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Effects of historical land-use change in the Mediterranean environment

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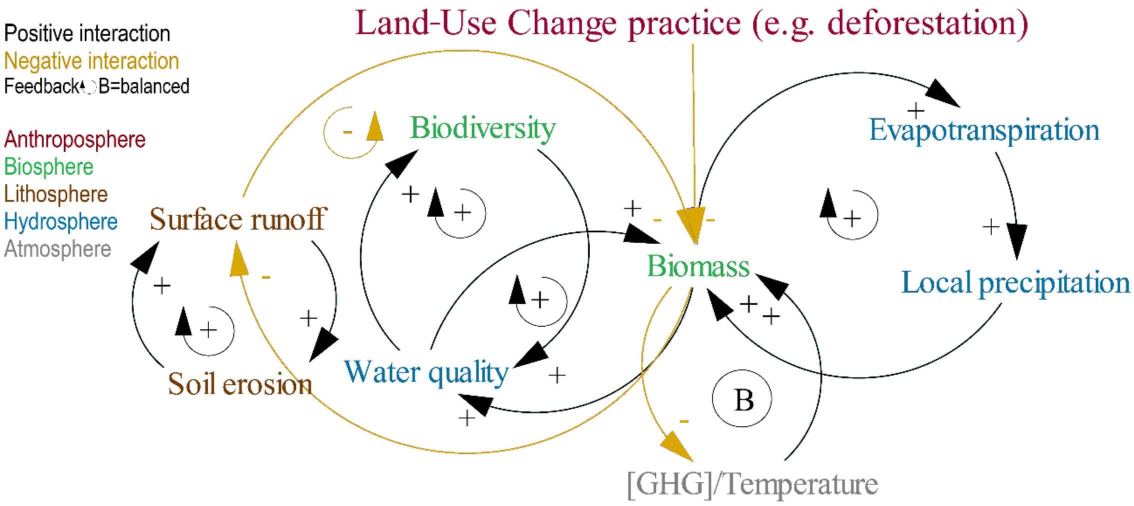
Graphical abstract



Highlights

- Collects specific case-studies and displays identified effects using a network map
- Highlights the importance of historical practices for developing adaptation strategies
- Argues the need for regional coordinated action within the Mediterranean Basin
- Assists in bridging the gap between scientific findings and policy-makers' knowledge

Keywords: Land-use change; Hydrological cycle; Mediterranean Basin; Holocene; Interdisciplinarity; Environmental management.

Abstract

During the Holocene (last ~11,700 years), societies have continuously modified the landscape of the Mediterranean Basin through changes in land-use, exerting extraordinary pressures onto the environment and adding variability to the climate. Despite its importance to current land management, knowledge of how past land-use practices have impacted the regional climate of the Basin remains largely in the scientific sphere. Thereby, this work aims to inform non-scientific actors and practitioners about the environmental effects of past land-use changes on the hydrologic cycle of the Mediterranean Basin. For this purpose we: i) summarize fundamental observed interactions between land-use change and the environment, identified through a semi-systematic review of 23 scientific case-studies from around the Basin; ii) reflect on the consequences to the Mediterranean environment (atmosphere, biosphere, lithosphere, and hydrosphere) in a synthesized and integrated way; iii) argue the need for taking into account the impact of local land-use practices from a broader, regional-scale perspective; iv) highlight the importance of understanding historical factors such as past land-use changes for developing protective strategies in the rural areas of the Basin. With this work, we provide a synthesized and more integrated understanding of the effects of past and local land-use changes in the regional Mediterranean environment, assisting to bridge the gap between scientific findings, Mediterranean watersheds stakeholders, and regional policy-makers.

1. Introduction

Land-use change (LUC) is not only among the largest anthropogenic impacts threatening the environment through the alteration of the biophysical properties of Earth's surface (Newbold et al. 2015) but it is also a major driver of climate change (Searchinger et al. 2018). LUCs in the Mediterranean Basin date back several thousand years, only to be exacerbated in the late-Holocene (Mercuri et al. 2019). First, with the establishment of trade networks across the Sea, and then, with the rising of affluence, demand of goods and services, industrialization that allowed production and consumption dissociation, and changes in the global diet, among others (Lambin and Meyfroidt 2011).

Along with the intensification of anthropologic activities, in the late-Holocene, a worldwide orbitally induced reorganization of the general atmospheric circulation caused the present-day warmer and drier climatic conditions of the Mediterranean (Bini et al. 2019). Currently, climate change further threatens the Basin’s landscapes by magnifying warming and aggravating both desertification and drought stresses, and undermining its adaptation and mitigation capacities (IPCC 2018).

Thus, the Mediterranean faces a greater demand of goods and services along with historical mismanagement of land and climate change aggravation, pushing for the need of understanding how LUCs might have affected and might continue to affect the regional climate variability (Plan Bleu 2016). Moreover, water scarcity within the Basin adds to the need to better understand how these affect the regional rainfall variability, and hence, the regional water supply. We argue in this paper that before exploring the sub-regional heterogeneities in climate patterns and historical trajectories of the Basin, that is, before narrowing the scope of the study to a watershed-scale, we must first understand the basic interactions between past LUC and the hydrological system of the Basin as a whole.

Because efforts to mitigate landscape degradation, restore water sources, and adapt to climate change are often shaped by historical factors (i.e. past LUC practices), understanding the impact of such factors in the Mediterranean environment is key to the development of protective strategies. In this context, the aim of this study is to inform regional policy-makers and Mediterranean watersheds stakeholders about the impacts that past LUC practices have had on the hydrological cycle of the Mediterranean Basin.

To meet this objective, we firstly carry out a semi-systematic literature review of case-studies that document the many particular environmental effects that have resulted from changes in land-use. These, thus, can be taken as an example of the numerous site-specific researches that exist on the topic. Next, we analyse the content of the reviewed studies and summarize the most important observed interactions. Based on these interactions, we develop an integrative network map which is used to holistically visualize and understand the effects of LUC in the Basin. Finally, we discuss the implications of past land-use changes on regional climate change and direct our findings to Mediterranean watersheds stakeholders and regional policy-makers.

The Mediterranean Basin is a key area to study such interactions, since this region is sensitive to regional and global climate change, is home to ancient civilizations, and is rich with information on the human-environment interaction i.e. archaeological sites, Quaternary deposits, etc. (Holmgren et al. 2016 and references therein). Thus, the Mediterranean constitutes an excellent area to convey the importance of accounting for the complex interactions between changes in the land-use and the regional climate, as synergies created between the two are crucial to assess their impacts on the long-term climate change of the Basin.

2. Materials and Methods

2.1. Literature search

We conduct a semi-systematic review of case-studies with the aim of acquiring an integrative view of the effects of LUC in the different systems of the Mediterranean environment. For this reason and to allow for different perspectives on this issue, we focus on the Land-Use Change (LUC)–environment interaction in the Holocene epoch.

For the compilation, we executed a search in the Web of Science database and the Science Direct collection with the following keywords: *paleoclimate, land-use, archaeology, Mediterranean, Holocene, and the name of all countries with Mediterranean coastal area or antique Mediterranean cultures*. The obtained results (n>500) were filtered following these three criteria: (a) date of publication between 2008–2018, as during these past years methodological developments have allowed for transdisciplinarity, permitting climate scientists, historians, and archaeologists to interact and provide a more holistic view of the results presented; (b) selection of studies taking place only within the Mediterranean sensu stricto biogeographical zone; (c) selection of studies that provide both, archaeological and environmental data (e.g. archaeological sites, pollen, charcoal, river geomorphology) related to paleoclimatic records (e.g. lake sediments, cave speleothems, deep-sea cores). After a screening of the abstracts and conclusions of the resulting filtered studies (n>45), we selected 16 studies that fulfilled the criteria of particularly assessing the LUC–environment interaction, i.e. LUC–landscape–climate interaction (Fig. 1 continuous-yellow circles).

Note that no studies are available along most of the coast of North Africa and the Ionian, Aegean, and Adriatic Seas. That is why we also considered 7 additional studies obtained from the review that inspected the LUC–landscape interaction but did not reflect on the effects on the local climate (Fig. 1 dashed-green triangles). In order to offer a more complete snapshot of the LUC–environment interaction in the Mediterranean Basin, we shortly discuss these as well. For the documentation of the paleoclimate, studies predominantly use speleothems, lacustrine and deep-sea sediment cores as proxy records, while information on past LUCs is commonly recorded by terrigenous sediment assemblages, archaeological sites, and pollen records. The majority of the developed work relates to the late-Holocene and reports on anthropogenic LUC intensification.

2.2. Analysis of the content of the selected studies

Following the review of case-specific studies, we analyse their content by collecting all identified LUC effects on the environment, and in particular, on the hydrological cycle (Table 1 in Results and Discussion). We then use the identified interactions to build a network map applying the Fuzzy Cognitive Mapping technique (FCM).

FCM is a system mapping method that computes the direct connections between elements (e.g. concepts, processes, actions). According to the number of connections incident on each element, it depicts its centrality (Kosko 1986). Without entering into the rationale of its statistical analysis, it might be said that the more interactions an element has, the more central its placement in the network (degree centrality). Thus, the resulting network map not only shows the different elements (input data) and how they interact among themselves (output 1), but it also allows us to inspect the importance (i.e. centrality) of each element (output 2).

To build the network map, both elements and connections had to be defined. First, we provided the FCM software with a total of 24 elements (keywords) that were identified when carrying out the text-analysis of the studies, namely: Regular fires / Deforestation; Hydraulic terrace / Aquifer; Farming and cropping; Overgrazing / Upstream pastoralism; Biodiversity; Salinization; Turbidity / Organic matter; River instability; Surface runoff; Biomass; Aridity & Soil erosion; Atmospheric [CO_2]; Aggradation / Increased sediment discharge; Temperature;

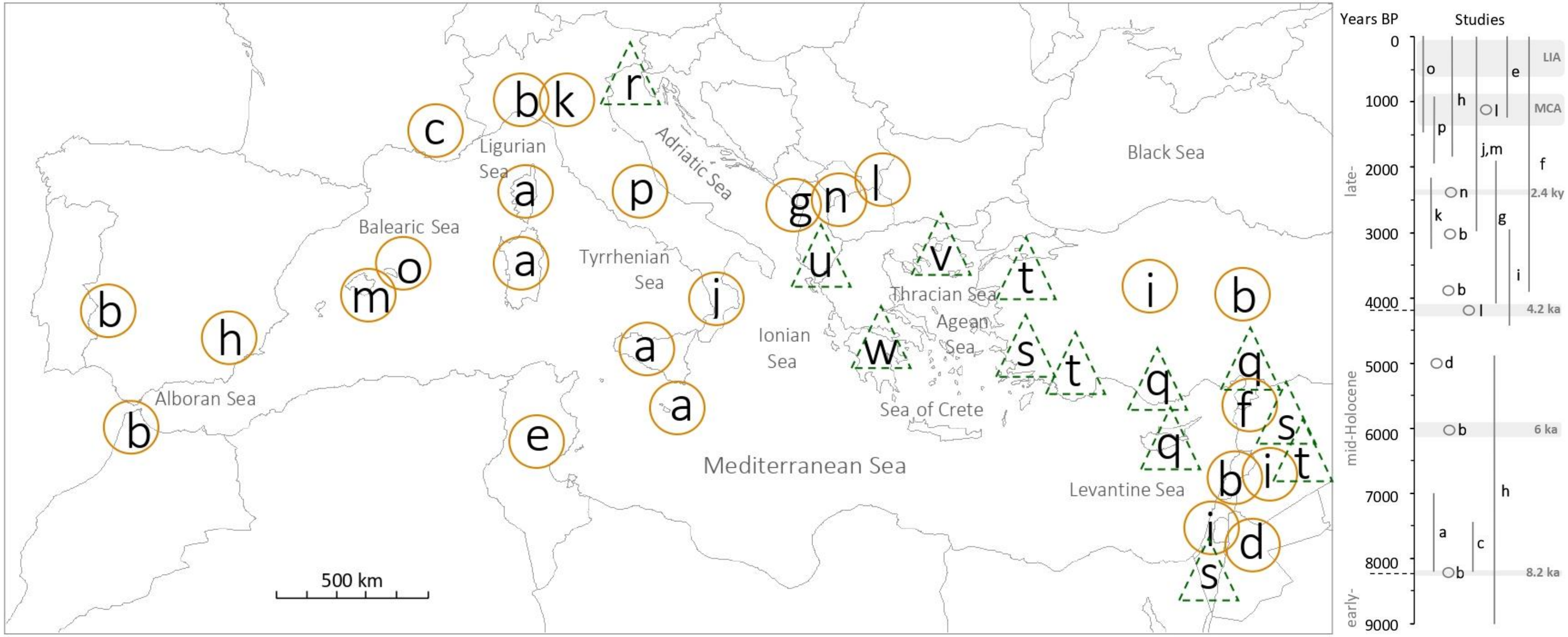


Figure 1. Geographical location and time-span of the reviewed studies. In continuous-yellow circles, studies that report Land-Use Change (LUC) practices in relation to the environment (i.e. landscape and climate) of the Holocene. In dashed-green triangles, studies that only document LUC practices in relation to the landscape. The shaded areas of the time-span represent major abrupt climatic events in years before present (BP, i.e. 1950), LIA refers to Little Ice Age, MWP to Medieval Warm Period, and ky/ka to thousand years. **LUC–environment**: **a.** Médali (2017); **b.** Mercuri et al. (2011); **c.** Berger et al. (2016); **d.** Meister et al. (2017); **e.** Zerai (2009); **f.** El Ouahabi et al. (2018); **g.** Mazzini et al. (2016); **h.** Baartman et al. (2011); **i.** Pustovoytov and Riehl (2016); **j.** Moser et al. (2017); **k.** Cremaschi et al. (2016); **l.** Thienemann et al. (2017); **m.** Picornell-Gelabert and Carrion-Marco (2017); **n.** Vogel et al. (2010); **o.** Balbo et al. (2018); **p.** Mensing et al. (2015). **LUC–landscape**: **q.** Zeder (2008); **r.** Fontana et al. (2017); **s.** Clarke et al. (2016); **t.** Flohr et al. (2016); **u.** Morellón et al. (2016); **v.** Gogou et al. (2016); **w.** Weiberg et al. (2016).

Redistribution of species; Flooding; Evapotranspiration; Water availability in wetlands; Topographic rainfall; Water quality; Groundwater flow; Soil Organic Carbon; Albedo; Pedogenesis. Following this, we assessed the presence of a positive and/or negative interaction for each pair of elements. For example, the following interaction "*Reinforcement of soil erosion and aridification through overgrazing*" was introduced into the FCM software by (1) identifying the elements related to this statement: 'Aridity & Soil erosion' and 'Overgrazing/ Upstream pastoralism'; and (2) identifying the interaction between the elements: we identified a positive connection from 'Overgrazing/ Upstream pastoralism' to 'Aridity & Soil erosion'. The resulting observed interactions can be found in Table 1 (Results and Discussion section).

For the network analysis, which calculates the centrality of each element (degree centrality), we normalized centrality measures to [0,1] for direct interactions between elements. For its layout, we applied the Yifan Hu algorithm, which is an algorithm for visualizing large networks.

FCM is mainly applied in social sciences, yet it has also been used in transdisciplinary studies such as climate change (Olazabal et al. 2018). In this study, we apply the FCM method to develop a network map that captures, in a synthetized manner, the complex structure of the hydrological system of the Mediterranean Basin and identify interactions among the observed components. This is made possible by the adaptability of the FCM technique, which allows for a flexible integration of very diverse but related components of the water system. Moreover, FCM is able to integrate results from several studies, often with different methodologies and aims, theoretically connect any identified components, and draw integrated conclusions.

3. Results and Discussion

3.1. Text-analysis of content

The selected literature provides a collection of 23 specific case-studies that exhibit many LUC**—**environmental interactions of several disciplines. We text-analyse the content of these studies and collect all the identified interactions (Table 1), which are described in the remainder of this section.

Table 1. Highlighted LUC–environment interactions from the 23 reviewed studies.

ID	Reference	Proxies & techniques	Highlighted LUC—environment interaction
a	Médali (2017)	Phylogenetical & phylogeographical data	Landscape fragmentation, soil erosion, disruption and extinction of multiple plant species related to a regime of sustained and regular fires.
b	Mercuri et al. (2011)	Archaeological & archaeobotanical data, pollen	Reinforcement of soil erosion and aridification through overgrazing.
c	Berger et al. (2016)	Alluvial sediments: charcoal, macrofauna, radiocarbon dating, geochemistry, phytoliths	Enhanced hydrosedimentary activity product of increased fire regime and upstream pastoralism. Soil erosion and lost of vegetation with decreased soil organic carbon storage capacity due to river instability.

d	Meister et al. (2017)	Sediment profiles: geochemistry, texture, phytoliths, diatoms, dung spherulites	Development of sophisticated water storage complex and terraces enabling conditions for settlement establishment in desertic areas.
e	Zerai (2009)	Alluvial sediments: radiocarbon dating, grain size, morphometry, microscopy, iron content, loss on ignition	Enhanced wind activity leading to erosion due to clearing and grazing. Downstream dunes expansion and increased geomorphic activity due to clearing and grazing.
f	El Ouahabi et al. (2018)	Sedimentary record: grain size, magnetic susceptibility, X-ray fluorescence, geochemistry	Processes of aggradation and changes in the chemistry of the soils and the watershed product of strong deforestation, large upland cultivation, stripping of thin soil covers, pastoralism practices, and ore exploitation.
g	Mazzini et al. (2016)	Sedimentary core: charophyte, ostracod data	Higher turbidity and impoverished lake's biodiversity by deforestation and cultivation around the lake. Enhanced swamp transformations into lakes due to greater amounts of water availability (decrease of precipitation via evapotranspiration). Reduction of water quality and biodiversity induced by soil erosion.
h	Baartman et al. (2011)	Paleo-lake sediment archives: inventory of sediments, radiocarbon dating	Episodes of erosion and sedimentation linked to deforestation, pastoral and agricultural activities.
i	Pustovoytov and Riehl (2016)	Archaeological & archaeobotanical GIS data: calculation of aquifer areas & watercourses	Changes in the local water regime, salinization of soils and increased resilience towards aridification by cause of aquifer exploitation.
j	Moser et al. (2017)	Soil profiles: radiocarbon dating, charcoal, pedological analysis	Soil erosion, sedimentary aggradation, and enhanced surface runoff due to natural cover removal.
k	Cremaschi et al. (2016)	Archaeological data: sediment & pollen assemblages, pedosedimentary analyses, radiocarbon dating	Soil erosion, decrease of woods, and expansion of pasturelands induced by deforestation for timber and overexploitation of intensive cereal cropping.
l	Thienemann et al. (2017)	Sediment core: lipid biomarker, palynological data	Loss of vegetation resilience to climatic events related to a previously degraded environment.
m	Picornell-Gelabert and Carrion-Marco (2017)	Prehistoric settlement site: charcoal, sediment samples, radiocarbon dating	Landscape fragmentation due to deforestation.
n	Vogel et al. (2010)	Sediment core: lithology, chronology, sedimentology, geochemistry, physics	Enhanced soil erosion, surface runoff and lake turbulence product of higher deforestation.
o	Balbo et al. (2018)	Alluvial sediments: radiocarbon dating, XRF, Particle size distribution (PSD), trace elements	High sediment discharge in relation to inland erosion. Amplified erosion due to LUC−environmental feedbacks.
p	Mensing et al. (2015)	Sediment core: pollen, non-pollen palynomorph, geochemical, paleomagnetic, sedimentary analysis. Historical documents, archeological surveys	Widespread deforestation and erosion during climatic optimums.
q-w	Zeder (2008); Fontana et al. (2017); Clarke et al.(2016); Flohr et al.(2016); Morellón et al. (2016); Gogou et al. (2016); Weiberg et al. (2016)	Archaeological records, stratigraphic & geochronological data, terrestrial & marine dated cores, …	Emergence, adaptation, and expansion of settlements thanks to farming and cropping intensification, watershed exploitation, storage strategies development, and deforestation.

The significant human threshold of the Mesolithic−Neolithic transition (~11,700 years) consisted of a cultural revolution from a subsistence model of hunter-gatherer to herder-farmer, with the emergence of agriculture and animal husbandry (Zeder, 2008). In the still climate-dominated environment of the early-Holocene (~11,700—8,200 years), evidence of

Mediterranean Neolithic impacts in the landscape was limited and likely overprinted. However, and despite the difficulty in distinguishing between human-induced versus natural LUC, some studies report on unequivocally anthropogenic pressures in close relation to the landscape and climate, such as a regime of sustained fires aimed at land opening for settlement establishment, farming, and cropping (Baartman et al., 2011). In particular, and following the propagation of the Neolithic front from Africa into Europe, the first recorded LUC practices have been found in the NE ancient world at around ~10,000 years, while in the W Mediterranean it was not until ~7,500 years when communities of farmers were established (Zeder, 2008).

Following the Neolithic, Chalcolithic cultures flourished in the Near East expanding their knowledge, control, and cooperation on managing the landscape and its resources. During this time (mid-Holocene ~8,200–4,200 years), several studies register the intensification of these practices (Médali et al., 2017; Mercuri et al., 2011) and further LUCs related to the development of runoff infrastructures, the onset of mining, and the exploitation of aquifers, among others (Meister et al., 2017). There is evidence of both civilization decline and local adaptation, through storage strategies and resource diversification, as a result of abrupt climatic events (Clarke et al., 2016; Flohr et al., 2016).

In contrast to the early- and mid-Holocene, many authors report that over the past ~4,200 years, anthropogenic LUC pressures on the Mediterranean Basin have resulted in various environmental consequences. Throughout the final Chalcolithic/early-Bronze Age and with the onset of the late-Holocene, a transition from climate- to human-dominated landscapes occurred (Balbo et al., 2018; Picornell-Gelabert and Carrion-Marco, 2017; Mensing et al., 2015;). This transition is likely to have been triggered by an enlarged LUC capacity aimed at adapting to the contemporary drier and warmer climate, further exacerbating aridification (El Ouahabi et al., 2018; Mazzini et al., 2016; Pustovoytov and Riehl, 2016). During that time, more complex adaptation measures were developed, such as storage systems, enlarged infrastructures, and extended trading networks, which raised pressures to the natural system (Fontana et al., 2017; Clarke et al., 2016; Flohr et al., 2016; Gogou et al., 2016; Morellón et al., 2016; Weiberg et al., 2016). As a result, LUC in the late-Holocene continued aggravating the effects of earlier practices by conducting them in a more intense manner (Moser et al., 2017; Thienemann et al., 2017).

3.2. Past LUC practices

From the review of studies resulting in Table 1, we categorize the different observed LUCs in four groups: (a) regular fires and deforestation; (b) farming and cropping activities; (c) overgrazing and upstream pastoralism; (d) hydraulic terraces and aquifers.

(a) Regular fires and deforestation. Vegetation changes and man-induced landscapes are reported by Médail (2017) on the islands of Sicily, Malta, Sardinia, and Corsica; by Moser et al.

(2017) in Calabria, south Italy; and by Picornell-Gelabert and Carrión-Marco (2017) in Mallorca, Spain. These authors, outline environmental degradation and extinction of multiple plant species related to a regime of sustained and regular fires. Vogel et al. (2010), Thienemann et al. (2017) and Mensing et al. (2015), moreover, describe how such past changes in the land-use likely destabilized ecosystems, making them less resilient to climatic changes and especially vulnerable to abrupt climatic events.

(b) Farming and cropping activities. Cremaschi et al. (2016) and Mazzini et al. (2016) describe how deforestation, farming and cropping activities induced to soil erosion and expansion of pasturelands in the Po Plain, and to the disappearance of Characeae algae in Lake Shkodra, respectively. El Ouahabi et al. (2018) document erosion phases on the Amik Basin in the Levant coast as a product of large upland cultivation, stripping of thin soil covers, deforestation, pastoralism, and ore exploitation. Baartman et al. (2011) instead, discuss the drivers of river dynamics at the Upper Guadalentín Basin, Spain, and correlate some episodes of river instability to deforestation, pastoral, and agricultural activities. Balbo et al. (2018) argue the implications of LUC–environment interactions amplifying fluctuations in watershed activity and enhancing sediment discharge on the island of Menorca, Spain. Lastly, Zeder (2008) reports on the emergence of agriculture and animal husbandry in the eastern Mediterranean around 11,000–8,000 years.

(c) Overgrazing and upstream pastoralism. The increase in the dominance of grassland and open areas is presented in the different study sites of Mercuri (2011) in SW Libya, N of Morocco, SW Spain, N Italy, and central Turkey; and of Zerai (2009) in the Wadi Sbeïtla Basin, Tunisia. These authors discuss the role of landscape clearing and grazing as powerful mechanisms enforcing aridity. Berger et al. (2016) instead, document geomorphological riverbed changes of the Citelle River in France, synchronous to periods of enhanced fire regime and upstream pastoralism.

(d) Hydraulic terraces and aquifers. The role of aquifers and hydraulic terrace systems as potential measures to increase resilience towards aridification has been explored by Meister et al. (2017) and Pustovoytov and Riehl (2016) respectively, in the Levantine coast. In the margins of the Ionian and Aegean Seas, the increase in clastic input, intensification of farming, watershed exploitation, and deforestation processes have been discussed by Morellón et al. (2016), Gogou et al. (2016), and Weiberg et al. (2016). In the Adriatic Sea, Fontana et al. (2017) document Holocene settlements' activities and locations in relation to the constant sea-level rise during the 4,000–2,000 year time-span. Last, Clarke et al. (2016) and Flohr et al. (2016) describe local efforts of adaptation through storage strategies and resource diversification of the early-Holocene societies, showing climate resilience. Most of these studies report LUCs but do not connect them to the effects of the local or regional climate. However, they are important to contextualize societies' development and level of excreted pressure on their surroundings.

3.3. Environmental interactions

The regional LUC—environment interactions highlighted by the review of the selected studies (Table 1), allow for the construction of a network map (Figure 2). This is possible because the selected studies take into account both paleoclimatological and archaeological data independent of each other, from the same time frame and geographic setting.

Rather than trying to review all possible existing interactions, we focus on the effects of local LUC practices that lead to broad regional variability (i.e. basin-wise scale) in the hydrological cycle. Reflecting upon the different time scales and the non-linear behaviors of the exposed interactions is beyond the scope of this study. Bear in mind, however, that responses to these may vary due to sub-regional differences in the natural conditions (i.e. vegetation, orography, etc.) or internal thresholds (von Suchodoletz and Faust, 2018).

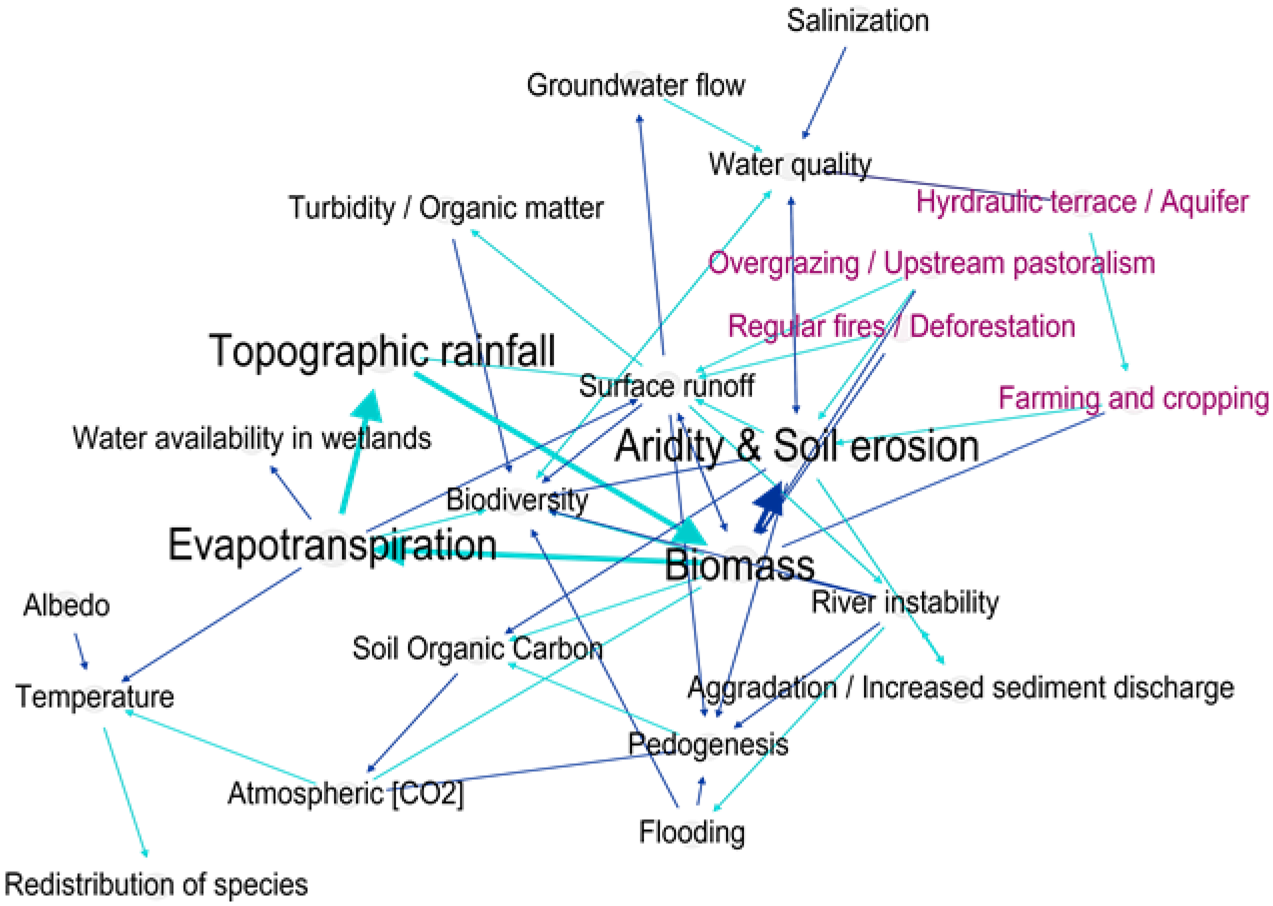


Figure 2. Network map framing the descriptive LUC–environment identified interactions. The most important elements, i.e. those with more interactions, are more centrally placed. Lines between elements represent interactions, with the arrow indicating direction and color indicating whether it is positive or negative.

Considering the reviewed information on fires, it can be said that during the whole Holocene, fires have cleared the landscape for farming, developing settlements, killing pests, etc., substantially enlarging the extension of grasslands. However, in addition to this, natural fires also occurred along the Holocene, as they are part of the seasonal dynamics of the Mediterranean vegetation. These mainly consist of an alternation of drier seasons with fuel burning and wetter seasons with biomass growth (Mercuri et al. 2019b; Vannière et al. 2016). As shown in the network map, besides affecting the vegetation cover through the expansion of grasslands and the biodiversity once encountered there (Fig.2 interaction between 'Regular fires/Deforestation', 'Biomass', and 'Biodiversity'), fires also have the capacity of modifying the atmospheric chemistry, since they are a major source of CO_2 and ^{13}C-enriched CH_4 (see Marlon et al. 2008 and references therein).

Grasslands, on the other side, have higher surface albedo than forestlands, and thus, retain less heat from the sun (Fig.2 'Overgrazing/Upstream pastoralism', 'Aridity & Soil erosion', and 'Albedo'). Additionally, they have less litter, shallower rooting plants, and lower leaf areas capable of capturing sunlight and Soil Organic Carbon (Fig.2 'Biomass', 'Aridity & Soil erosion', and 'Soil Organic Carbon'). This also reduces the uptake of atmospheric CO_2, enhancing the rise of temperatures and yet, promoting the expansion of biomass, which will uptake more CO_2 and increase Soil Organic Carbon levels (Fig.2 'Biomass', 'Soil Organic Carbon', 'Atmospheric [CO_2]', and 'Temperature'). As a result, grasslands have lower control over the surface water system and a decreased ability for water recycling than forestlands, with major effects on the land-surface water balance and local temperatures (Costa et al. 2003). These interactions shape the network map, which also conveys the many effects that they have on the broader environment. These can be summarised into three key effects.

First, promoting deforestation or biomass reduction limits the water vapour available for local precipitation coming from evapotranspiration (Fig.2 'Biomass', 'Evapotranspiration', and 'Topographic rainfall'). Lack of evapotranspiration is also connected with the increase in temperatures (Fig.2 'Evapotranspiration' and 'Temperature'), since evaporation has a cooling effect (Patz and Olson 2006). An increase in the availability of moisture, otherwise used for evapotranspiration, might instead promote wetland formation and expansion (Fig.2 'Evapotranspiration' and 'Water availability in wetlands'), and induce swamp transformations into lakes (Mazzini et al. 2016).

Second, the network map shows that eliminating biomass and, thus, deep rooting infiltration, restricts groundwater flow and enhances surface runoff, causing aridification and soil erosion (Fig.2 'Biomass', 'Aridity & Soil erosion', 'Surface runoff', and 'Groundwater flow') (Moser et al., 2017). The lack of biomass also negatively affects biodiversity by harming inland ecosystems and fostering higher contents of organic material and sediment discharge in runoff waters, which increases turbidity and diminishes the photic zone of riverine ecosystems (Fig.2 'Biomass', 'Biodiversity', 'Surface runoff', and 'Turbidity/Organic matter') (Mazzini et al., 2016). Similar to deforestation, increased farming and cropping also has a negative impact on water quality and biodiversity, as these practices boost nutrient-enriched soils that cause water quality degradation, altogether reducing biodiversity (Fig.2 ‘Biodiversity’, ‘Turbidity/Organic matter’, and ‘Water quality’).

Third, the lack of biomass caused by deforestation also appears to be connected to river discharge and seasonal peaks that respond to rainfall patterns. This is due to the increase in surface runoff (Fig.2 ‘Aridity & Soil erosion’, ‘Surface runoff', and ‘River instability’). Both enhanced river discharge and peaks in river discharge also affect river stability, by increasing soil erosion, and promoting flooding, sediment reallocation, and aggradation (Fig.2 ‘River instability’, ‘Aggradation/Increased sediment discharge’, and ‘Flooding’) (von Suchodoletz and Faust 2018). Thus, in times of river instability, soil formation and pedological processes are prevented, hampering the densification of the vegetation, biodiversity expansion and Soil Organic Carbon storage (Fig.2 ‘River instability’, ‘Aggradation/Increased sediment discharge’, ‘Pedogenesis’, ‘Soil Organic Carbon’, and ‘Redistribution of species’) (Berger et al. 2016).

The three resulting highlighted interactions are in line with empirical findings documenting a reduction of the local precipitation, i.e. topographic rainfall, and thus, a modification of the hydrological system of the Mediterranean Basin as a product of land-use change (Millán et al., 2005) (Fig.2 ‘Biomass’, ‘Evapotranspiration’, and ‘Topographic rainfall’).

Besides deforestation, anthropogenic changes in vegetation have been directed towards weather-resistant crops (e.g. cereals resistant to dry conditions during the late-Holocene) or fruit supplying crops (e.g. grapevines or hazelnut trees), suppressing the natural regeneration of regional vegetation (Cremaschi et al. 2016) (Fig.2 ‘Farming and cropping’ and ‘Biomass’). Past changes in the land-use have been recorded to destabilize ecosystems, making them less resilient to climatic changes and especially vulnerable to abrupt climatic events (e.g. Thienemann et al., 2017), although this might differ according to the characteristic of the environment of a particular place (Fig.2 ‘Farming and cropping’ and ‘Aridity & Soil erosion’).

Lastly, the network map shows how in addition to altering the surface water balance in several ways and modifying inland water properties, humans have also increased water exploitation through artificial measures like cultivation terraces, water-reservoirs and storage systems, among others. Water infrastructure development has been used to enhance agricultural production and settlement expansion, creating both environmental benefits and problems (Rosegrant et al. 2002). On the one hand, rainfall harvesting and water storage constructions have reduced soil erosion and increased water availability, while on the other hand, overexploitation and inappropriate management of water sources have caused water pollution, depletion of groundwater, soil erosion, waterlogging, and salinization (Fig.2 ‘Hydraulic terrace/Aquifer’, ‘Salinization’, and ‘Water quality’).

3.4. Knowledge transfer

Adaptation strategies in the rural landscape are often motivated by historical arguments. While such knowledge is passed along generations of land-users and learned by scientists through the investigation of archaeological records (among others), policy-makers and stakeholders might remain oblivious to it. Moreover, they often face time limitations to decision-making that pushes them to rely on their intuitive thinking. In this line, and with the focus of transmitting the here obtained science-based results to the policy/practice interface, we provide a synthesized analysis of these, followed by two key messages.

Foremost, to assist the need for quick thinking and understanding, we highlight the key concepts of the environmental interactions from the network map (Figure 2) and develop a synthetized causal loop diagram (Figure 3). Besides unraveling and simplifying the network map, the causal loop diagram upscales the identified LUC—environmental interactions and reflects on those interactions, which are reinforced through feedback processes and affect the regional climate of the Basin, contributing to climate variability, and further aggravating climate change.

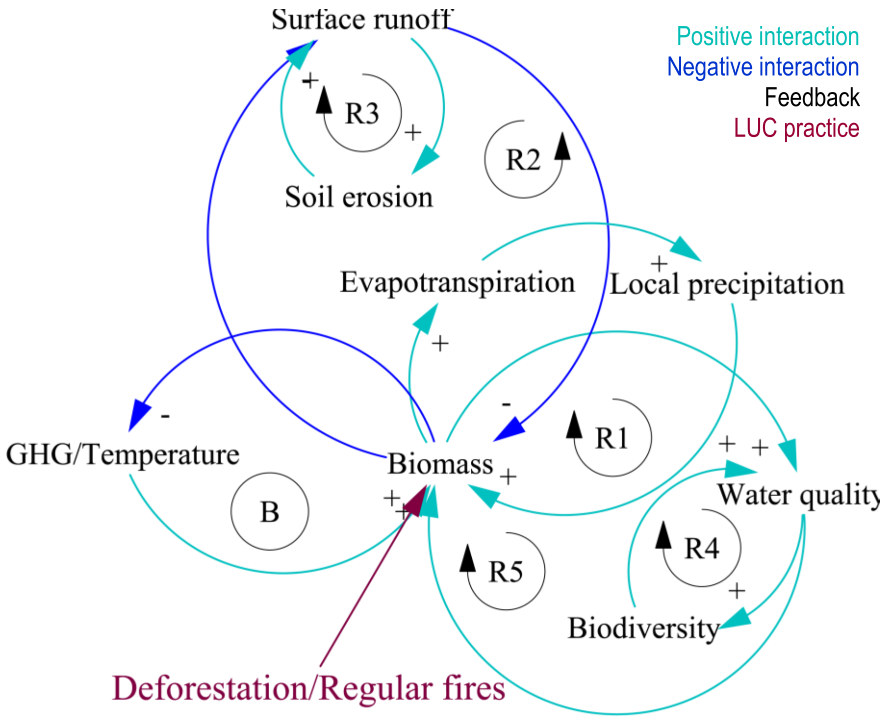


Figure 3. Causal loop diagram summarizing the encountered key feedback processes among the key environmental aspects altered by deforestation practices in the Mediterranean Basin. R refers to feedback processes. Clockwise feedbacks reinforce themselves in a positive manner, while anti-clockwise feedbacks do it on a negative one. B refers to feedback processes that balance themselves.

The causal loop diagram shows that deforestation for farming and cropping (Fig. 3-red) leads to the decrease of biomass, reducing the uptake of atmospheric CO_2 and yet, promoting the expansion of more biomass due to CO_2 availability (Fig. 3-B). It also modifies the surface water balance by halting evapotranspiration, which reduces water vapour available for local precipitation (Fig. 3-R1); and limits groundwater flow by eliminating wood cover deep rooting infiltration (Fig. 3-R2). At the same time, diminished deep rooting infiltration implies enhanced surface runoff, which causes higher aridification and further soil erosion (Fig. 3-R3). In addition, deforestation affects biodiversity and water quality and quantity, as the health of the ecosystems regulating the quality and the quantity of surface water, are ultimately determined by the quality and the quantity of it (Fig. 3-R4 and R5).

Demonstrating these basic interactions and understanding how small changes in land-use may simultaneously affect multiple components of the environment, enables decision-makers to have a more holistic perspective when making decisions involving land-use, one which addresses both locally-specific needs, as well as broader, regional effects. This is important as only with the implementation of coordinated, consistent and coherent policies across regions and watersheds of the Mediterranean, basin-wide challenges such as its impoverished water cycle, might be addressed. Related to this, we argue that before focusing on local scales, it is important to consider the wider (i.e. regional) context wherein rural adaptation actions will be implemented.

In addition to the four types of LUC practices identified in this study that have unfavourable effects on the environment (i.e. Regular fires and deforestation; Farming and cropping activities; Overgrazing and upstream pastoralism; Hydraulic terraces and aquifers), we also identified sustainable land management practices aimed at rural adaptation. For example, the presence of multifunctional landscapes, which are a mix of sylvopastoral and crop systems that allow the land for a better distribution of nutrients and water use, common since the early-Holocene (Mercuri et al., 2019). These findings highlight the importance of learning from historical practices in order to inform rural adaptation strategies that intend to limit environmental degradation and promote climate change adaptation. From this perspective, learning from past land-use practices and subsequently knowing what to avoid and/or promote, could serve as an important tool for managing the rural landscapes of the Basin in a sustainable way (e.g. future policies and programs could learn from past LUC practices aimed at decreasing pressures on freshwater resources and conserving the cultural mosaic-like landscape of the Basin).

4. Conclusions

Changes in land-use in the Mediterranean Basin during the Holocene have intensified desertification and landscape degradation, further aggravating climate change. However, decision-making often does not integrate scientific discourse on how past LUCs have modified (and thus, are able to modify) the ecosystem's stability and how local LUCs have an impact beyond the scale of implementation.

To make scientific findings on these two issues accessible to regional environmental policy-makers, we performed a semi-systematic review of 23 scientific case-studies that exhibits

LUC—environmental interactions in the Mediterranean Basin (Table 1) and synthetized them under a holistic point of view. The reviewed studies cover different regions of the Basin throughout the whole Holocene epoch (~11,700 years). Despite the diverse aim and applied methodologies of the reviewed studies, and the different time scales and non-linear behaviours of the reviewed LUC effects, the integration of the encountered interactions has been possible through the Fuzzy Cognitive Mapping technique.

After undertaking a content analysis of the studies, we identified four types of LUC practices, namely: Regular fires and deforestation; Farming and cropping activities; Overgrazing and upstream pastoralism; Hydraulic terraces and aquifers. Among them, the one with the largest consequence in the Mediterranean environment is the sustained regime of fires aimed at land opening (i.e. deforestation). The most salient consequences of this practice have historically been the loss of biomass together with the loss of biodiversity, the erosion of the soil, and the alteration of the hydrological cycle of the Basin in three main ways: first, halting evapotranspiration by slashing canopy, causing a reduction of the available moisture necessary to further induce local precipitation; second, limiting groundwater flow by eliminating deep rooting infiltration, causing soil aridification, while enhancing surface runoff by limiting infiltration, causing soil erosion and loss of biodiversity; third, preventing pedological processes by amplifying river discharge and seasonal peaks, promoting flooding, further erosion, and sediment aggradation, while limiting Soil Organic Carbon storage (Figure 2).

Our findings illustrate how small changes in land-use may have multiple effects of varying frequency and strength on several components of the environment and hydrological system, which, subsequently, can affect the regional climate (Figure 3). Based on this, we argue that sub-regional and local climate policies should move towards addressing the common challenges that the Mediterranean Basin faces as a whole, such as its fragile water cycle. In the same way, understanding the impact of past land-use changes on the environment can be used as a basis for developing future adaptation strategies in the region.

This study is inevitably limited by the data gap encountered along the coast of North Africa and the Ionian, Aegean, and Adriatic Seas (Figure 1). Moreover, if we are to engage in climate change adaptation and mitigation by looking into the past to inform anticipatory learning, it is essential to keep unfolding the quantification of such interactions, for which large uncertainties exist nowadays. The investigation of LUC-environment interactions in the Mediterranean Basin could benefit from further site-based studies conducted in these areas, as well as, from the design of interdisciplinary projects that target particular environments within the mosaic of the Mediterranean landscape.

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