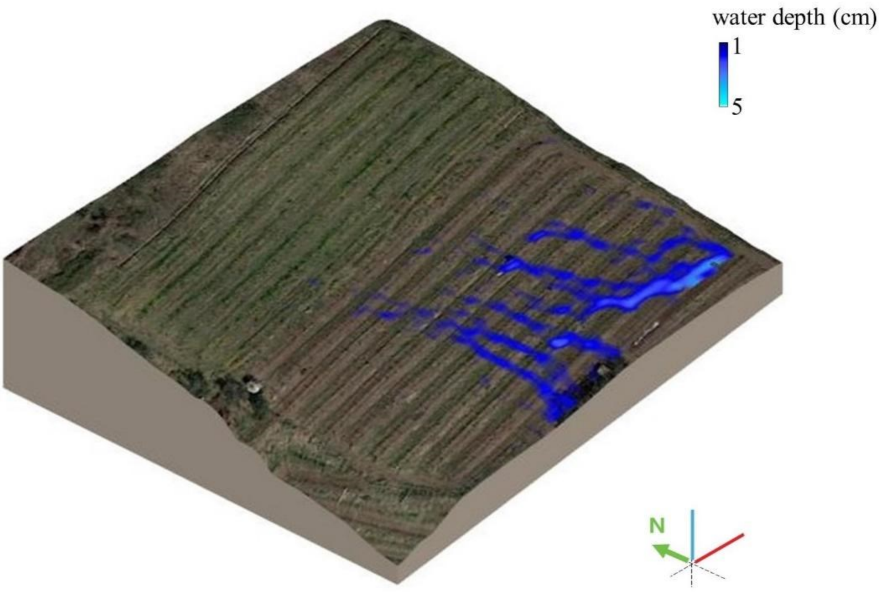


Figure 11.4 – A 3D example of simulated overland flowing a steep-slope agricultural system, based on high-resolution LiDAR topography data and the physical hydrological model SIMWE.

of climate change (e.g. extreme rainfall events and the long period of drought) for sustainable farming in steep slope agricultural Landscapes. For steep-slope agricultural areas, we need to understand and answer such important questions as i) which kind of water resource management can optimize the sustainability, social-ecosystem services as well we crop production in steep slope cultivation systems, and ii); How to manage rainfed cultivated hillslopes at different scale resilient to the long period of droughts in climatic condition.

11.2.2 Technological innovation and non-structural solutions

Technological innovation (e.g. high-resolution remote sensing techniques such as LiDAR (Light Detection And Ranging) and a photogrammetric survey by drones, or cloud computation and sharing platforms such as Google Earth Engine) offers unprecedented access to detailed spatial and temporal geo-data to guide the design of resilient water management systems in steep slope environments. Figure 11.4 illustrates a 3D example of simulated overland flow based on a real rainfall event (82.4 mm/h) with high-resolution LiDAR data and the physically-based hydrological model SIMWE (Mitas and Mitasova, 1998) in a small part of a vineyard (Soave, Italy). Simulations show a runoff concentration along the vineyard slope and accurately show the areas most susceptible to forming preferential pathways. The accurate and high-resolution simulations allow practical insight for designing diverse drainage systems and water storage. Such workflows have been previously demonstrated in comparing soil and water conservation impacts by different terracing systems (Pijl et al., 2020) or their drainage systems (Pijl et al., 2019b). GIS-based hydrological simulations and designs can furthermore be used to determine the water harvesting potential (Sekar and Randhir, 2007), optimal sizing (Vema et al., 2018), and optimal location of new water storage facilities in watersheds (Singh et al., 2017). While the relevance of protecting these landscapes is evident because of their diverse values and the high hydrogeological risks, research is biased toward developed countries (Tarolli and Straffelini, 2020).

Accurate monitoring and forecasting of drought severity have received increasing attention in recent years (Ma et al., 2017). For instance, (Wang et al., 2022a) quantified the impact of future climate change zones on steep slope agriculture. Using Google Earth Engine, they accurately predicted the percentage of areas at high risk of water scarcity in the future (2071-2100). This study has brought to light the urgency of sustainable water management practices in agricultural areas on steep slopes. Notably, the development of resilient water management in steep cultivation systems is not solely the result of scientific research, technological innovation, or efficient engineering design. Traditions, cultural practices, and indigenous knowledge in water resource management in these landscapes are often invaluable, as they naturally developed in response to their environment and site-specific conditions. In the Mediterranean area, where vineyards are widely spread, different types of nature-based solutions like organic farming mulches, geotextiles, cover crops, catch crops, chipped branches, no-tillage, managed rewilding, land restoration, etc. were applied for agricultural productivity improvement, climate change adaption, flood regulation, water provision (Cerdà et al., 2016; Keesstra et al., 2018, 2009). In Africa, grass strips, soil bunds and agroforestry were used for catching water and sediment from upstream for millennia (Keesstra et al., 2018; Vancampenhout et al., 2006). Studies have shown that these nature-based solutions can effectively reduce average runoff by 70%, reduce average soil erosion by 40-70% and increase crop yields on steep slopes by at least 20% (Wolka et al., 2018). Explicit inclusion of local, often marginalised rural communities is relevant for achieving resilient steep-slope agricultural systems.

As the implementers of the water resource management practice, it is necessary to recognise farmers' important role in the application and adaptation of water resource measurement. Water conservation techniques may be successfully carried out in experimental stations, but remaining low adoption rates on steep slope farmland in some countries such as Uganda (Piemontese et al., 2021). The information on potential agronomic and environmental benefits of planning water resource measurement can be delivered in a straightforward approach for local farmers before making an adaptation decision. There is a great demand for policymakers to strengthen the dissemination of new water conservation technologies, interaction between professionals and farmers as well as the increasement of farmer participation (Piemontese et al., 2021).

11.2.3 Sustainable Development Goals (SDGs) and future resilient steep-slope agricultural Landscapes

Agricultural expansion worldwide has created a few problems, such as declining carbon sequestration or water depletion in arid areas (Zeng et al., 2018). On the other hand, millions of people live on steep slopes, and their subsistence depends on agriculture in such areas. Sustainable agriculture is one meeting point for ensuring food security while respecting natural resources. Indications for mitigating water issues are already on the table. In 2015, the United Nations Member States adopted the 2030 Agenda for Sustainable Development. The document's core is a set of 17 Sustainable Development Goals (SDGs), a global and shared calling for improving life on Earth within 2030 by solving social and environmental problems. One of the Agenda's cardinal points is sustainability, the rational use of available resources to meet current and future needs. In the light of climate change and water scarcity threatening agriculture, this concept should guide any intervention in rural steep-slope environments.

This paper proposes an innovative conceptualisation of steep-slope agricultural Landscapes in a future scenario where water management will have embraced SDG principles (Figure 11.5). The first goal able to shape tomorrow's landscapes is the SDG2 (End Hunger), one of the most ambitious of the entire Agenda (Zhang et al., 2022). The role of steep slope agriculture is necessary as it ensures food production for millions of people worldwide (Wang et al., 2022a).

2.3 - Double the agricultural productivity and incomes of small-scale food producers […]

2.4 - Ensure sustainable food production systems and implement resilient agricultural practices that increase productivity, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters […]

- Increased use of sustainable farming practices, optimising water resources and increasing production efficiency
- Increased cultivated steep-slope areas by reclaiming abandoned farmland restoring drainages
- Slopes cultivated with native crops crossed by ecological corridors, limiting monocultures and pollutants in the water

6.4 - Substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity

6.6 - Protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes

- Agricultural slopes rich in water storages able to collect rainwater and making it available to farmers
- Enhancement of traditional farming systems capable of maximising water regulation ecosystem services
- Increased use of precision irrigation systems to optimise water resources

7.3 - Double the global rate of improvement in energy efficiency

7.a - Enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology

- Widespread use of clean energy systems on agricultural slopes
- Implementation of micro-hydroelectric plants for clean energy production; the systems can also operate with the runoff generated by extreme rainfall, limiting the associated hazard and making the water available for agriculture.

9.4 - Upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies […]

9.5 - Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries […] encouraging innovation

- Innovation & technology become an essential element of steep slope farming
- Use of high-resolution 3D models for mapping water-related terrain surface processes
- Widespread use of precision farming with in-situ/remote sensors for resource optimisation
- Improvement of road infrastructures in rural areas

13.1 - Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries

13.3 - Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning

- Slope farms embrace resistance & resilience measures thanks to improved stakeholder awareness about climate change
- Diffusion of nature-based solutions, coexistence of farming and sustainable silviculture, water storages drainage networks to face hydrogeological risk
- Early warning systems based on hi-tech sensors & remote sensing

15.1 - Ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services […]

15.3 - combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods […]

15.5 - Take urgent and significant action to reduce the degradation of natural habitats […]

- Slope farming balances food security with native land & water flora/fauna
- Widespread soil protection measures by herbaceous cover and nature-based anti water erosion solutions
- Spreading forested spots and wetlands on rural slopes to improve water management and protect biodiversity and habitats

Figure 11.5 – The Sustainable Development Goals, as well as their specific targets, are a solid guide for the design of future agricultural slope areas promoting the sustainable management of water resources.

Optimising water use in such areas means ensuring food security. Farming practices should become more resilient by minimising waste and improving drainage networks (with particular efforts on abandoned land restoration) to mitigate the impact of drought seasons and protect crops from extreme weather events. These aspects are also aligned with SDG6 (Clean Water and Sanitation), which is committed to securing such resources across all sectors. For instance, radical terraces have been recognised as effective in purifying water in some regions of Rwanda (Uwacu et al., 2021). A good practice could be exploiting the slope morphology to store excess water in reservoirs. If they are well designed, they ensure a usable supply in emergencies, such as long periods of drought. At the same time, they can collect excess surface runoff generated after heavy rainfall, limiting its critical accumulation. In addition, on slopes with water courses and high gradients, it could be interesting to develop micro-hydroelectric systems. They can convert water motion into clean and renewable energy, in line with the SDG7 (Affordable and clean energy), ensuring minimal environmental and landscape impacts (Fuso Nerini et al., 2018). The optimisation of water resources cannot ignore scientific and technological research, a key point of SDG9 (Industry, Innovation and Infrastructure). Modernization should support traditional knowledge, offering new ideas for improving agricultural activities.

A fitting example is 3D digital terrain models of cultivated slopes and high-definition GIS mapping of surface processes, which could guide stakeholders in improving farming sustainability by respecting ancestors' knowledge. Together, these approaches are fundamental to achieving SDG13 (Climate Action), which is based on increasing resilience and adaptive capacity (De Neve and Sachs, 2020). On cultivated slopes, it is crucial to implement natural-based solutions (e.g. to limit soil erosion by water) and to upgrade water conservation systems. The SDG15, “Life on Earth”, is a further key goal that will be reflected in the landscapes of the future (De Neve and Sachs, 2020). Rural areas should be integrated with distributed forested spots, where water can favour habitats and ecosystems. Finally, widespread dissemination of micro wetlands, in line with the principle of water storage, can also be a suitable solution.

11.3. Final remarks

Steep-slope agricultural systems play an important role in global food production. Climate-proof water resource management is more than urgent for steep-slope agricultural areas. This paper highlighted firstly the importance of traditional water resource management that balances food production and ecosystem services, such as the Globally Important Agricultural Heritage Systems (GIAHS) defined by FAO. Secondly, we illustrated how key innovative methods and technologies like high-resolution remote sensing (e.g. LiDAR and drones) and GIS-based modelling provide valuable tools for time-efficient and cost-effectiveness designing water management solutions. Such structural and non-structural solutions are of utmost importance in light of the SDGs to promote the future resilience of steep-slope agricultural Landscapes in the face of climate change. In general, this study provides a practical guideline for stakeholders and policymakers work in the agriculture sector to implement reasonable water resource intervention systems and design diverse water storage facilities.

12. Expanding the View on UNESCO Cultural Landscapes

12.1. Introduction: The Importance of Zooming Out

Sauer's 1935 definition of the Cultural Landscape highlights its inherent complexity and heterogeneity, with examples distributed across the globe. Cultural Landscapes are present on every continent, yet only some achieve international recognition and are included in dynamic, continually updated protection lists such as UNESCO's.

This thesis, due to the practical need to limit the scope within case studies, focuses on landscapes defined as "representative" by the specific objectives. This approach allows for the analysis, interpretation, and understanding of these representative landscapes to be extrapolated to other landscapes, even those that are geographically or culturally distant. Therefore, it is crucial to zoom out from these representative examples to gain a global perspective on the broader implications for Cultural Landscapes worldwide, particularly in the context of climate change.

This final section of the thesis aims to do just that: analyze the entirety of Cultural Landscapes and their climatic evolution, along with the associated risks. By "entirety," it is referred to the current, updated list of UNESCO Cultural Landscapes, with a particular focus on those with a strong rural character. This chapter embarks on a preliminary exploration of the potential impacts of climate change on UNESCO-designated agricultural Landscapes on a global scale, starting with a broad analysis of all sites and then delving in on rural landscapes. The insights from this analysis will be incorporated into a scientific article that is currently in preparation.

> While the analysis remains preliminary and not fully complete, this section contributes to addressing Specific Objectives A (SO-A) and B (SO-B) of this PhD thesis.

12.2. Understanding the Uniqueness of Each Site

12.2.1. Mapping UNESCO Cultural Landscapes

Currently, over 120 UNESCO Cultural Landscapes are documented globally. UNESCO provides the geographical coordinates of each site as a generic point within each site (Figure 12.1).

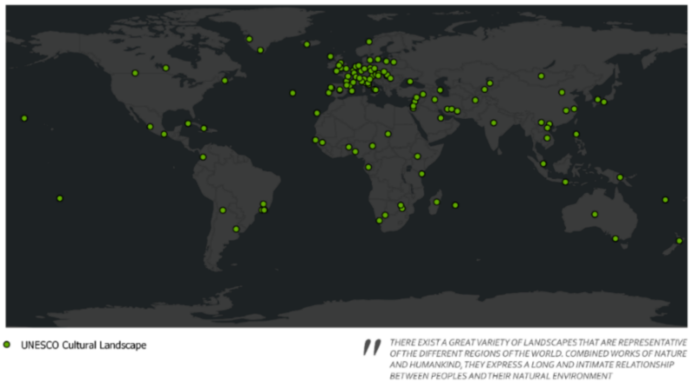
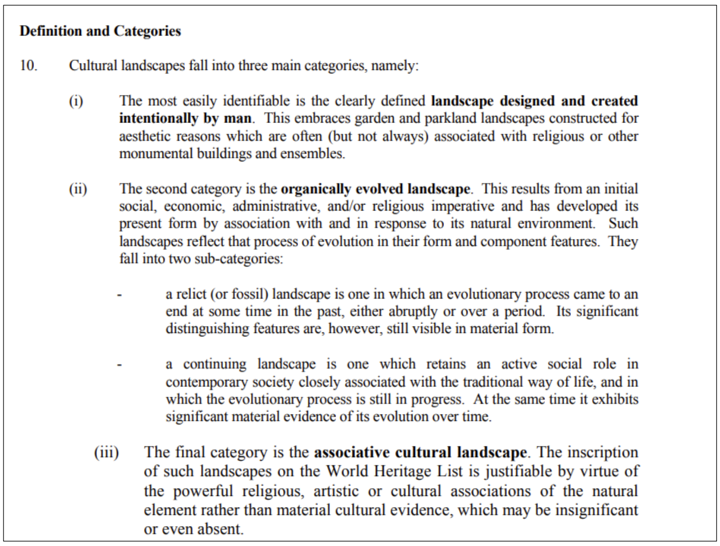


Figure 12.1. Global location of UNESCO Cultural Landscape. Source: author elaboration from UNESCO data.

Given that some of these sites cover extensive areas, spanning multiple square kilometers, there can be significant variations in geographical contexts and climates within each site. Therefore, the first step was to digitize the boundaries of each site. This process involved manually georeferencing the maps of each site provided in UNESCO documentation. See Appendix 1 for detailed information.

12.2.1. What's Inside? The Unique Values of Each Cultural Landscape

Understanding the potential impacts of climate change on UNESCO Cultural Landscapes requires insight into what makes each site unique and eligible for protection: essentially, the "values" of each site that may be at risk. This task is complex because each site is distinct, with a variety of factors contributing to its uniqueness and significance. For example, a site might simultaneously possess cultural value due to traditional agricultural practices and historical value due to the presence of significant buildings. A major challenge lies in the brevity and generality of UNESCO's guidelines for determining a site's eligibility for inclusion, which ideally should provide clarity on the values at stake (see Figure 12.2). The broad and generalized nature of these guidelines makes detailed categorization difficult, as previously noted by previous researchers (e.g., Sirisrisak & Akagawa, 2007).



Definition and Categories

10. Cultural landscapes fall into three main categories, namely:

(i) The most easily identifiable is the clearly defined **landscape designed and created intentionally by man**. This embraces garden and parkland landscapes constructed for aesthetic reasons which are often (but not always) associated with religious or other monumental buildings and ensembles.

(ii) The second category is the **organically evolved landscape**. This results from an initial social, economic, administrative, and/or religious imperative and has developed its present form by association with and in response to its natural environment. Such landscapes reflect that process of evolution in their form and component features. They fall into two sub-categories:

- a relict (or fossil) landscape is one in which an evolutionary process came to an end at some time in the past, either abruptly or over a period. Its significant distinguishing features are, however, still visible in material form.
- a continuing landscape is one which retains an active social role in contemporary society closely associated with the traditional way of life, and in which the evolutionary process is still in progress. At the same time it exhibits significant material evidence of its evolution over time.

(iii) The final category is the **associative cultural landscape**. The inscription of such landscapes on the World Heritage List is justifiable by virtue of the powerful religious, artistic or cultural associations of the natural element rather than material cultural evidence, which may be insignificant or even absent.

Figure 12.2. Operational Guidelines for the Implementation of the World Heritage Convention - Annex 3. https://whc.unesco.org/archive/opguide08-en.pdf#annex3; Definition and Categories; Page 86.

To address this complexity, this PhD thesis individually analyzed documents for all sites listed as UNESCO Cultural Landscapes. For each site, up to four primary **values** were identified. Table 12.1 provides a detailed overview of these values, classified into broad categories: *Anthropic* and *Natural*, which are further divided into *Tangible* and *Intangible* values. Figure 12.2 displays on the map such information. This approach helps to understand each site's distinctive characteristics and to identify which values might be at risk due to climate change.

See Appendix 2 for detailed information.

Table 12.1. Summary of values attributable to UNESCO Cultural Landscape sites. The "num" column indicates the number of sites involved, and the "%" column the percentage of an individual value out of the total.

Value	**Num**	**%**	**Description**		
Archaeology	27	21%	Presence of archaeological finds/elements/repertoires/sites	Tangible	Anthropic
Art/Architecture	25	20%	Presence of buildings/constructions/works with architectural and/or artistic value		
Human settlement	51	40%	Presence of urban conglomerates and/or traditional villages		
Mining/Industrial landscape	9	7%	Landscape largely influenced by industrial activity and presence of mines		
Hunting	2	2%	Presence of hunting activities	Intangible	
Mining	4	3%	Presence of mining activities		
Local communities	21	17%	Presence of indigenous communities or sites where value is largely determined by local traditions		
Religious/Spiritual	21	17%	Site where value is largely determined by religious/spiritual aspects of local communities		
Natural value	61	48%	Presence of significant natural features	Tangible	Natural
Rural landscape	64	50%	Landscape largely influenced by agricultural activity		
Forestry	7	6%	Presence of forest-related productive activity		
Gardens/Parks	21	17%	Presence of parks and/or gardens		
Traditional Agriculture	53	42%	Presence of traditional agricultural practices	Intangible	
Traditional fishing	9	7%	Presence of traditional fishing practices		
Traditional water management	26	20%	Presence of significant water management systems		
Pasture	15	12%	Presence of productive activities related to pastoralism and/or transhumance		

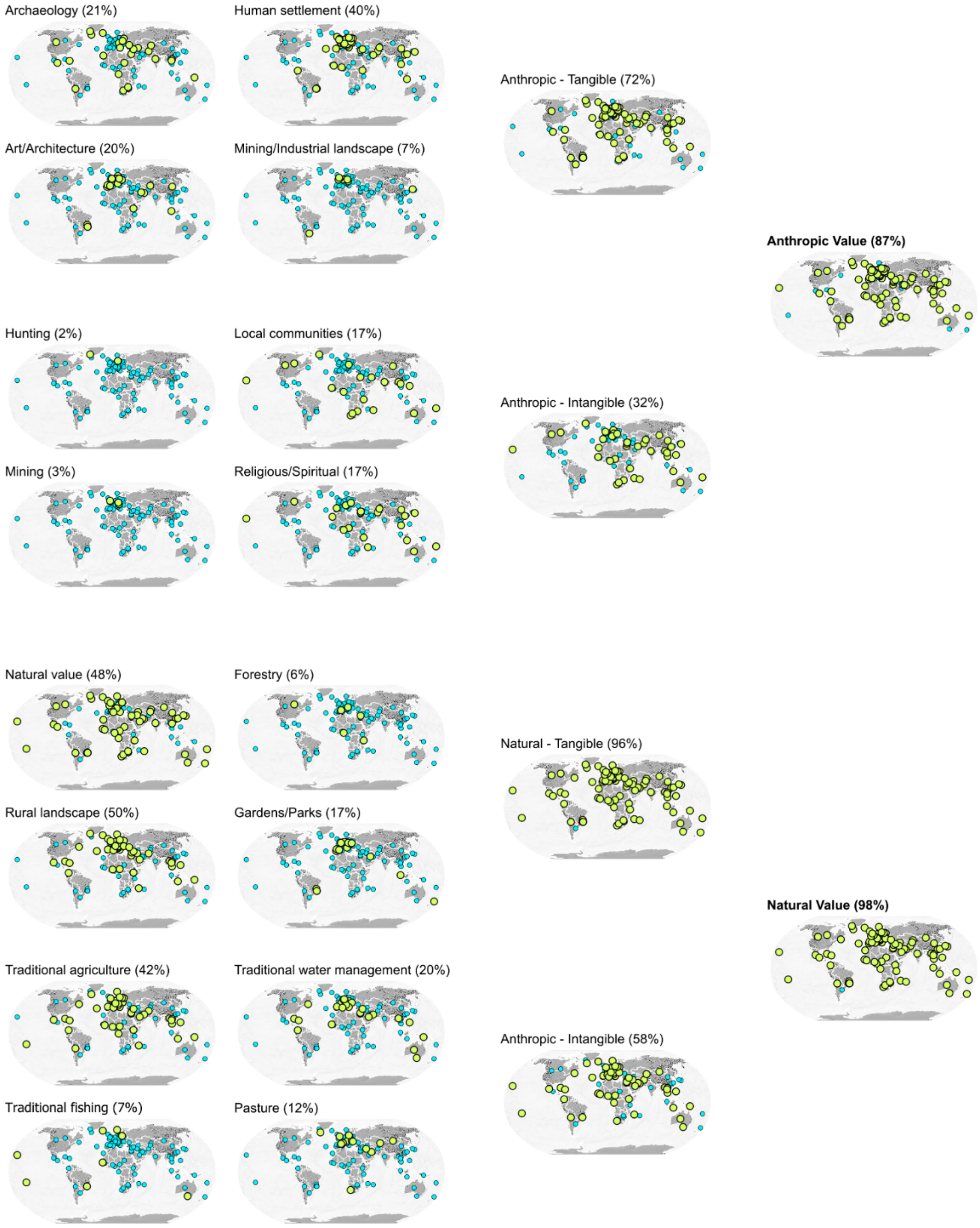
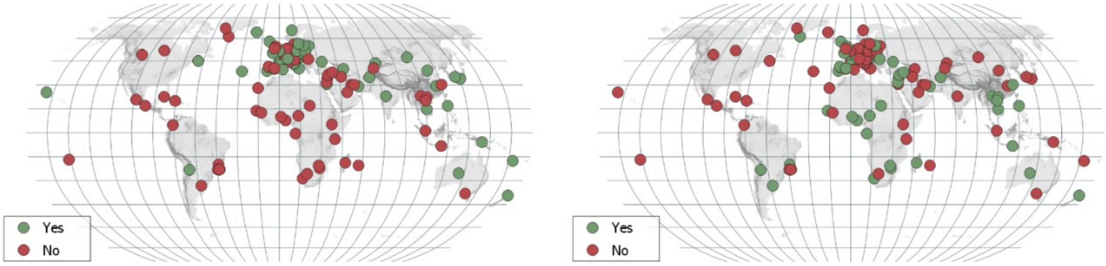


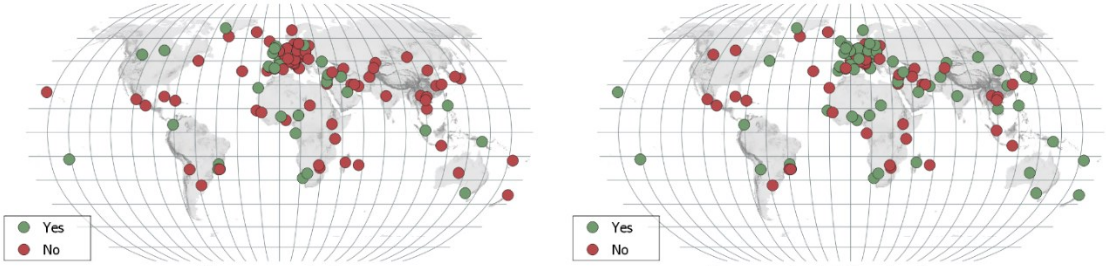
Figure 12.2. Mapping of UNESCO Cultural Landscapes that host specific values and their classification into tangible/intangible and anthropogenic/natural. Green dots indicate Cultural Landscapes that hold the analyzed value compared to all Cultural Landscapes (in blue).

12.2.2. Traces of Climate Change in UNESCO Documents

Once the values of each site were identified, the next step was to analyze the reported impacts of climate change on landscapes. The analysis involved reviewing UNESCO site reports available through open-access online resources to determine if they address climate change issues. The primary focus was on "*Periodic Reporting*," which provides a brief overview of any climate change concerns at each site and their nature. In cases where these reports were unavailable, the "*State of Conservation Report*" and the "*Management Plan*" were also consulted, as they may contain additional relevant information. This review is crucial for identifying each site's specific vulnerabilities. Figure 12.3 shows which sites have a Periodic Report, a State of Conservation Report, and a Management Plan, and whether these documents mention climate change-related threats such as drought or storms. This preliminary step is necessary to establish a foundation for a more in-depth analysis, allowing to map potential climate change-related threats to Cultural Landscapes and identify their possible consequences on the site's values. See Appendix 3 for detailed information.



Periodic Reporting State of conservation report



Management plan Documents & Climate change

Figure 12.3. Presence (yes) or lack (no) of Periodic Reporting, State of conservation report and Management Plan in UNESCO Cultural Landscapes. The map at the bottom right indicates whether climate change issues are mentioned in some of these documents.

12.2.3. Identification of the Main Climate Change-related Potential Threats and Consequences

Building on the information provided in UNESCO documents, a comprehensive analysis was conducted to identify four broad macro-classes of potentially critical **threats** challenging each Cultural Landscape. These macro-classes were determined by carefully examining the specific vulnerabilities and challenges outlined in the UNESCO documentation (Table 12.2).

Table 12.2. Summary of potentially critical threats to UNESCO Cultural Landscapes. Column num indicates the number of sites affected.

Threat	**Num**	**Description**
Changes to oceanic waters	25	Changes to oceanic waters
Drought	54	Occurrence of periods of drought
Storm	116	Occurrence of extreme precipitation events, involving heavy rainfall and/or strong winds
Temperature change	89	Variation of typical area temperature

Identifying the main climate change-related threats is crucial for understanding their potential consequences—and thus, their impacts—on each UNESCO site. Through this analysis, 19 key potential consequences were identified, which are listed and described in Table 12.3 below.

Table 12.3. Summary of the consequences potentially driven by climate change in UNESCO Cultural Landscapes. Column num indicates the number of sites involved.

Consequence	**Num**	**Description**
Erosion (arch. findings)	23	Erosion and damage to archaeological finds
Erosion (artifacts)	33	Erosion on buildings, artifacts and, in general, anthropogenic elements
Erosion (agr. + nat. soil)	17	Agricultural and natural soil erosion
Erosion (agr. soil)	33	Agricultural soil erosion
Slope failure (cultivated)	24	Failure of cultivated slope
Slope failure (mine)	2	Failure of mining slope
Slope failure (natural)	22	Failure of natural slope
Slope failure (pasture)	3	Failure of slope in pasture area
Desertification	10	Desertification
Permafrost melting	3	Permafrost melting
Heatwave (agriculture)	22	Impact of heatwave on agricultural land
Heatwave (park greenery)	17	Impact of heatwave on garden/park
Heatwave (natural)	28	Impact of heatwave on natural environment
Flooding	84	Impact of flood
Changes to non-oceanic waters	6	Change in the level of inland waters, e.g., lakes/rivers
Water scarcity	47	Less water available, water scarcity
Wildfire	7	Occurrence of wildfires
Erosion (coastal)	25	Coastal erosion
Salinization	9	Saltwater intrusion

This reporting-based background information serves two primary purposes: (1) it provides a global overview of the problems Cultural Landscapes may encounter due to climate change impacts, and (2) it offers a benchmark for cross-referencing with the climate analysis that will be conducted in the following sections.

As with the identification of values, potential threats and consequences are also plotted on a map (Figure 12.4)..

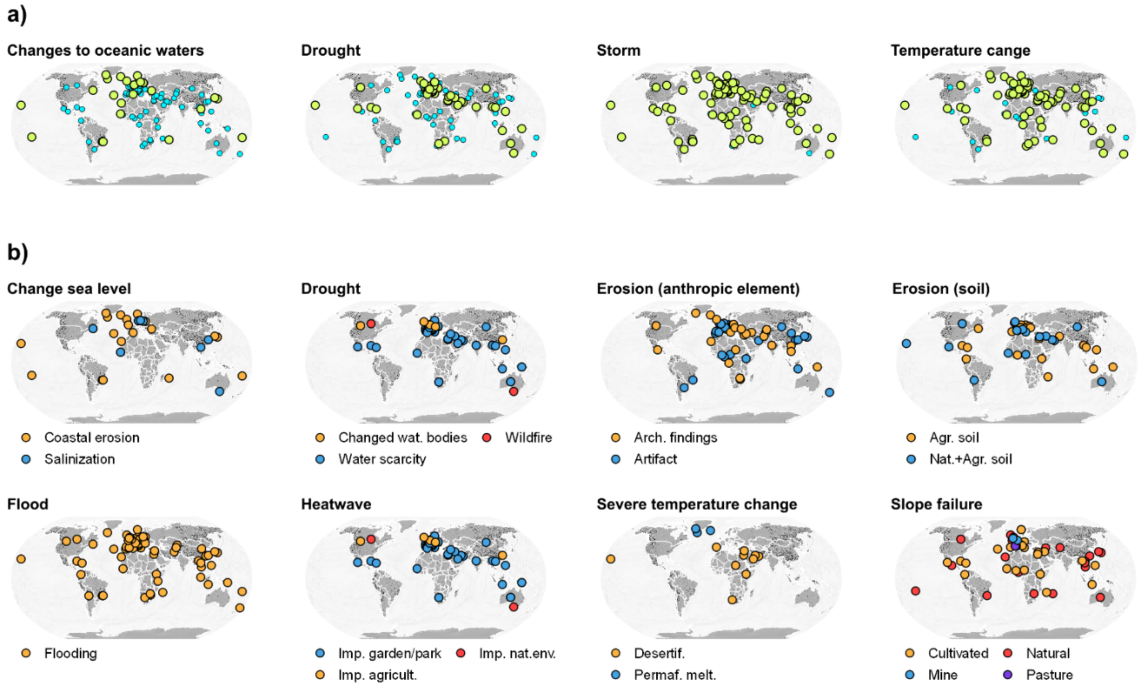


Figure 12.4. (a) Major potentially critical threats to UNESCO Cultural Landscapes (green dots out of blue dots).; (b) Major potential consequences.

See Appendix 3 for detailed information.

12.2.4. A Lens on Agricultural UNESCO Cultural Landscapes Worldwide

Analyzing the values, threats, and consequences for the entire list of UNESCO Cultural Landscapes provides a solid foundation for more specific analyses. This PhD research focuses on Cultural Landscapes with a strong rural character, comprising a total of 86 sites distributed as described in Table 12.4.

Table 12.3. Summary UNESCO Cultural Landscapes with strong rural characters.

Value	**Num**	**% (On total CL)**	**Description**
Rural landscape	64	50%	Landscape largely influenced by agricultural activity
Hunting	2	2%	Presence of hunting activities
Pasture	15	12%	Presence of productive activities related to pastoralism and/or transhumance
Traditional Agriculture	53	42%	Presence of traditional agricultural practices
Traditional fishing	9	7%	Presence of traditional fishing practices
Traditional water management	26	20%	Presence of significant water management systems

12.3. Climate Change within the UNESCO Cultural Landscapes

12.3.1 Historical and Future Climate Data

Data used to investigate climate change impacts on UNESCO agricultural Cultural Landscapes were retrieved from the WorldClim project (https://worldclim.org/) at a resolution of 2.5 minutes. Historical data were sourced from the WorldClim v2 database, which includes monthly data on temperature, precipitation, solar radiation, vapor pressure, and wind speed, aggregated across the period from 1970 to 2000, utilizing data from up to 60,000 weather stations (Fick and Hijmans, 2017). Future data were obtained from the Coupled Model Intercomparison Project Phase 6 (CMIP6), downscaled and calibrated using WorldClim v2.1 as a baseline. This dataset includes outputs from 23 global climate models (GCMs) for four Shared Socio-economic Pathways (SSPs: 126, 245, 370, and 585). WorldClim also offers a set of bioclimatic variables (BCs) that represent annual trends, seasonality, and extreme or limiting environmental factors.

In this research, we analyzed the selected BCs described in Table 12.4 to investigate the evolution of annual precipitation and temperature from historical to future scenarios in UNESCO agricultural Cultural Landscapes worldwide. Additionally, we examined summer precipitation and temperature conditions, as this season is typically at higher risk for drought, heatwaves, and storms.

Table 12.4. List of Bioclimatic Variables (BCs) Investigated in this Study, including their purpose, use, and processes analyzed.

BC	Name	Purpose	Use	Process
BIO1	Annual Mean Temperature (°C)	General climate warming	Analyze the projected increase in the annual mean temperature to understand general warming trends. This helps in evaluating long-term climate shifts and potential impacts on agriculture & ecosystems.	Temperature
BIO5	Max Temperature of Warmest Month (°C)	Maximum temperature extremes	Focus on the projected peak temperatures during the warmest month to understand the severity of future heatwaves, which can damage crops and/or altering cultivation practices	
BIO12	Annual Precipitation (mm)	Overall water availability	Examine the changes in total annual precipitation to understand shifts in overall water availability. This helps in evaluating potential impacts on water resources, agriculture, and ecosystems.	Precipitation
BIO13	Precipitation of Wettest Month (mm)	Extreme rainfall events	Investigate projected maximum precipitation during wettest month to assess the potential for extreme rainfall events and flooding. This is crucial for understanding changes in flood risks and water management needs	
BIO10	Mean Temperature of Warmest Quarter (°C)	Sustained high temperatures during summer	Evaluate projected average temperatures during future summers to understand the impacts of sustained high temperatures. This includes potential effects on agricultural productivity and water consumption	Summer Precipitation and Temperature
BIO18	Precipitation of Warmest Quarter (mm)	Summer rainfall dynamics	Assess changes in precipitation during summer to understand the interaction between high temperatures and rainfall. This analysis is important for evaluating drought conditions and water stress during summer	

12.3.2 Future Climate Scenario: Selection of Bests Global Climate Models (GCMs)

Given the global distribution of UNESCO Cultural Landscapes, it is crucial to use Global Climate Models (GCMs) that have been thoroughly tested for each region to simulate future climate scenarios accurately. The WorldClim database offers access to 23 GCMs, from which the most suitable model must be selected for each Cultural Landscape.

To achieve this, the world was divided into macro-regions. For each region, scientific studies were identified that had tested the performance of various GCMs available in the WorldClim database. These studies helped identify a set of potentially effective GCMs for each macro-region, as summarized in the "Model Tested" and "Model Available" columns in Table 12.5. The selection process was then refined to four of the most consistently validated GCMs across all regions: BCC-CSM2-MR, EC-Earth3-Veg, HadGEM3-GC31-LL, and MPI-ESM1-2-HR. The final objective was to assign each Cultural Landscape one of these four models, ensuring that the chosen GCM accurately represents the climatic conditions of the respective region.

Table 12.5 summarizes the scientific studies that evaluated the GCMs for each macro-region. The "Model Selected" column highlights the best GCMs for the UNESCO Cultural Landscapes within each region, with the chosen model indicated by a distinct color.

Table 12.5. Literature review for selecting the most suitable GCMs for UNESCO Cultural Landscapes in each region.

Region	Model Tested (N)	Model Available	Model selected	Reference
Africa (Central)	15	BCC-CSM2-MR EC-Earth3-Veg GFDL-ESM4 IPSL-CM6A-LR MRI-ESM2-0 UKESM1-0-LL	GFDL-ESM4 **EC-EARTH3-Veg** MRI-ESM2-0	(Ngoma et al., 2021)
Africa (East)	15	BCC-CSM2-MR EC-EARTH3-Veg GFDL-ESM4 INM-CM5-0 MPI-ESM1-2-HR	BCC-CSM2-MR **EC-EARTH3-Veg** GFDL-ESM4 INM-CM5-0 MPI-ESM1-2-HR	(Ayugi et al., 2021)
Africa (North)	21	ACCESS-CM2 BCC-CSM2-MR INM-CM5-0 MIROC6 MPI-ESM1-2-HR MRI-ESM2-0 EC-Earth3-Veg FIO-ESM-2-0 GISS-E2-1-G	ACCESS-CM2 **BCC-CSM2-MR** MRI-ESM2-0	(Hamed et al., 2022)
Africa (West)	13	ACCESS-CM2 BCC-CSM2-MR IPSL-CM6A-LR MIROC6 MPI-ESM1-2-LR MRI-ESM2-0	**BCC-CSM2-MR** MIROC6 MRI-ESM2-0	(Shiru and Chung, 2021)
Africa (South)	49	ACCESS-CM2 BCC-CSM2-MR CMCC-ESM2 FIO-ESM-2-0 GFDL-ESM4 GISS-E2-1-H HadGEM3-GC31-LL	GISS-E2-1-H MIROC6 **HadGEM3-GC31-LL**	(Nooni et al., 2023)

		INM-CM5-0 IPSL-CM6A-LR MIROC6 MPI-ESM1-2-HR MRI-ESM2-0 UKESM1-0-LL		
America (North)	9	BCC-CSM2-MR EC-Earth3-Veg GFDL-ESM4 HadGEM3- GC31-LL IPSL-CM6A-LR IPSL-CM6A-LR MRI-ESM2-0	BCC-CSM2-MR **EC-Earth3-Veg** GFDL-ESM4 HadGEM3- GC31-LL	(Srivastava et al., 2020)
America (North)	5	BCC-CSM2-MR EC-Earth3-veg MRI-ESM2.0	**EC-Earth3-Veg**	(Masud et al., 2021)
America (South)	14	BCC-CSM2-MR CanESM5 CESM2 CESM2-WACCM E3SM-1-0	**BCC-CSM2-MR**	(Juan A. Rivera and Arnould, 2020)
America (South)	50	ACCESS-CM2 BCC-CSM2-MR CMCC-ESM2 EC-Earth3-Veg FIO-ESM-2-0 GFDL-ESM4 GISS-E2-1-G INM-CM5-0 IPSL-CM6A-LR MIROC6 MPI-ESM1-2-HR MRI-ESM2-0	ACCESS-CM2 **EC-Earth3-Veg** INM-CM5-0	(Reboita et al., 2024)
America (Central)		ACCESS–CM2 BCC–CSM2–MR EC–Earth3–Veg FIO–ESM–2–0 GFDL–ESM4 INM–CM5–0 IPSL–CM6A–LR MIROC6 MRI–ESM2–0 UKESM1–0–LL	BCC–CSM2–MR **EC–Earth3–Veg** FIO–ESM–2–0 GFDL–ESM4 INM–CM5–0 MIROC6	(Almazroui et al., 2021)
Asia (Central)	19	ACCESS-CM2 BCC-CSM2-MR CMCC-ESM2 CMCC-ESM2 EC-Earth3-Veg IPSL-CM6A-LR MIROC6 MPI-ESM1-2-HR MRI-ESM2-0	CMCC-ESM2 **MPI-ESM1-2-HR**	(Salehie et al., 2023)
Asia (Southeast)	35	ACCESS-CM2 MRI-ESM2-0 EC-Earth3 EC-Earth3-Veg	**EC-Earth3-Veg** MRI-ESM2-0	(Iqbal et al., 2021)
Asia (Southeast)	13	ACCESS-CM2 BCC-CSM2-MR EC-Earth3-Veg INM-CM5-0 MPI-ESM1-2-HR MRI-ESM2-0	**MPI-ESM1-2-HR**	(Jose and Dwarakish, 2022)

Asia (East)	46	ACCESS-CM2 BCC-CSM2-MR EC-Earth3 EC-Earth3-Veg FIO-ESM-2-0 GFDL-ESM4 GISS-E2-1-G IPSL-CM6A-LR IPSL-CM6A-LR MIROC6 MPI-ESM1-2-HR MRI-ESM2-0	**EC-Earth3-Veg**	(Ngoma et al., 2021)
Asia (East)	20	BCC-CSM2-MR IPSL-CM6A-LR MIROC6 MPI-ESM1-2-LR MRI-ESM2-0	**BCC-CSM2-MR** MRI-ESM2-0	(Shiru et al., 2022)
Australia	45	GFDL-ESM4 HadGEM3-GC31-LL MRI-ESM2-0	**EC-Earth3-Veg** HadGEM3-GC31-LL	(Di Virgilio et al., 2022)
Europe	31	ACCESS-CM2 BCC-CSM2-MR EC-Earth3-Veg GFDL-CM4 HadGEM3- GC31-LL MPI-ESM1-2-HR MRI-ESM2-0 UKESM1-0-LL	**HadGEM3- GC31-LL**	(Palmer et al., 2023)
MENAP	11	BCC-CSM2-MR BCC-ESM1 IPSL-CM6A-LR MIROC6 MPI-ESM1-2-HR MRI-ESM2-0	MPI-ESM1-2-HR	(Mesgari et al., 2022)

12.3.3. Assessment of Climatic Variability and Potential Risk Indicators for UNESCO Agricultural Cultural Landscapes

We conducted a zonal statistical analysis of UNESCO agricultural Cultural Landscapes, calculating the median values of key climatic variables (see Table 12). By comparing these median values for historical and future conditions (2081-2100; SSP585; using site-specific GCMs as discussed in Section 12.3.2), we aimed to understand potential climatic shifts and their global impacts.

Our analysis involved two main approaches: (1) Clustering and (2) Potential Future Risk Evaluation. These analyses focused on percentage variations (Δ) in pairs (X and Y) of temperature and precipitation variables:

- **Temperature**: Annual Mean Temperature (AMT; X) and Max Temperature of Warmest Month (MTWM; Y).
- **Precipitation**: Annual Precipitation (AP; X) and Precipitation of Wettest Month (PWM; Y).

We also investigated potentially critical summer conditions related to temperature and precipitation using the following variables:

- **Summer Conditions**: Mean Temperature of Warmest Quarter (MTWQ; X) and Precipitation of Warmest Quarter (PWQ; Y).

See Appendix 4 and Appendix 5 for detailed information.

ANALYSIS 1 – Clustering

We analyzed the historical-to-future variations (Δ) of AMT, MTWM, AP, PWM, MTWQ, and PWQ individually using a clustering approach. This method graphically visualized the variations and grouped sites with similar climatic changes. This information is valuable for UNESCO and landscape managers to update their understanding of potential future impacts and risks due to climate change. The results are presented in Figure 12.5.

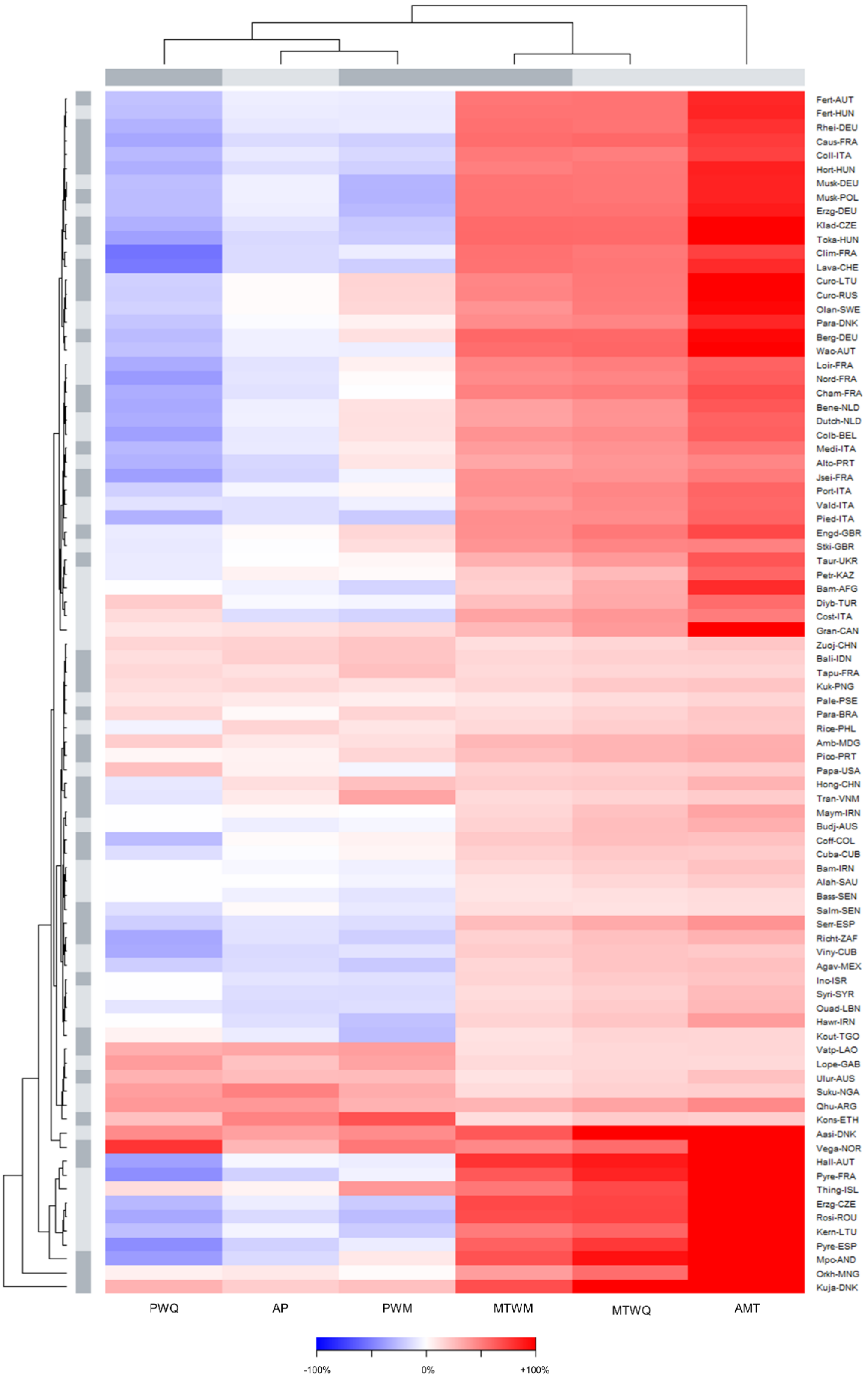


Figure 12.5. Clustering of Climatic Variations in UNESCO Agricultural Cultural Landscapes 8indicated on the right with the country code) based on historical-to-future changes in temperature, precipitation, and summer climate conditions. The clusters group sites with similar climatic shifts, helping to visualize and compare the expected variations and potential impacts of climate change across different regions.

ANALYSIS 2 – Potential Future Risk Evaluation

For each variable pair (X and Y), we computed the percentage changes (Δ) to quantify climatic variations at each site and assess potential future risks to UNESCO agricultural Cultural Landscapes. To understand and visualize these variations, we developed a composite index (I) as a weighted average of the normalized changes, which evaluates the combined variations of the climatic parameters. This index facilitates effective trend analysis and scenario comparison and is calculated as follows:

$$\mathrm{I} = w_X \times N_{\Delta X} + w_Y \times N_{\Delta Y}$$

where ($N_{\Delta X}$) is the normalized value of ΔX, and ($N_{\Delta Y}$) is the normalized value of ΔY. The normalized value (N) for any variation (Δ) is calculated using the formula:

$$N_\Delta = \frac{\Delta - \min(\Delta)}{\max(\Delta) - \min(\Delta)}$$

Here, (Δ) represents either ΔX or ΔY. The weights (w_X) and (w_Y) are assigned based on the sign of ΔX and ΔY to reflect their relative impacts and contributions to the final index: (1) If both ΔX and ΔY are positive, both weights are positive (+0.5), reflecting their additive effects; (2) If both ΔX and ΔY are negative, both weights are negative (-0.5), indicating their combined negative impact; (3) If ΔX is negative and ΔY is positive, or vice versa, the weights are adjusted accordingly (+0.5 or -0.5) to account for their opposing effects.

This approach for calculating the index (I) was applied separately to two indices:

- **Temperature Index (TI)**: (ΔX) represents the percentage change in BIO1, and (ΔY) represents BIO5. Positive values suggest an increased future risk related to elevated temperatures, while negative values indicate a reduction in temperature.
- **Precipitation Index (PI)**: (ΔX) represents the percentage change in BIO12, and (ΔY) represents BIO13. Positive values indicate an increase in precipitation, potentially signaling a higher risk of severe events, whereas negative values suggest reduced water availability.

The resulted indexes have values ranging from -1 to 1, with positive values indicating positive changes and negative values indicating negative changes. A larger absolute value denotes greater severity of the variation.

To assess potentially critical summer climatic conditions, we propose a simple discrete index:

- **Summer Condition Index (SCI)**. It examines the historical-to-future variation of Mean Temperature of Warmest Quarter (MTWQ) and Precipitation of Warmest Quarter (PWQ) to identify two possible scenarios:
  - **(A)** An increase in both summer temperature and precipitation, indicating a warmer and more humid climate;
  - **(B)** An increase in temperature coupled with a decrease in precipitation, representing a warmer and drier summer climate, which poses the greatest challenge due to risks such as prolonged droughts, water stress, and desertification.

These three indices serve as effective indicators for Cultural Landscape management, signaling predicted climate variations due to climate change. The visualization of these results is displayed in the figure below.

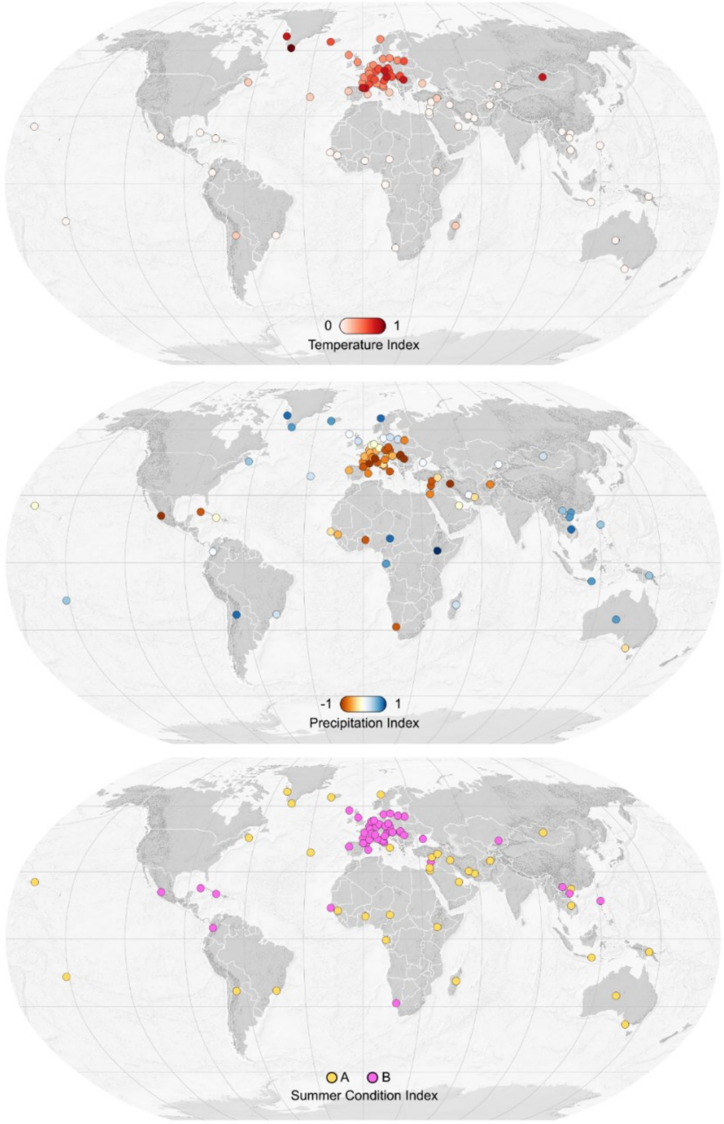


Figure 12.6. Global climate change impact indices for UNESCO agricultural Cultural Landscapes. Top Map: Temperature Index (TI) from 0 (no change) to 1 (maximum increase), with light to deep red showing varying levels of temperature rise. Middle Map: Precipitation Index (PI) from -1 (decrease) to 1 (increase), with blue to orange illustrating shifts in precipitation patterns. Bottom Map: Summer Condition Index (SCI) showing Scenario A (warmer and more humid) in yellow and Scenario B (warmer and drier) in pink.

13. Final Remarks

13.1. Looking Back

The main objective of this PhD thesis was to contribute to understanding the impact of global environmental changes on selected representative agricultural Cultural Landscapes, with a particular focus on climate change. It also explores how human management practices influence the resilience of these landscapes in the face of such changes.

The broad concept of Cultural Landscapes allowed this thesis to explore various spatial scales, ranging from individual agricultural fields to a global perspective. To achieve this, remote sensing and GIS-based approaches were utilized to monitor and understand the processes necessary for promoting informed and resilient landscape management.

Chapter 1.1 delves into the primary definitions of Cultural Landscapes, discussing their complexity and uniqueness. It underscores the importance of conducting research in these valuable and unique areas, leading to Chapter 1.2, which outlines the research questions and specific objectives (SO). The current state of knowledge was summarized in a baseline study of published scientific works on this topic (Chapter 1.3). This chapter specifically analyzed the challenges and threats posed by global environmental changes to Cultural Landscapes and explored the remote sensing and GIS techniques employed to achieve the thesis objectives.

In addition to scientific articles, official UNESCO sources and documents were consulted and cited, particularly reports on factors threatening UNESCO sites and guidelines for scientists on addressing these issues. These sources helped structure the thesis.

Specific Objective A (SO-A) is covered in **Part A**. It focuses on analyzing the impacts of drought and high temperatures on representative Cultural Landscapes. Chapter 2 explores the severe drought and heatwaves that hit European vineyards during the summer of 2022, a critical period that threatened the cultural and economic value of viticulture across the continent. By employing satellite data analysis, this research identified the vineyards most at risk and proposed strategies to enhance their resilience, significantly contributing to SO-A. In Chapter 3, the analysis extends to steep-slope croplands in Europe, regions severely affected by the 2022 drought. The study reveals the vulnerability of these culturally significant agricultural areas during similar events. Chapter 4 narrows its focus to Northeast Italy, examining how climate change-induced aridity is shifting climate zones and threatening traditional agricultural practices in culturally significant landscapes. This research emphasizes the crucial role of sustainable water management in mitigating these impacts, directly addressing SO-A. Chapter 5 investigates the side effects of drought in the Po River Delta, particularly the increasing risk of salinization in this UNESCO World Heritage site. Remote sensing techniques were used to assess how saltwater intrusion, exacerbated by drought, impacts costal agriculture and related cultural values, comprehensively contributing to SO-A by highlighting the complex challenges that drought poses to both agriculture and cultural heritage.

Specific Objective B (SO-B) is covered in **Part B** of this thesis. It aims to analyze the impacts of extreme rainfall events on representative Cultural Landscapes, focusing on their vulnerability and resilience. Chapter 6 first examines global mountain grasslands, emphasizing their ecological and cultural importance. It identifies how soil erosion, driven by intense precipitation, threatens these landscapes and the communities that depend on them. By mapping erosion risks using satellite data, the study highlights the urgent need for mitigation strategies, particularly nature-based solutions. Chapter 7 narrows down the analysis to the farm scale using LiDAR data. It explores the challenges faced by traditional agricultural terraces, such as those in the UNESCO World Heritage site of Cinque Terre. It proposes a remote sensing-based monitoring workflow that identifies areas most vulnerable to hydro-erosive processes during extreme rainfall. This approach enables more targeted interventions to preserve these culturally significant landscapes. Chapter 8 investigates sustainable water harvesting methods for steep-slope agricultural terraces, demonstrating how these methods can enhance resilience to extreme weather. The research highlights the dual benefits of these facilities in managing both excessive rainfall and drought conditions. Part B addresses SO-B by providing a comprehensive analysis of how extreme rainfall affects Cultural Landscapes, offering innovative solutions to enhance their resilience.

Specific Objective C (SO-C) is covered in **Part C** of this thesis. It aims to assess how human management practices affect the resilience of Cultural Landscapes to global environmental changes. Chapter 9 explores how Argentinian vineyards are adapting to climate change, specifically investigating the strategic shift of vineyards from plains to higher elevations in response to increasing heatwaves. While this relocation aims to mitigate heat stress, it introduces new challenges, such as heightened risks of soil erosion and flooding due to extreme rainfall. This case highlights the complex interplay between human decisions and environmental resilience. Chapter 10 examines the impact of mechanization in traditional viticulture. The study reveals that while mechanization increases productivity, it also leads to soil compaction and erosion, particularly during heavy rainfall. This section underscores the need for sustainable practices to maintain the resilience of these Cultural Landscapes. Chapter 11 delves into the sustainable management of water resources in steep-slope agricultural Landscapes, emphasizing the importance of integrating traditional knowledge with modern technology to enhance resilience. The research demonstrates how human interventions can either exacerbate or mitigate climate-related challenges, emphasizing the critical role of sustainable management in preserving these culturally significant landscapes. Through these studies, the thesis addresses SO-C by analyzing the dual impact of human management on the resilience of Cultural Landscapes under global environmental change.

13.2. Future Outlook

Future research should build upon the scientifically robust insights provided in this thesis on the impacts of global environmental changes on Cultural Landscapes. Expanding this investigation to include all UNESCO Cultural Landscapes could be an interesting starting point for achieving a comprehensive understanding of how climate change affects these sites globally. This expansion, only preliminarily explored in Chapter 12, should be a priority to inform long-term conservation planning. Future studies must employ regionally calibrated and validated Global Climate Models (GCMs) to simulate climate impacts with higher spatial and temporal resolution. This will enable the identification of both global climate patterns and site-specific vulnerabilities across a diverse array of Cultural Landscapes. By combining GCM outputs with detailed remote sensing data, such as multispectral and hyperspectral imagery, it will be possible to assess how these landscapes are likely to respond to future climate scenarios. This interdisciplinary approach will form the basis for developing targeted, data-driven management strategies that are sensitive to local conditions while addressing global trends.

Cutting-edge technologies in remote sensing and GIS science will be crucial for enhancing these analyses. High-resolution satellite imagery, Unmanned Aerial Vehicles (UAVs), and LiDAR are increasingly providing unprecedented levels of detail on landscape features, from vegetation dynamics to erosion patterns. These datasets can be processed through advanced GIS-based spatial analyses to map vulnerability hotspots and simulate landscape evolution under different climate change scenarios. Moreover, the use of data fusion techniques from different sensors (therefore combining data from multiple remote sensing platforms) will improve the accuracy and effectiveness of environmental monitoring across UNESCO sites. In addition, Artificial Intelligence (AI) and machine learning hold enormous potential for automating and enhancing these analyses. Deep learning algorithms can process massive amounts of remotely sensed data to identify patterns and changes in landscape conditions with remarkable precision. AI-driven predictive models can be integrated with GIS to create dynamic simulations of future landscape trajectories, identifying critical thresholds for ecosystem collapse or cultural degradation.

By applying these advanced techniques across all UNESCO Cultural Landscapes, future research will offer easy-to-read, scalable insights into how different sites may be affected by ongoing global environmental changes, laying the foundation for prioritizing conservation efforts and designing adaptive management. Ultimately, it will help ensure that the rich cultural heritage embedded in Cultural Landscapes (the living memory of who we are and where we come from) remains resilient and continues to thrive, even as the world around us changes at an unprecedented pace.

The End.

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Appendix 1 – UNESCO Agricultural Cultural Landscape: Basic Info

name_en	abb	date	lat	long	states_nam	states_ code	region_en
Cultural Landscape and Archaeological Remains of the Bamiyan Valley	Bam	2003	34.85	67.83	Afghanistan	AFG	Asia and the Pacific
Madriu-Perafita-Claror Valley	Mpc	2004	42.49	1.60	Andorra	AND	Europe and North America
Quebrada de Humahuaca	Qhu	2003	-23.20	-65.35	Argentina	ARG	Latin America and the Caribbean
Uluru-Kata Tjuta National Park	Ulur	1987	-25.33	131.00	Australia	AUS	Asia and the Pacific
Budj Bim Cultural Landscape	Budj	2019	-38.08	141.89	Australia	AUS	Asia and the Pacific
Hallstatt-Dachstein / Salzkammergut Cultural Landscape	Hall	1997	47.56	13.65	Austria	AUT	Europe and North America
Wachau Cultural Landscape	Wac	2000	48.36	15.43	Austria	AUT	Europe and North America
Fertö / Neusiedlersee Cultural Landscape	Fert	2001	47.72	16.72	Austria	AUT	Europe and North America
Colonies of Benevolence	Colb	2021	53.04	6.39	Belgium	BEL	Europe and North America
Paraty and Ilha Grande – Culture and Biodiversity	Para	2019	-23.02	-44.69	Brazil	BRA	Latin America and the Caribbean
Landscape of Grand Pré	Gran	2012	45.12	-64.31	Canada	CAN	Europe and North America
Cultural Landscape of Honghe Hani Rice Terraces	Hong	2013	23.09	102.78	China	CHN	Asia and the Pacific
Zuojiang Huashan Rock Art Cultural Landscape	Zuoj	2016	22.26	107.02	China	CHN	Asia and the Pacific
Coffee Cultural Landscape of Colombia	Coff	2011	4.89	-75.77	Colombia	COL	Latin America and the Caribbean
Viñales Valley	Viny	1999	22.62	-83.72	Cuba	CUB	Latin America and the Caribbean
Archaeological Landscape of the First Coffee Plantations in the South-East of Cuba	Cuba	2000	20.03	-75.39	Cuba	CUB	Latin America and the Caribbean
Erzgebirge/Krušnohoří Mining Region	Erzg	2019	50.41	12.84	Czechia	CZE	Europe and North America
Landscape for Breeding and Training of Ceremonial Carriage Horses at Kladruby nad Labem	Klad	2019	50.06	15.48	Czechia	CZE	Europe and North America
The par force hunting landscape in North Zealand	Para	2015	55.91	12.36	Denmark	DNK	Europe and North America
Kujataa Greenland: Norse and Inuit Farming at the Edge of the Ice Cap	Kuja	2017	61.16	-45.60	Denmark	DNK	Europe and North America

Aasivissuit – Nipisat. Inuit Hunting Ground between Ice and Sea	Aasi	2018	67.06	-51.43	Denmark	DNK	Europe and North America
Konso Cultural Landscape	Kons	2011	5.30	37.40	Ethiopia	ETH	Africa
Pyrénées - Mont Perdu	Pyre	1997	42.69	0.00	France	FRA	Europe and North America
Jurisdiction of Saint-Emilion	Jsei	1999	44.89	-0.16	France	FRA	Europe and North America
The Loire Valley between Sully-sur-Loire and Chalonnes	Loir	2000	47.40	0.70	France	FRA	Europe and North America
The Causses and the Cévennes, Mediterranean agro-pastoral Cultural Landscape	Caus	2011	44.22	3.47	France	FRA	Europe and North America
Nord-Pas de Calais Mining Basin	Nord	2012	50.46	3.55	France	FRA	Europe and North America
Champagne Hillsides, Houses and Cellars	Cham	2015	49.08	3.95	France	FRA	Europe and North America
The Climats, terroirs of Burgundy	Clim	2015	47.06	4.86	France	FRA	Europe and North America
Taputapuātea	Tapu	2017	-16.84	-151.37	France	FRA	Europe and North America
Ecosystem and Relict Cultural Landscape of Lopé-Okanda	Lope	2007	-0.50	11.50	Gabon	GAB	Africa
Upper Middle Rhine Valley	Rhei	2002	50.17	7.69	Germany	DEU	Europe and North America
Muskauer Park / Park Mużakowski	Musk	2004	51.58	14.73	Germany	DEU	Europe and North America
Bergpark Wilhelmshöhe	Berg	2013	51.32	9.39	Germany	DEU	Europe and North America
Erzgebirge/Krušnohoří Mining Region	Erzg	2019	50.41	12.84	Germany	DEU	Europe and North America
Hortobágy National Park - the Puszta	Hort	1999	47.59	21.16	Hungary	HUN	Europe and North America
Fertö / Neusiedlersee Cultural Landscape	Fert	2001	47.72	16.72	Hungary	HUN	Europe and North America
Tokaj Wine Region Historic Cultural Landscape	Toka	2002	48.15	21.35	Hungary	HUN	Europe and North America
Þingvellir National Park	Thing	2004	64.25	-21.04	Iceland	ISL	Europe and North America
Cultural Landscape of Bali Province: the Subak System as a Manifestation of the Tri Hita Karana Philosophy	Bali	2012	-8.26	115.40	Indonesia	IDN	Asia and the Pacific
Bam and its Cultural Landscape	Bam	2004	29.12	58.37	Iran (Islamic Republic of)	IRN	Asia and the Pacific
Cultural Landscape of Maymand	Maym	2015	30.17	55.38	Iran (Islamic Republic of)	IRN	Asia and the Pacific
Cultural Landscape of Hawraman/Uramanat	Hawr	2021	35.11	46.48	Iran (Islamic Republic of)	IRN	Asia and the Pacific

Incense Route - Desert Cities in the Negev	Inc	2005	30.54	35.16	Israel	ISR	Europe and North America
Costiera Amalfitana	Cost	1997	40.63	14.60	Italy	ITA	Europe and North America
Portovenere, Cinque Terre, and the Islands (Palmaria, Tino and Tinetto)	Port	1997	44.11	9.73	Italy	ITA	Europe and North America
Val d'Orcia	Vald	2004	43.07	11.55	Italy	ITA	Europe and North America
Medici Villas and Gardens in Tuscany	Medi	2013	43.86	11.30	Italy	ITA	Europe and North America
Vineyard Landscape of Piedmont: Langhe-Roero and Monferrato	Pied	2014	44.61	7.96	Italy	ITA	Europe and North America
Le Colline del Prosecco di Conegliano e Valdobbiadene	Coll	2019	45.95	12.23	Italy	ITA	Europe and North America
Petroglyphs within the Archaeological Landscape of Tamgaly	Petr	2004	43.80	75.53	Kazakhstan	KAZ	Asia and the Pacific
Vat Phou and Associated Ancient Settlements within the Champasak Cultural Landscape	Vatp	2001	14.85	105.82	Lao People's Dem. Rep.	LAO	Asia and the Pacific
Ouadi Qadisha (the Holy Valley) and the Forest of the Cedars of God (Horsh Arz el-Rab)	Ouad	1998	34.24	36.05	Lebanon	LBN	Arab States
Curonian Spit	Curo	2000	55.27	20.96	Lithuania	LTU	Europe and North America
Kernavė Archaeological Site (Cultural Reserve of Kernavė)	Kern	2004	54.89	24.83	Lithuania	LTU	Europe and North America
Royal Hill of Ambohimanga	Amb	2001	-18.76	47.56	Madagascar	MDG	Africa
Agave Landscape and Ancient Industrial Facilities of Tequila	Agav	2006	20.86	-103.78	Mexico	MEX	Latin America and the Caribbean
Orkhon Valley Cultural Landscape	Orkh	2004	47.48	102.68	Mongolia	MNG	Asia and the Pacific
Dutch Water Defence Lines	Dutch	1996	52.56	4.79	Netherlands	NLD	Europe and North America
Colonies of Benevolence	Bene	2021	53.04	6.39	Netherlands	NLD	Europe and North America
Sukur Cultural Landscape	Suku	1999	10.74	13.57	Nigeria	NGA	Africa
Vegaøyan – The Vega Archipelago	Vega	2004	65.62	11.75	Norway	NOR	Europe and North America
Palestine: Land of Olives and Vines – Cultural Landscape of Southern Jerusalem, Battir	Pale	2014	31.72	35.13	Palestine	PSE	Arab States
Kuk Early Agricultural Site	Kuk	2008	-5.78	144.33	Papua New Guinea	PNG	Asia and the Pacific
Rice Terraces of the Philippine Cordilleras	Rice	1995	16.93	121.14	Philippines	PHL	Asia and the Pacific
Muskauer Park / Park Mużakowski	Musk	2004	51.58	14.73	Poland	POL	Europe and North America

Alto Douro Wine Region	Alto	2001	41.10	-7.80	Portugal	PRT	Europe and North America
Landscape of the Pico Island Vineyard Culture	Pico	2004	38.51	-28.54	Portugal	PRT	Europe and North America
Roşia Montană Mining Landscape	Rosi	2021	46.31	23.13	Romania	ROU	Europe and North America
Curonian Spit	Curo	2000	55.27	20.96	Russian Federation	RUS	Europe and North America
Al-Ahsa Oasis, an Evolving Cultural Landscape	Alah	2018	25.40	49.63	Saudi Arabia	SAU	Arab States
Saloum Delta	Salm	2011	13.84	-16.50	Senegal	SEN	Africa
Bassari Country: Bassari, Fula and Bedik Cultural Landscapes	Bass	2012	12.59	-12.85	Senegal	SEN	Africa
Richtersveld Cultural and Botanical Landscape	Richt	2007	-28.60	17.20	South Africa	ZAF	Africa
Pyrénées - Mont Perdu	Pyre	1997	42.69	0.00	Spain	ESP	Europe and North America
Cultural Landscape of the Serra de Tramuntana	Serr	2011	39.73	2.69	Spain	ESP	Europe and North America
Agricultural Landscape of Southern Öland	Olan	2000	56.33	16.48	Sweden	SWE	Europe and North America
Lavaux, Vineyard Terraces	Lava	2007	46.49	6.75	Switzerland	CHE	Europe and North America
Ancient Villages of Northern Syria	Syri	2011	36.33	36.84	Syrian Arab Republic	SYR	Arab States
Koutammakou, the Land of the Batammariba	Kout	2004	10.07	1.13	Togo	TGO	Africa
Diyarbakır Fortress and Hevsel Gardens Cultural Landscape	Diyb	2015	37.90	40.24	Turkey	TUR	Europe and North America
Ancient City of Tauric Chersonese and its Chora	Taur	2013	44.61	33.49	Ukraine	UKR	Europe and North America
St Kilda	Stki	1986	57.82	-8.58	United Kingdom of Great Britain and Northern Ireland	GBR	Europe and North America
The English Lake District	Engd	2017	54.48	-3.08	United Kingdom of Great Britain and Northern Ireland	GBR	Europe and North America
Papahānaumokuākea	Papa	2010	25.35	-170.15	United States of America	USA	Europe and North America
Trang An Landscape Complex	Tran	2014	20.26	105.90	Viet Nam	VNM	Asia and the Pacific

A1 – Legend

Field	**Description**
name_en	Name of the UNESCO Cultural Landscape, in English
abb	Name abbreviation
date	Date of inclusion in the list
lat	Latitude
long	Longitude
states_nam	Name of Country
states_code	Code of the Country

Appendix 2 – UNESCO Agricultural Cultural Landscape: Values

abb	**state**	**V_ARCH**	**V_ARTC**	**V_HSET**	**V_MIND**	**V_HUNT**	**V_MINE**	**V_LOCM**	**V_RELS**	**V_NATV**	**V_RURL**	**V_FORE**	**V_GARD**	**V_TRAG**	**V_TRFI**	**V_TWAT**	**V_PAST**	**G_ATAV**	**G_AINV**	**G_NTNV**	**G_NINV**	**G_ANTV**	**G_NATV**	**A_AGRR**
Bam	AFG	1	0	1	0	0	0	0	1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1
Mpc	AND	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	1	1	0	1
Qhu	ARG	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	0	1	1	1	1
Ulur	AUS	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0	1	0	1	1	1	1	1
Budj	AUS	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	0	1	1	0	1
Hall	AUT	1	0	0	1	0	1	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1
Wac	AUT	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Fert	AUT	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Colb	BEL	0	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	1	1	0	1	1	1	1
Para	BRA	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	1	1	0	1	1	1	1
Gran	CAN	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	0	0	1	1	0	1
Hong	CHN	0	0	0	0	0	0	1	0	0	1	0	0	1	0	1	0	1	0	1	1	1	1	1
Zuoj	CHN	1	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Coff	COL	0	0	1	0	0	0	0	0	0	1	0	0	1	0	1	0	1	1	0	1	1	1	1
Viny	CUB	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	0	0	1	1	0	1
Cuba	CUB	1	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	1	0	1	1	1	1
Erzg	CZE	0	0	1	1	0	1	0	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1
Klad	CZE	0	0	0	0	0	0	1	0	0	1	0	0	1	0	1	0	1	0	1	1	1	1	1
Para	DNK	0	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	1	1	1
Kuja	DNK	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	1	1	0	1	1	1	1
Aasi	DNK	1	0	0	0	1	0	1	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1
Kons	ETH	0	1	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Pyre	FRA	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	0	0	1	1	0	1
Jsei	FRA	0	1	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Loir	FRA	0	1	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	0	1	1	1	1
Caus	FRA	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	0	1
Nord	FRA	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1	1	1

Cham	FRA	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Clim	FRA	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Tapu	FRA	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	1	0	0	1	1	0	1
Lope	GAB	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	0	1	1	1	1
Rhei	DEU	0	1	1	0	0	0	0	0	0	1	0	0	1	0	1	0	1	1	0	1	1	1	1
Musk	DEU	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	0	0	1	1	1
Berg	DEU	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	0	0	1	1	1
Erzg	DEU	0	0	1	1	0	1	0	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1
Hort	HUN	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	0	1	1	1	1
Fert	HUN	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Toka	HUN	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Thing	ISL	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	1	1	0	1	1	1	1
Bali	IDN	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1
Bam	IRN	0	1	1	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	1	1	1	1
Maym	IRN	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	1	0	1	1	1	1	1
Hawr	IRN	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	1	1	0	1
Inc	ISR	1	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	1	1	1	1	1	1	0
Cost	ITA	0	0	1	0	0	0	0	0	1	1	0	0	1	0	1	0	1	1	0	1	1	1	1
Port	ITA	0	0	1	0	0	0	0	0	1	1	0	0	1	0	1	0	1	1	0	1	1	1	1
Vald	ITA	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Medi	ITA	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	0	0	1	1	1
Pied	ITA	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Coll	ITA	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Petr	KAZ	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	1	1	1	1
Vatp	LAO	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1
Ouad	LBN	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0	0	1	0	1	1	1	1	1
Curo	LTU	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	1	1	0	1	1	1	1
Kern	LTU	1	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Amb	MDG	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	1	0	1	1	1	1	1
Agav	MEX	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	1	0	0	1	1	0	1
Orkh	MNG	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	1	0	1	1	1	1	1

Dutch	NLD	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	1	1	1	0
Bene	NLD	0	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	1	1	0	1	1	1	1
Suku	NGA	0	0	0	0	0	0	0	1	1	1	0	0	1	0	0	0	1	0	1	1	1	1	1
Vega	NOR	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	1	0	0	1	1	0	1
Pale	PSE	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	0	0	1	1	0	1
Kuk	PNG	1	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	1	0	1	1	1	1
Rice	PHL	0	0	0	0	0	0	1	0	0	1	0	0	1	0	1	0	1	0	1	1	1	1	1
Musk	POL	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	0	0	1	1	1
Alto	PRT	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	0	0	1	1	0	1
Pico	PRT	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Rosi	ROU	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	0	1
Curo	RUS	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	1	1	0	1	1	1	1
Alah	SAU	0	0	0	0	0	0	0	0	1	1	0	0	1	0	1	0	1	0	0	1	1	0	1
Salm	SEN	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	0	1	0	1	1	1	1	1
Bass	SEN	0	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	0	1	1	1	1
Richt	ZAF	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	1	0	1	1	1	1	1
Pyre	ESP	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	1	0	0	1	1	0	1
Serr	ESP	0	0	0	0	0	0	0	0	1	1	0	0	1	0	1	0	1	0	0	1	1	0	1
Olan	SWE	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	1	1	1	0	1	1	1	1
Lava	CHE	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Syri	SYR	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0	0	1	1	1	0	1	1	1
Kout	TGO	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	1	1	1
Diyb	TUR	1	0	1	0	0	0	0	0	0	1	0	0	1	0	1	0	1	1	0	1	1	1	1
Taur	UKR	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	1	1	1
Stki	GBR	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	1	1	1
Engd	GBR	0	0	1	0	0	0	0	0	1	1	0	0	1	0	0	1	1	1	0	1	1	1	1
Papa	USA	0	0	0	0	0	0	1	1	1	0	0	0	0	1	0	0	1	0	1	1	1	1	1
Tran	VNM	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	1	1	1	1	1	1	1

A2 - Legend

Abb	**Field**	**Description**
V_ARCH	Archaeology	Presence of archaeological finds/elements/repertoires/sites
V_ARTC	Art/Architecture	Presence of buildings/constructions/works with architectural and/or artistic value
V_HSET	Human settlement	Presence of urban conglomerates and/or traditional villages
V_MIND	Mining/Industrial landscape	Landscape largely influenced by industrial activity and presence of mines
V_HUNT	Hunting	Presence of hunting activities
V_MINE	Mining	Presence of mining activities
V_LOCM	Local communities	Presence of indigenous communities or sites where value is largely determined by local traditions
V_RELS	Religious/Spiritual	Site where value is largely determined by religious/spiritual aspects of local communities
V_NATV	Natural value	Presence of significant natural features
V_RURL	Rural landscape	Landscape largely influenced by agricultural activity
V_FORE	Forestry	Presence of forest-related productive activity
V_GARD	Gardens/Parks	Presence of parks and/or gardens
V_TRAG	Traditional Agriculture	Presence of traditional agricultural practices
V_TRFI	Traditional fishing	Presence of traditional fishing practices
V_TWAT	Traditional water management	Presence of significant water management systems
V_PAST	Pasture	Presence of productive activities related to pastoralism and/or transhumance
G_ATAV	ANTR_tang	Tangible_Anthropic_Value
G_AINV	ANTR_INtang	Intangible_Anthropic_Value
G_NTNV	NAT_tang	Tangible_Natural_Value
G_NINV	NAT_Intan	Intangible_Natural_Value
G_ANTV	ANTR_VALUE	Anthropic_Value
G_NATV	NAT_VALUE	Natural_Value

Appendix 3 – UNESCO Agricultural Cultural Landscape: Threats & Consequences

abb	state	T_STOR	T_DROU	T_TEMP	T_COWA	C_ERAC	C_ERAT	C_ERNA	C_ERAG	C_SLCU	C_SLMN	C_SLNT	C_SLPS	C_DESR	C_PMEL	C_HGAG	C_HGPG	C_HGNT	C_FLOO	C_CNOW	C_WATS	C_WILD	C_ERCO	C_SALT	U_UNPR	U_UNSC	U_UNMP	U_UNCC
Bam	AFG	1	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1
Mpc	AND	1	1	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	1	1	0	1
Qhu	ARG	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1
Ulur	AUS	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	1	1	0	0	1	1	0	1
Budj	AUS	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	1	1
Hall	AUT	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0
Wac	AUT	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	1
Fert	AUT	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	1
Colb	BEL	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Para	BRA	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0
Gran	CAN	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	0	1
Hong	CHN	1	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0
Zuoj	CHN	1	1	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0
Coff	COL	1	0	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	1	1
Viny	CUB	1	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0
Cuba	CUB	1	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Erzg	CZE	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
Klad	CZE	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1
Para	DNK	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0
Kuja	DNK	1	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	1	0	0
Aasi	DNK	1	0	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	1
Kons	ETH	1	0	1	0	0	1	0	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Pyre	FRA	1	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1
Jsei	FRA	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1	0
Loir	FRA	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1	1	1
Caus	FRA	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1	1
Nord	FRA	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0

Cham	FRA	1	1	1	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	1	0	0
Clim	FRA	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	1	0	0
Tapu	FRA	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	1
Lope	GAB	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0
Rhei	DEU	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	0
Musk	DEU	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	1	0	0	1
Berg	DEU	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0
Erzg	DEU	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
Hort	HUN	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0
Fert	HUN	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	1
Toka	HUN	1	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1	0	1
Thing	ISL	1	0	1	1	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	1	0	0	0
Bali	IDN	1	1	1	0	0	1	0	1	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0
Bam	IRN	0	1	1	0	0	1	1	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	1	1	0	1
Maym	IRN	1	1	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
Hawr	IRN	1	1	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0
Inc	ISR	0	1	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	1	0	0	0
Cost	ITA	1	1	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	0	0	1
Port	ITA	1	1	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	1	1	1
Vald	ITA	1	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	0	0	0
Medi	ITA	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	1	0	0	0
Pied	ITA	1	1	1	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0
Coll	ITA	1	1	1	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0
Petr	KAZ	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	1
Vatp	LAO	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1
Ouad	LBN	1	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	1	0
Curo	LTU	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	1	1	1	1
Kern	LTU	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0
Amb	MDG	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	1
Agav	MEX	1	1	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
Orkh	MNG	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1

Dutch	NLD	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0
Bene	NLD	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Suku	NGA	1	0	1	0	0	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1
Vega	NOR	1	0	1	1	0	0	0	0	1	0	1	0	0	0	0	0	1	1	0	0	0	1	0	1	0	0	1
Pale	PSE	1	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	1	1	1
Kuk	PNG	1	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	1	0	1	1
Rice	PHL	1	1	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	1	1	1
Musk	POL	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	1	0	0	1
Alto	PRT	1	0	1	0	0	0	0	1	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	1	1	0	1
Pico	PRT	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0
Rosi	ROU	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
Curo	RUS	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	1	1	1	1
Alah	SAU	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	1	1
Salm	SEN	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	1
Bass	SEN	1	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0
Richt	ZAF	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	1	1
Pyre	ESP	1	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1
Serr	ESP	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	0	1	0	0	1
Olan	SWE	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	1
Lava	CHE	1	1	1	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	0	0	1
Syri	SYR	1	1	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1	0
Kout	TGO	1	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Diyb	TUR	1	1	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	1
Taur	UKR	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1
Stki	GBR	1	1	1	1	1	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	1	0	1	1	0	1
Engd	GBR	1	1	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1
Papa	USA	1	1	1	1	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	1	0	0	1
Tran	VNM	1	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	1	0	0

A3 - Legend

Abb	**Field**	**Description**
T_STOR	T_Sto	Storm
T_DROU	T_dro	Drought
T_TEMP	T_TemC	Temperature Change
T_COWA	T_COW	Changes to oceanic waters
C_ERAC	C_ErArc	Erosion (arch. findings)
C_ERAT	C_ErArti	Erosion (artifacts)
C_ERNA	C_ErAgNa	Erosion (nat. + agr. soil)
C_ERAG	C_ErAgr	Erosion (agr. soil)
C_SLCU	C_SloCul	Slope failure (cultivated)
C_SLMN	C_SloMin	Slope failure (mine)
C_SLNT	C_SloNat	Slope failure (natural)
C_SLPS	C_SloPas	Slope failure (pasture)
C_DESR	C_Des	Desertification
C_PMEL	C_PerMel	Permafrost melting
C_HGAG	C_HeaAgr	Heatwave (agriculture)
C_HGPG	C_HeaPar	Heatwave (park greenery)
C_HGNT	C_HeaNat	Heatwave (natural)
C_FLOO	C_Flo	Flooding
C_CNOW	C_CNOW	Changes to non-oceanic waters (changed water bodies)
C_WATS	C_WatSca	Water scarcity
C_WILD	C_WilF	Wildfire
C_ERCO	C_ErCoa	Erosion (coastal)
C_SALT	C_Sal	Salinization
U_UNPR	UN_PeRep	Periodic Report
U_UNSC	UN_SOC	State of Conservation
U_UNMP	UN_MaPl	Management plan
U_UNCC	UN_talk_ClCh	Storm

Appendix 4 – UNESCO Agricultural Cultural Landscape: Climate Values

abb	state_code	GCM_code	HM_B1	HM_B5	HM_B10	HM_B12	HM_B13	HM_B18	FM_DY_B1	FM_DY_B5	FM_DY_B10	FM_DY_B12	FM_DY_B13	FM_DY_B18
Bam	AFG	MPI	6.4	26.1	17.2	193.0	42.0	6.0	11.7	30.9	22.8	183.0	35.0	6.0
Mpc	AND	HAD	2.1	18.1	10.7	1416.0	158.0	249.0	9.6	30.3	20.7	1214.0	172.0	153.0
Qhu	ARG	BCC	10.6	21.5	14.0	239.0	60.0	134.0	15.5	27.8	19.0	335.0	78.0	188.0
Ulur	AUS	ECE	21.6	38.2	29.0	312.0	49.0	114.0	26.8	42.4	33.7	393.0	62.0	148.0
Budj	AUS	ECE	13.4	24.2	17.5	740.0	92.0	101.0	17.6	28.4	22.0	693.0	89.0	101.0
Hall	AUT	HAD	3.6	16.2	11.1	1520.0	201.0	557.0	12.1	29.1	21.1	1472.0	187.0	351.0
Wac	AUT	HAD	8.3	23.2	17.1	664.0	92.5	261.0	16.8	36.4	27.3	626.5	86.5	198.5
Fert	AUT	HAD	10.3	25.7	19.5	578.0	70.0	194.0	19.0	39.4	30.2	540.0	65.0	148.0
Colb	BEL	HAD	10.1	23.0	17.0	808.0	78.0	209.0	16.4	32.8	24.7	739.0	87.0	132.0
Para	BRA	ECE	20.2	28.1	23.0	1800.5	278.0	769.5	24.6	31.8	26.9	1841.0	324.0	890.0
Gran	CAN	ECE	6.7	24.6	17.7	1162.0	118.0	230.0	14.0	31.4	24.7	1296.0	136.0	252.0
Hong	CHN	ECE	17.2	25.4	21.2	1228.0	258.0	716.0	22.3	30.3	25.6	1386.0	321.0	652.0
Zuoj	CHN	ECE	22.5	32.3	28.5	1562.0	280.0	824.0	27.5	36.4	33.0	1842.0	343.0	959.0
Coff	COL	ECE	19.6	24.9	19.9	2171.0	270.0	514.0	24.3	30.1	24.9	2206.0	283.0	380.0
Viny	CUB	ECE	23.9	31.1	26.2	1549.0	212.0	598.0	28.9	37.3	32.2	1329.0	189.0	400.0
Cuba	CUB	ECE	23.1	28.9	24.9	1470.5	226.5	462.0	27.8	34.1	30.1	1455.5	235.0	404.0
Erzg	CZE	HAD	5.1	18.0	13.0	921.0	109.0	304.0	12.9	30.9	22.5	858.0	87.0	220.0
Klad	CZE	HAD	8.0	23.2	17.5	544.0	79.0	218.0	16.5	36.7	27.6	486.0	62.0	151.0
Para	DNK	HAD	7.9	19.9	15.7	605.0	65.0	174.5	14.6	28.8	23.2	597.0	68.5	135.0
Kuja	DNK	HAD	0.2	11.7	6.9	808.5	92.0	236.5	7.2	19.8	14.4	966.5	114.5	307.0
Aasi	DNK	HAD	-5.8	12.9	7.2	280.5	49.0	113.5	2.7	21.3	15.3	384.0	71.0	165.0
Kons	ETH	ECE	21.7	31.6	23.5	664.0	110.0	122.0	25.8	35.7	28.2	985.0	184.5	152.0
Pyre	FRA	HAD	2.8	19.7	11.5	1362.0	144.0	249.0	10.3	32.6	21.4	1122.0	137.0	139.0
Jsei	FRA	HAD	13.0	26.6	19.9	905.5	99.0	166.5	19.7	38.0	28.3	755.5	94.5	104.0
Loir	FRA	HAD	11.4	25.1	18.4	668.0	68.0	141.0	18.4	36.9	27.7	596.0	72.0	95.0
Caus	FRA	HAD	9.9	23.8	17.4	890.0	123.0	151.0	17.5	37.4	27.7	767.5	100.0	99.5
Nord	FRA	HAD	10.3	23.3	17.2	713.0	70.0	183.0	16.8	33.9	25.4	642.0	71.0	111.0

Cham	FRA	HAD	10.4	24.5	17.8	609.0	58.0	167.0	17.6	36.6	27.0	541.0	58.0	114.0
Clim	FRA	HAD	10.5	24.6	18.4	815.0	89.0	201.0	18.3	38.3	28.1	701.0	83.0	91.0
Tapu	FRA	HAD	24.8	29.1	26.0	2072.0	256.0	642.0	28.8	33.3	30.1	2324.0	319.0	740.0
Lope	GAB	BCC	24.7	30.4	25.6	1871.0	334.5	594.0	28.3	34.7	29.5	2318.0	455.0	823.0
Rhei	DEU	HAD	9.2	22.8	17.1	680.5	71.5	195.0	16.6	35.5	26.4	620.0	66.0	136.5
Musk	DEU	HAD	8.9	23.2	17.4	663.0	99.0	232.0	16.6	35.8	26.7	624.0	70.0	173.0
Berg	DEU	HAD	7.5	20.6	15.3	852.0	82.0	228.0	14.8	32.8	24.3	803.0	92.0	168.0
Erzg	DEU	HAD	8.5	22.6	17.0	744.0	95.0	250.0	16.1	35.0	26.4	695.0	69.0	185.0
Hort	HUN	HAD	10.4	28.1	20.7	533.0	72.0	192.0	19.5	42.1	31.7	466.0	59.0	132.0
Fert	HUN	HAD	10.3	25.5	19.5	589.5	74.0	201.0	19.1	39.4	30.2	546.0	68.0	151.0
Toka	HUN	HAD	9.1	24.9	18.7	618.0	85.0	231.5	18.3	39.5	29.6	527.0	68.0	146.0
Thing	ISL	HAD	3.3	12.6	9.3	1100.5	107.5	243.5	10.4	19.3	15.9	1148.5	151.0	275.5
Bali	IDN	ECE	20.3	25.1	20.8	2350.5	399.0	758.5	24.1	29.0	24.6	2785.0	489.0	853.5
Bam	IRN	MPI	21.7	37.1	30.7	148.0	36.0	4.0	26.8	42.5	36.4	144.0	34.0	4.0
Maym	IRN	MPI	14.4	34.3	25.0	153.0	34.0	5.0	19.5	39.8	31.0	156.0	34.0	5.0
Hawr	IRN	MPI	13.5	35.4	25.6	695.0	133.0	1.0	18.7	41.4	31.4	609.0	101.0	1.0
Inc	ISR	MPI	19.3	33.9	26.4	115.5	25.0	0.0	23.7	39.5	31.8	103.5	22.0	0.0
Cost	ITA	HAD	13.7	26.3	20.9	967.0	142.0	94.0	20.7	35.7	29.5	841.0	118.0	107.0
Port	ITA	HAD	12.8	27.2	20.6	1129.0	158.0	146.5	20.5	39.0	30.3	1089.0	162.5	120.0
Vald	ITA	HAD	13.2	28.5	21.4	625.0	80.0	99.5	21.0	39.7	31.3	550.0	75.5	88.5
Medi	ITA	HAD	14.5	30.6	23.0	879.0	114.5	154.5	22.4	42.4	32.8	808.5	123.0	112.0
Pied	ITA	HAD	13.2	27.9	22.1	632.0	82.0	121.0	21.2	40.2	32.0	557.0	65.0	84.0
Coll	ITA	HAD	11.7	27.0	20.9	983.0	109.5	283.5	20.4	41.1	31.4	899.5	93.0	206.5
Petr	KAZ	MPI	8.2	31.3	22.3	388.0	58.5	79.0	13.1	37.5	28.3	406.5	59.5	73.0
Vatp	LAO	ECE	27.2	34.7	29.2	2251.0	618.0	334.0	31.5	38.8	33.6	3034.0	851.0	439.0
Ouad	LBN	MPI	14.8	30.2	22.6	1091.0	235.0	10.0	18.9	34.8	27.2	933.0	205.0	9.0
Curo	LTU	HAD	7.5	20.5	16.3	761.0	90.0	215.0	15.1	30.2	24.9	770.5	105.0	176.0
Kern	LTU	HAD	6.2	22.0	16.1	624.0	76.0	217.0	14.9	33.3	25.8	598.0	61.0	163.0
Amb	MDG	HAD	18.7	26.4	21.1	1254.0	300.0	746.0	24.6	33.8	27.3	1366.0	337.0	890.0
Agav	MEX	ECE	23.1	37.4	26.3	787.0	211.0	177.0	28.8	43.4	32.3	682.0	166.5	143.5
Orkh	MNG	ECE	-0.5	22.3	14.7	262.0	75.0	191.0	7.2	30.8	23.1	285.0	76.0	202.0

Dutch	NLD	HAD	9.6	21.3	16.1	824.0	91.5	198.5	15.5	29.0	22.9	775.5	102.5	135.0
Bene	NLD	HAD	9.0	21.5	15.7	844.0	86.0	217.0	14.9	29.4	22.4	793.0	96.0	144.0
Suku	NGA	BCC	24.6	35.8	27.8	901.5	267.5	111.5	29.2	40.6	32.8	1345.0	353.5	153.5
Vega	NOR	HAD	6.5	15.9	12.7	1574.0	190.0	320.0	13.7	23.3	20.0	2021.0	291.0	574.5
Pale	PSE	MPI	19.7	26.1	21.3	2799.5	460.0	794.0	22.9	28.7	24.2	3036.5	489.5	875.5
Kuk	PNG	ECE	19.0	25.1	19.4	2634.5	318.5	897.0	23.3	29.1	23.5	3029.5	356.0	1015.5
Rice	PHL	ECE	20.6	27.1	22.3	3056.0	465.0	975.0	24.9	31.1	26.5	3562.0	512.0	931.0
Musk	POL	HAD	8.9	23.1	17.4	663.0	101.0	234.0	16.6	35.7	26.7	624.0	71.0	173.0
Alto	PRT	HAD	14.0	25.6	19.6	1246.0	182.0	97.0	20.6	34.4	27.6	1055.0	200.0	68.0
Pico	PRT	HAD	17.6	25.6	21.8	1130.5	152.5	180.0	23.2	32.0	28.2	1185.5	176.5	186.0
Rosi	ROU	HAD	6.2	21.0	15.4	766.0	115.0	287.5	15.4	35.7	26.8	657.0	85.0	190.0
Curo	RUS	HAD	7.6	20.7	16.4	772.0	86.0	220.0	15.3	30.6	25.0	782.0	100.0	178.0
Alah	SAU	MPI	26.5	41.6	34.5	79.0	24.0	0.0	31.7	46.1	39.9	79.0	23.0	0.0
Salm	SEN	BCC	26.3	32.5	27.4	729.0	282.0	494.0	29.7	36.5	30.5	742.0	258.0	433.0
Bass	SEN	BCC	27.9	38.7	31.3	1160.5	315.5	55.0	31.7	42.8	35.1	1096.5	282.5	55.0
Richt	ZAF	HAD	19.3	31.1	23.5	76.5	16.0	35.0	25.1	36.6	29.3	68.0	13.0	23.0
Pyre	ESP	HAD	4.4	20.8	12.7	1277.0	137.0	241.0	11.9	33.6	22.6	1048.0	127.0	134.0
Serr	ESP	HAD	14.3	27.6	21.5	627.0	91.5	100.5	20.3	34.8	28.6	558.5	79.5	81.5
Olan	SWE	HAD	7.4	21.1	15.9	487.0	52.0	136.0	14.6	30.0	24.1	493.5	60.0	112.5
Lava	CHE	HAD	10.2	24.4	18.3	1214.0	136.0	362.0	18.7	37.8	28.1	1046.0	110.0	173.0
Syri	SYR	MPI	17.0	34.3	26.7	502.0	96.0	5.0	21.5	38.9	31.6	437.0	83.0	5.0
Kout	TGO	BCC	27.6	37.3	30.2	1116.0	242.5	92.0	32.0	41.5	35.1	1034.5	180.5	96.5
Diyb	TUR	HAD	15.7	38.9	28.7	512.0	79.0	10.0	24.7	48.6	38.3	501.0	76.0	12.0
Taur	UKR	HAD	11.0	27.0	21.2	450.0	57.5	107.5	18.3	35.3	29.6	450.0	59.5	99.5
Stki	GBR	HAD	7.7	12.9	10.9	1636.0	189.0	372.0	11.5	18.3	16.1	1623.0	214.0	341.0
Engd	GBR	HAD	7.7	17.6	13.1	1598.0	179.5	315.0	13.2	25.3	20.0	1628.0	208.0	291.5
Papa	USA	ECE	22.7	28.7	26.5	1405.0	194.0	324.0	27.3	33.7	31.4	1479.0	187.0	404.0
Tran	VNM	ECE	23.7	32.4	28.9	1769.0	413.0	790.0	28.4	37.0	33.8	1914.0	560.0	712.0

A4 – Legend

- **GCM_code** indicates the Global Climate Model (GCM) utilized:
    - BCC_CSM2_MR; Code: BCC
    - EC_Earth3_Veg; Code: ECE
    - HadGEM3_GC31_LL: Code: HAD
    - MPI_ESM1_2_HR; Code: MPI

- **HM** indicates the analysis is based on Historical scenario (**H**) researching median values (**M**) within each site:
    - 1970-2000: Code: H (historical)

- **FM** indicates the analysis is based on Future scenario (**F**) researching median values (**M**) in different scenario (**X** or **Y**) within each site:
    - Time:
        - 2021-2040: Code: A *(not included in this PhD thesis; it will be studied in the future)*
        - 2041-2060: Code: B *(not included in this PhD thesis; it will be studied in the future)*
        - 2061-2080: Code: C *(not included in this PhD thesis; it will be studied in the future)*
        - **2081-2100: Code: D**
    - Scenario:
        - ssp245: Code: X *(not included in this PhD thesis; it will be studied in the future)*
        - **ssp585: Code: Y**

- **B** is the investigated Bioclimatic Variables:
    - Temperature
        - B1; Annual Mean Temperature (°C)
        - B5: Max Temperature of Warmest Month (°C)
    - Precipitation:
        - B12: Annual Precipitation (mm)
        - B13: Precipitation of Wettest Month (mm)
    - Summer Conditions:
        - B10: Mean Temperature of Warmest Quarter (°C)
        - B18): Precipitation of Warmest Quarter (mm)

Appendix 5 – UNESCO Agricultural Cultural Landscape: Climate Analysis

abb	State	DA_DY_B1	DA_DY_B5	DA_DY_B12	DA_DY_B13	DA_DY_B10	DA_DY_B18	DP_DY_B1	DP_DY_B5	DP_DY_B12	DP_DY_B13	DP_DY_B10	DP_DY_B18	D_DY_T	D_DY_P	D_DY_TP
Bam	AFG	5.30	4.80	-10.00	-7.00	5.60	0.00	0.83	0.18	-0.05	-0.17	0.33	0.00	0.13	-0.43	3
Mpc	AND	7.50	12.20	-202.00	14.00	10.00	-96.00	3.57	0.67	-0.14	0.09	0.93	-0.39	0.47	-0.33	4
Qhu	ARG	4.90	6.30	96.00	18.00	5.00	54.00	0.46	0.29	0.40	0.30	0.36	0.40	0.19	0.63	3
Ulur	AUS	5.20	4.20	81.00	13.00	4.70	34.00	0.24	0.11	0.26	0.27	0.16	0.30	0.07	0.46	3
Budj	AUS	4.20	4.20	-47.00	-3.00	4.50	0.00	0.31	0.17	-0.06	-0.03	0.26	0.00	0.11	-0.23	3
Hall	AUT	8.50	12.90	-48.00	-14.00	10.00	-206.00	2.36	0.80	-0.03	-0.07	0.90	-0.37	0.53	-0.21	4
Wac	AUT	8.50	13.20	-37.50	-6.00	10.20	-62.50	1.02	0.57	-0.06	-0.06	0.60	-0.24	0.37	-0.27	4
Fert	AUT	8.70	13.70	-38.00	-5.00	10.70	-46.00	0.84	0.53	-0.07	-0.07	0.55	-0.24	0.35	-0.30	4
Colb	BEL	6.30	9.80	-69.00	9.00	7.70	-77.00	0.62	0.43	-0.09	0.12	0.45	-0.37	0.28	-0.15	4
Para	BRA	4.40	3.70	40.50	46.00	3.90	120.50	0.22	0.13	0.02	0.17	0.17	0.16	0.09	0.15	3
Gran	CAN	7.30	6.80	134.00	18.00	7.00	22.00	1.09	0.28	0.12	0.15	0.40	0.10	0.19	0.23	3
Hong	CHN	5.10	4.90	158.00	63.00	4.40	-64.00	0.30	0.19	0.13	0.24	0.21	-0.09	0.13	0.31	4
Zuoj	CHN	5.00	4.10	280.00	63.00	4.50	135.00	0.22	0.13	0.18	0.23	0.16	0.16	0.08	0.35	3
Coff	COL	4.70	5.20	35.00	13.00	5.00	-134.00	0.24	0.21	0.02	0.05	0.25	-0.26	0.13	0.05	4
Viny	CUB	5.00	6.20	-220.00	-23.00	6.00	-198.00	0.21	0.20	-0.14	-0.11	0.23	-0.33	0.13	-0.58	4
Cuba	CUB	4.70	5.20	-15.00	8.50	5.20	-58.00	0.20	0.18	-0.01	0.04	0.21	-0.13	0.12	0.00	4
Erzg	CZE	7.80	12.90	-63.00	-22.00	9.50	-84.00	1.53	0.72	-0.07	-0.20	0.73	-0.28	0.47	-0.53	4
Klad	CZE	8.50	13.50	-58.00	-17.00	10.10	-67.00	1.06	0.58	-0.11	-0.22	0.58	-0.31	0.38	-0.66	4
Para	DNK	6.70	8.90	-8.00	3.50	7.50	-39.50	0.85	0.45	-0.01	0.05	0.48	-0.23	0.29	0.00	4
Kuja	DNK	7.00	8.10	158.00	22.50	7.50	70.50	35.00	0.69	0.20	0.24	1.09	0.30	0.93	0.38	3
Aasi	DNK	8.50	8.40	103.50	22.00	8.10	51.50	1.47	0.65	0.37	0.45	1.13	0.45	0.43	0.71	3
Kons	ETH	4.10	4.10	321.00	74.50	4.70	30.00	0.19	0.13	0.48	0.68	0.20	0.25	0.08	0.99	3
Pyre	FRA	7.50	12.90	-240.00	-7.00	9.90	-110.00	2.68	0.65	-0.18	-0.05	0.86	-0.44	0.45	-0.57	4
Jsei	FRA	6.70	11.40	-150.00	-4.50	8.40	-62.50	0.52	0.43	-0.17	-0.05	0.42	-0.38	0.28	-0.54	4
Loir	FRA	7.00	11.80	-72.00	4.00	9.30	-46.00	0.61	0.47	-0.11	0.06	0.51	-0.33	0.30	-0.26	4
Caus	FRA	7.60	13.60	-122.50	-23.00	10.30	-51.50	0.77	0.57	-0.14	-0.19	0.59	-0.34	0.37	-0.70	4
Nord	FRA	6.50	10.60	-71.00	1.00	8.20	-72.00	0.63	0.45	-0.10	0.01	0.48	-0.39	0.29	-0.27	4

Cham	FRA	7.20	12.10	-68.00	0.00	9.20	-53.00	0.69	0.49	-0.11	0.00	0.52	-0.32	0.32	-0.31	4
Clim	FRA	7.80	13.70	-114.00	-6.00	9.70	-110.00	0.74	0.56	-0.14	-0.07	0.53	-0.55	0.36	-0.50	4
Tapu	FRA	4.00	4.20	252.00	63.00	4.10	98.00	0.16	0.14	0.12	0.25	0.16	0.15	0.09	0.31	3
Lope	GAB	3.60	4.30	447.00	120.50	3.90	229.00	0.15	0.14	0.24	0.36	0.15	0.39	0.09	0.51	3
Rhei	DEU	7.40	12.70	-60.50	-5.50	9.30	-58.50	0.80	0.56	-0.09	-0.08	0.54	-0.30	0.36	-0.38	4
Musk	DEU	7.70	12.60	-39.00	-29.00	9.30	-59.00	0.87	0.54	-0.06	-0.29	0.53	-0.25	0.35	-0.66	4
Berg	DEU	7.30	12.20	-49.00	10.00	9.00	-60.00	0.97	0.59	-0.06	0.12	0.59	-0.26	0.39	-0.07	4
Erzg	DEU	7.60	12.40	-49.00	-26.00	9.40	-65.00	0.89	0.55	-0.07	-0.27	0.55	-0.26	0.36	-0.64	4
Hort	HUN	9.10	14.00	-67.00	-13.00	11.00	-60.00	0.88	0.50	-0.13	-0.18	0.53	-0.31	0.33	-0.65	4
Fert	HUN	8.80	13.90	-43.50	-6.00	10.70	-50.00	0.85	0.55	-0.07	-0.08	0.55	-0.25	0.35	-0.34	4
Toka	HUN	9.20	14.60	-91.00	-17.00	10.90	-85.50	1.01	0.59	-0.15	-0.20	0.58	-0.37	0.38	-0.75	4
Thing	ISL	7.10	6.70	48.00	43.50	6.60	32.00	2.15	0.53	0.04	0.40	0.71	0.13	0.36	0.34	3
Bali	IDN	3.80	3.90	434.50	90.00	3.80	95.00	0.19	0.16	0.18	0.23	0.18	0.13	0.10	0.35	3
Bam	IRN	5.10	5.40	-4.00	-2.00	5.70	0.00	0.24	0.15	-0.03	-0.06	0.19	0.00	0.09	-0.17	3
Maym	IRN	5.10	5.50	3.00	0.00	6.00	0.00	0.35	0.16	0.02	0.00	0.24	0.00	0.11	0.02	3
Hawr	IRN	5.20	6.00	-86.00	-32.00	5.80	0.00	0.39	0.17	-0.12	-0.24	0.23	0.00	0.11	-0.75	3
Inc	ISR	4.40	5.60	-12.00	-3.00	5.40	0.00	0.23	0.17	-0.10	-0.12	0.20	0.00	0.11	-0.49	3
Cost	ITA	7.00	9.40	-126.00	-24.00	8.60	13.00	0.51	0.36	-0.13	-0.17	0.41	0.14	0.23	-0.65	3
Port	ITA	7.70	11.80	-40.00	4.50	9.70	-26.50	0.60	0.43	-0.04	0.03	0.47	-0.18	0.28	-0.08	4
Vald	ITA	7.80	11.20	-75.00	-4.50	9.90	-11.00	0.59	0.39	-0.12	-0.06	0.46	-0.11	0.26	-0.43	4
Medi	ITA	7.90	11.80	-70.50	8.50	9.80	-42.50	0.54	0.39	-0.08	0.07	0.43	-0.28	0.25	-0.17	4
Pied	ITA	8.00	12.30	-75.00	-17.00	9.90	-37.00	0.61	0.44	-0.12	-0.21	0.45	-0.31	0.29	-0.68	4
Coll	ITA	8.70	14.10	-83.50	-16.50	10.50	-77.00	0.74	0.52	-0.08	-0.15	0.50	-0.27	0.34	-0.49	4
Petr	KAZ	4.90	6.20	18.50	1.00	6.00	-6.00	0.60	0.20	0.05	0.02	0.27	-0.08	0.13	0.06	4
Vatp	LAO	4.30	4.10	783.00	233.00	4.40	105.00	0.16	0.12	0.35	0.38	0.15	0.31	0.08	0.63	3
Ouad	LBN	4.10	4.60	-158.00	-30.00	4.60	-1.00	0.28	0.15	-0.14	-0.13	0.20	-0.10	0.10	-0.62	4
Curo	LTU	7.60	9.70	9.50	15.00	8.60	-39.00	1.01	0.47	0.01	0.17	0.53	-0.18	0.31	0.14	4
Kern	LTU	8.70	11.30	-26.00	-15.00	9.70	-54.00	1.40	0.51	-0.04	-0.20	0.60	-0.25	0.34	-0.45	4
Amb	MDG	5.90	7.40	112.00	37.00	6.20	144.00	0.32	0.28	0.09	0.12	0.29	0.19	0.18	0.18	3
Agav	MEX	5.70	6.00	-105.00	-44.50	6.00	-33.50	0.25	0.16	-0.13	-0.21	0.23	-0.19	0.10	-0.73	4
Orkh	MNG	7.70	8.50	23.00	1.00	8.40	11.00	15.40	0.38	0.09	0.01	0.57	0.06	0.46	0.10	3

Dutch	NLD	5.90	7.70	-48.50	11.00	6.80	-63.50	0.61	0.36	-0.06	0.12	0.42	-0.32	0.24	-0.08	4
Bene	NLD	5.90	7.90	-51.00	10.00	6.70	-73.00	0.66	0.37	-0.06	0.12	0.43	-0.34	0.24	-0.08	4
Suku	NGA	4.60	4.80	443.50	86.00	5.00	42.00	0.19	0.13	0.49	0.32	0.18	0.38	0.09	0.74	3
Vega	NOR	7.20	7.40	447.00	101.00	7.30	254.50	1.11	0.47	0.28	0.53	0.57	0.80	0.31	0.68	3
Pale	PSE	3.20	2.60	237.00	29.50	2.90	81.50	0.16	0.10	0.08	0.06	0.14	0.10	0.06	0.13	3
Kuk	PNG	4.30	4.00	395.00	37.50	4.10	118.50	0.23	0.16	0.15	0.12	0.21	0.13	0.10	0.24	3
Rice	PHL	4.30	4.00	506.00	47.00	4.20	-44.00	0.21	0.15	0.17	0.10	0.19	-0.05	0.10	0.24	4
Musk	POL	7.70	12.60	-39.00	-30.00	9.30	-61.00	0.87	0.55	-0.06	-0.30	0.53	-0.26	0.35	-0.66	4
Alto	PRT	6.60	8.80	-191.00	18.00	8.00	-29.00	0.47	0.34	-0.15	0.10	0.41	-0.30	0.22	-0.35	4
Pico	PRT	5.60	6.40	55.00	24.00	6.40	6.00	0.32	0.25	0.05	0.16	0.29	0.03	0.16	0.17	3
Rosi	ROU	9.20	14.70	-109.00	-30.00	11.40	-97.50	1.48	0.70	-0.14	-0.26	0.74	-0.34	0.46	-0.84	4
Curo	RUS	7.70	9.90	10.00	14.00	8.60	-42.00	1.01	0.48	0.01	0.16	0.52	-0.19	0.31	0.13	4
Alah	SAU	5.20	4.50	0.00	-1.00	5.40	0.00	0.20	0.11	0.00	-0.04	0.16	0.00	0.07	-0.07	3
Salm	SEN	3.40	4.00	13.00	-24.00	3.10	-61.00	0.13	0.12	0.02	-0.09	0.11	-0.12	0.08	-0.13	4
Bass	SEN	3.80	4.10	-64.00	-33.00	3.80	0.00	0.14	0.11	-0.06	-0.10	0.12	0.00	0.07	-0.33	3
Richt	ZAF	5.80	5.50	-8.50	-3.00	5.80	-12.00	0.30	0.18	-0.11	-0.19	0.25	-0.34	0.12	-0.63	4
Pyre	ESP	7.50	12.80	-229.00	-10.00	9.90	-107.00	1.70	0.62	-0.18	-0.07	0.78	-0.44	0.41	-0.62	4
Serr	ESP	6.00	7.20	-68.50	-12.00	7.10	-19.00	0.42	0.26	-0.11	-0.13	0.33	-0.19	0.17	-0.53	4
Olan	SWE	7.20	8.90	6.50	8.00	8.20	-23.50	0.97	0.42	0.01	0.15	0.52	-0.17	0.28	0.13	4
Lava	CHE	8.50	13.40	-168.00	-26.00	9.80	-189.00	0.83	0.55	-0.14	-0.19	0.54	-0.52	0.36	-0.71	4
Syri	SYR	4.50	4.60	-65.00	-13.00	4.90	0.00	0.26	0.13	-0.13	-0.14	0.18	0.00	0.09	-0.59	3
Kout	TGO	4.40	4.20	-81.50	-62.00	4.90	4.50	0.16	0.11	-0.07	-0.26	0.16	0.05	0.07	-0.63	3
Diyb	TUR	9.00	9.70	-11.00	-3.00	9.60	2.00	0.57	0.25	-0.02	-0.04	0.33	0.20	0.16	-0.12	3
Taur	UKR	7.30	8.30	0.00	2.00	8.40	-8.00	0.66	0.31	0.00	0.03	0.40	-0.07	0.20	0.03	4
Stki	GBR	3.80	5.40	-13.00	25.00	5.20	-31.00	0.49	0.42	-0.01	0.13	0.48	-0.08	0.27	0.08	4
Engd	GBR	5.50	7.70	30.00	28.50	6.90	-23.50	0.71	0.44	0.02	0.16	0.53	-0.07	0.28	0.14	4
Papa	USA	4.60	5.00	74.00	-7.00	4.90	80.00	0.20	0.17	0.05	-0.04	0.18	0.25	0.11	-0.01	3
Tran	VNM	4.70	4.60	145.00	147.00	4.90	-78.00	0.20	0.14	0.08	0.36	0.17	-0.10	0.09	0.35	4

A5 – Legend

- **DA** indicates the Difference (**D**) in absolute terms (**A**) between the future scenario (time: A, B, C; or **D**; scenario: X or **Y**; each site with a specific GCM_code; see Appendix 4) and the historical scenario (1970-2000) for the various Bioclimatic variable (**B**) B1, B5, B12, B13, B10, B18.

- **DP** indicates the Difference (**D**) in percentage terms (**P**) between the future scenario (time: A, B, C; or **D**; scenario: X or **Y**; each site with a specific GCM_code; see Appendix 4) and the historical scenario (1970-2000) for the various Bioclimatic variable (**B**) B1, B5, B12, B13, B10, B18.

- In the last 3 columns: D_DY_**T**, D_DY_**P**, and D_DY_T**P** (see section 12.3.3):
    - _**T**: refers to the Temperature Index (TI)
    - _**P**: refers to the Precipitation Index (PI)
    - _T**P**: refers to the Summer Condition Index (SCI)
