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Review

Soil degradation in the European Mediterranean region: Processes, status and consequences

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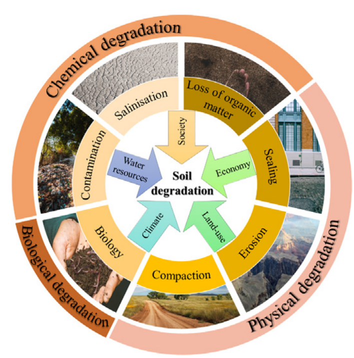
HIGHLIGHTS

- The Mediterranean is the most susceptible region in Europe to soil degradation and desertification.
- Multiple forms of physical, chemical and biological degradation affect the Mediterranean soils.
- Some Mediterranean soils are reaching critical limits for its ability to provide ecosystem services.
- A continuous and harmonised soil assessment is required to evaluate trends in soil degradation.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil, a non-renewable resource, sustains life on Earth by supporting around 95% of global food production and providing ecosystem services such as biomass production, filtration of contaminants and transfer of mass and energy between spheres. Unsustainable management practices and climate change are threatening the natural capital of soils, particularly in the Mediterranean region, where increasing population, rapid land-use changes, associated socio-economic activities and climate change are imposing high pressures on the region's shallow soils. Despite evidence of high soil susceptibility to degradation and desertification, the true extent of soil degradation in the region is unknown. This paper reviews and summarises the scientific literature and relevant official reports, with the aim to advance this knowledge by synthesizing, mapping, and identifying gaps regarding the status, causes, and consequences of soil degradation processes in the European Mediterranean region. This is needed as scientific underpinning of efforts to counteract soil degradation in the region. Three main degradation categories are then considered: physical (soil sealing, compaction, erosion), chemical (soil organic matter, contamination, salinisation), and biological. We find some degradation processes to be relatively well-documented (e.g. soil erosion), while others, such as loss of biodiversity, remain poorly addressed, with limited data availability. We suggest establishment of a continuous, harmonised soil monitoring system at national and regional scale in the Mediterranean region to provide comparable datasets and chart the spatial extent and temporal changes in soil degradation, and corresponding economic implications. This is critical to support decision-making and fulfilment of related sustainable development goals.

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Contents

1. Introduction

Soil forms a thin layer of material at the Earth's surface, but plays a pivotal role in regulating flow and transfer of mass and energy between the lithosphere, biosphere, hydrosphere and atmosphere (FAO, 2015). It is a vital medium for human life by supporting agricultural production, which provides 95% of global food (Borrelli et al., 2020). Soils also provide valuable goods and services relevant for ecosystems and human well-being, such as biomass production, supply of raw materials, filtration of contaminants, regulation of water, nutrient cycles and climate, and an archive of cultural heritage (e.g. CEC, 2006; Panagos et al., 2020). Soils are major pools of global biodiversity (FAO, 2015), and the second largest carbon pool on Earth, after the oceans (Stolte et al., 2016).

Soils are the result of complex physical, chemical and biological processes in time and space (UN, 2015, 2017). Their properties and functions are threatened by overexploitation and degradation due to poor management, with impacts on their biological and economic productivity (e.g. Eswaran et al., 2001). Recently, the increasing threats have pushed soils world-wide to the critical limit for ecosystem services (FAO, 2015). In the European Union (EU), 60-70% of soils are degraded as a direct result of unsustainable management practices and have lost significant capacity to provide ecological functions for various forms of life (EC, 2020b).

Persistent reduction or loss of soil productivity can lead to land abandonment and desertification (Eswaran et al., 2001; Panagos et al., 2018a). In 2017, 25% of European land (411,000 km^2), particularly in southern Europe, was identified as being at high or very high risk of desertification, a 14% increase since 2008 (Pravalie et al., 2017). In the EU, the main soil threats are erosion, declining organic matter and biodiversity, contamination, sealing, compaction and salinisation (EC, 2006). The Mediterranean region has been identified as particularly vulnerable to soil degradation (Lahmar and Ruellan, 2007). It has the overall highest erosion rates within the EU (Panagos et al., 2020), the lowest levels of soil organic matter (Aguilera et al., 2013) and severe salinisation problems (Stolte et al., 2016). It also has high abundance of shallow soils (Lagacherie et al., 2018), strong and increasing human pressures (Guittonny-Philippe et al., 2014) and high climate change vulnerability (Bourlion and Ferrer, 2018; IPCC, 2019).

Early soil degradation assessments identified various socio-economic and biophysical causes at case-study scale. Different frameworks have since been developed to assess soil degradation and trade-offs between inter-related components of associated ecosystems, e.g. Global Assessment of Soil Degradation (GLASOD) (Oldeman et al., 1991) and Land Degradation Assessment in Drylands (LADA, 2010). However, systematic inventories on soil degradation status are rarely produced at national or regional scale (FAO, 2015). Thus, little is known about the areas where major soil degradation takes place, the impact of soil degradation on societies, and future economic implications of soil degradation for governments and land users (FAO and ITPS, 2015).

This paper reviews and summarises the scientific literature and relevant official reports, aiming to synthesize, map, and identify knowledge gaps regarding the status, causes and consequences of soil degradation processes in the European Mediterranean region. Available information on main socio-economic and biophysical factors, soil threats and their environmental impacts, and current degradation status in the region is synthesized to provide an overall vision of regional soil degradation problems. Major knowledge gaps on spatial and temporal trends in soil degradation are identified, to aid progress in this area that can support relevant decision-making and formulation of guidelines for future research on the region.

2. The Mediterranean region

2.1. Socio-economic and land-use characteristics

The European Mediterranean region, i.e. the southern part of the continent bounded by the Mediterranean Sea, comprises ~1.2 million km^2 of land (11% of European territory) distributed across 12 countries (Fig. 1). Although some of these countries are only partially included in the Mediterranean region (e.g. France, Italy, Spain and Portugal), their whole territory is included in this study due to data availability. Furthermore, even though the west part of Turkey is located in Europe and integrated in the Mediterranean region, it is not included in the study area, due to limited data availability or accessibility.

Since the Bronze Age the region has been home to many civilisations (Pérez-Lambán et al., 2014) with diversified agroecosystems and high ecological value (Aguilera et al., 2020). An estimated 209 million people currently live in the region, comprising ~20% of the European population (Worldmeter, 2020) and 40% of the population in the Mediterranean Hydrological Basin (including southern Europe, Middle East and North Africa) (Riccaboni et al., 2020). Since 1960, the population has increased by 33%, although population growth during 2008-2018 ranged from 2% in Western Europe to -3% in Eastern Europe (Riccaboni et al., 2020).

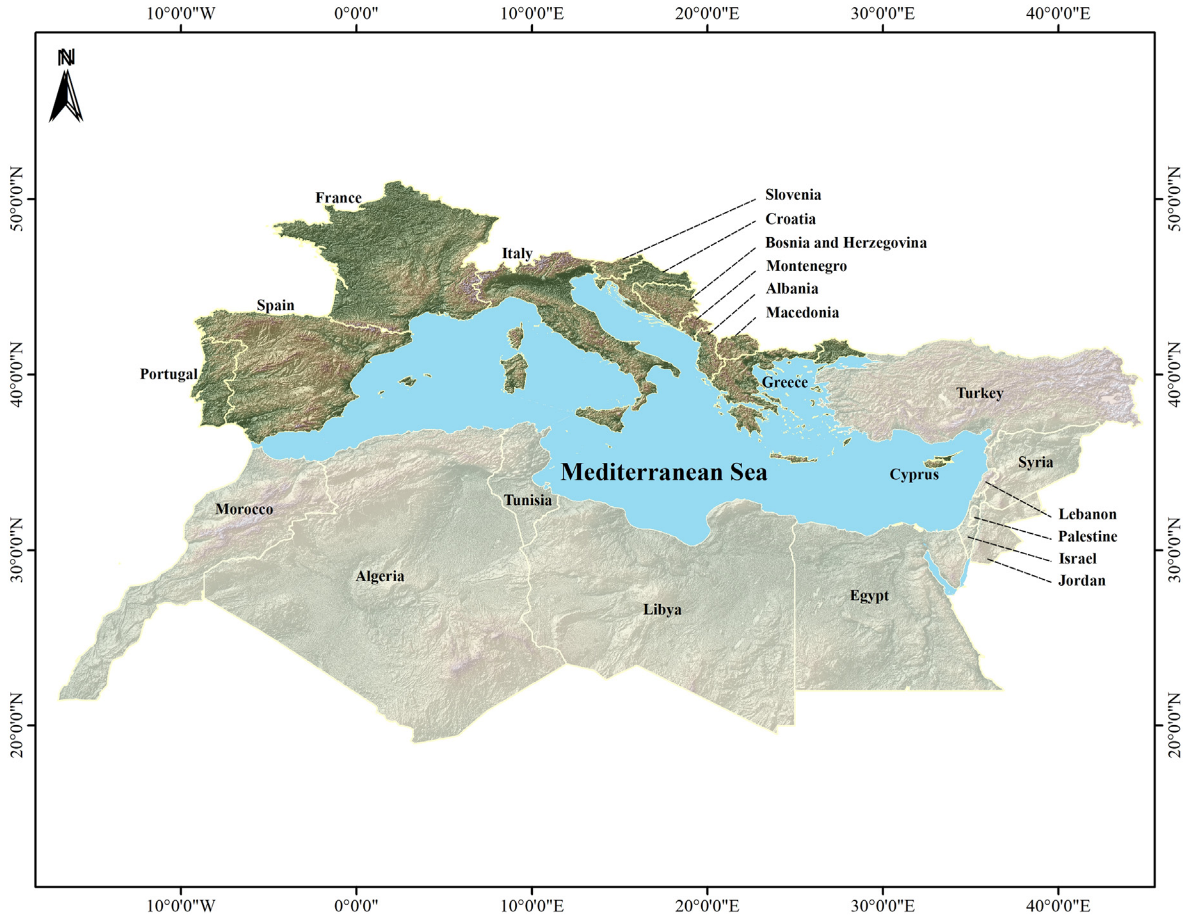

Fig. 1. Map of the Mediterranean region showing Mediterranean Basin countries. The green color identifies the countries in the Mediterranean Europe considered in this analysis.

Demographic change in the Mediterranean region in recent decades has mainly been driven by population migration from rural to urban areas, resulting in a 38% increase in the average urban population since 1990 (Riccaboni et al., 2020). These changes have led to considerable variations in population density and significant land-use changes, characterised by abandonment of rural areas, decreasing area of agricultural land, expansion of forest and urban sprawl (Egidi et al., 2020).

Many ancient/historic pastoral regimes have been abandoned as no longer economically viable, leading to increased natural vegetation and afforestation of unproductive land with fast-growing tree species (EC, 2020a). As a result, Mediterranean forests have undergone large-scale changes in their general extent and in terms of vegetation structure, composition and dynamics, leading to changes in fire regime (Doblas-Miranda et al., 2017) compared with the natural regimes associated with the seasonal dynamics of Mediterranean vegetation (Ruiz and Sanz-Sánchez, 2020).

Forestry covers a considerable proportion of the Mediterranean region (Fig. 2). In 2015, forest/wooded cover in Mediterranean countries such as Montenegro, Spain, Portugal, Greece and Croatia exceeded the 42% average area recorded for the 28 countries forming the EU (Eurostat, 2019). The rural exodus has favoured fuel build-up, resulting in large forest fires, despite the decrease in population reducing the probability of human-induced fires (Miranda et al., 2018). Wildfires have increased dramatically in frequency and extent in the European Mediterranean region since the 1960s, particularly in France, Greece, Italy, Spain and Portugal (Oliveira et al., 2018). This increase is due to socio-economic changes (rural depopulation, land abandonment, afforestation with flammable species) and to a generally warming and drying climate (Shakesby, 2011).

A current characteristic of the Mediterranean region is rapid urbanisation (Myers et al., 2000), often occupying fertile agricultural land (EEA, 2019a). In 2016, around 65% of people in the considered European Mediterranean countries (Fig. 1) lived in urban areas, exceeding the global average of 55% (Bourlion and Ferrer, 2018). Urbanisation is partially driven by tourism, since the Mediterranean region is one of the world's leading holiday destinations due to its rich natural and cultural resources (Bourlion and Ferrer, 2018). According to UNWTO (2017), international tourist arrivals to the Mediterranean marine Basin is estimated to have grown from 58 million in 1970 to more than 349 million in 2015, and are projected to reach 500 million by 2030. This massive inflow of people exacerbates environmental pressures and risks of land degradation.

To feed an increasing regional population, agricultural activities have increased in recent decades and productive agricultural land is being used more intensively (Miranda et al., 2018), exacerbating the risk of soil degradation. The Mediterranean countries are the European leaders for some crops (e.g. olives, fruit and vegetables) (Eurostat, 2019). However, the average land footprint per capita in the considered European Mediterranean countries (Fig. 1), i.e. the area of land needed per unit product, is also among the highest in Europe due to extensive production forms (EC, 2019). This is combined with extensive livestock production, shaping 23% of landscapes as complex agro-sylvo-pastoral mosaics across the Mediterranean region (Malek and Verburg, 2017). Increasing abandonment of extensive livestock systems affects the current land footprint through changes in the mosaic landscape and increasing wildfire risk (Shakesby, 2011). Changes to agricultural systems, together with other land-use changes, are leading to critical levels of habitat loss (Bourlion and Ferrer, 2018). This is a particular

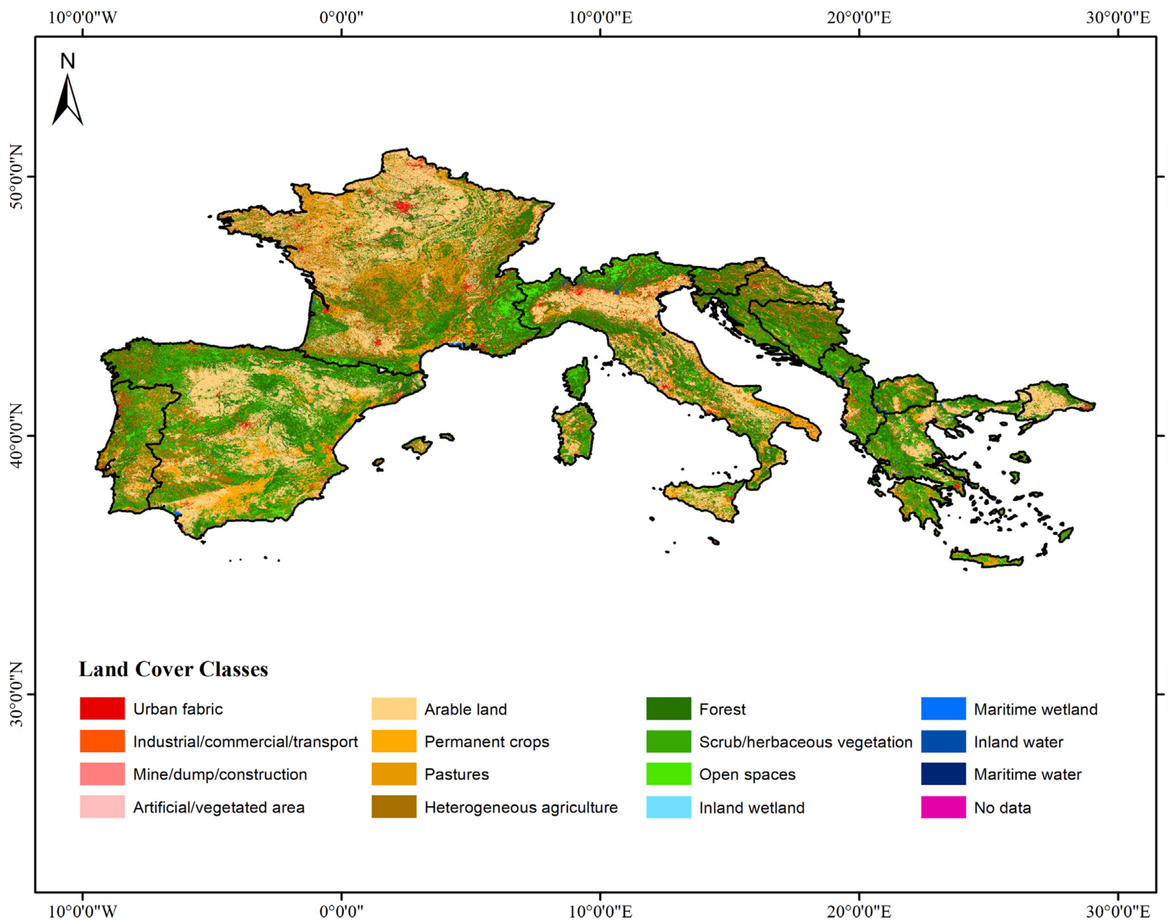

Fig. 2. Land use in the European Mediterranean countries.(Based on Corine Land Cover, 2018.)

concern since the Mediterranean region is characterised by extraordinary biodiversity, with large numbers of endemic species (EC, 2020a), favoured by the biogeographical interface between temperate and dryland biomes (Yves et al., 2020).

2.2. Climate and water resources

The Mediterranean region is located in a transition zone between mid-latitude and sub-tropical atmospheric circulation regimes, and is characterised by complex morphology ranging from mountain chains to land-sea contrasts (Cramer et al., 2018). This results in large spatial variability of atmospheric circulation manifested in a wide variety of weather types and climate zones (Peña-Angulo et al., 2019). This variability in turn leads to a gradient ranging from hot and arid regions to humid mountain climate and permanent glaciers over the Mediterranean countries (Lionello et al., 2006). On average over this gradient, the Mediterranean climate is typically characterised by hot dry summers and humid mild winters. Mean annual temperature and precipitation in the Mediterranean European countries ranges from 5 °C to 2027 mm, respectively, in northern Italy to 18 °C and 228 mm, correspondingly, in south-east Spain (Llorens and Domingo, 2007). About 65% of annual precipitation falls in winter months (Sanz-Cobena et al., 2017), although in mountainous areas the proportion can exceed 80% (Fayad et al., 2017). The seasonal variability in precipitation leads to associated temporal dynamics in soil moisture, which may yield water scarcity in various areas during the driest periods (Yves et al., 2020) and determine vegetation patterns to considerably higher degree in this southern part than in other parts of Europe (Orth and Destouni, 2018). Generally, Mediterranean soils have a xeric moisture regime, characterised by dry moisture content for at least 45 consecutive days, and a thermic temperature regime marked by mean annual soil temperature between 15 °C and 22 °C (Verheye and Rosa, 2005). Dynamics of both soil moisture and temperature regimes play an important role for some soil properties and the susceptibility to degradation (Verheye and Rosa, 2005).

Since the 1950s, the frequency and intensity of droughts have increased in the Mediterranean region (MedEC, 2019), associated with longer dry periods and shorter wet periods (Brilli et al., 2014), particularly in the Iberian Peninsula (Portugal and Spain) (Yves et al., 2020). The Mediterranean region has also been identified as one of the most climate-vulnerable regions and a climate change "hotspot" (Salvia et al., 2021). Droughts lead to marked reductions in soil moisture (EEA, 2019a), and prolonged anomalous moisture deficiency that may severely affect biodiversity (FAO, 2011) and crop yields (Martín-Ortega et al., 2018; Yves et al., 2020) especially if agriculture is predominantly rain-fed (Orth et al., 2020). Rain-fed agriculture is of great relevance in the Mediterranean countries, and reduced profitability and competitiveness driven by precipitation scarcity in high-temperature periods (summer season) have led to abandonment of agricultural land (Martín-Ortega et al., 2018).

To achieve high yields, irrigation is required during the whole vegetative cycle (Katerji et al., 2008). Thus, irrigation systems have become a common component of agriculture (Aguilera et al., 2020), representing 72% of water use in the Mediterranean Basin (Hamdy and Lacirignola, 1999). A combination of irrigation and growing demands for water from domestic, industrial to tourism activities (mainly seasonal) have placed severe constraints on the Mediterranean's water resources and on multiple economic sectors (Bourlion and Ferrer, 2018).

Water availability across the Mediterranean is decreasing (Gudmundsson et al., 2017), as indicated by increased frequency of low flows in rivers, particularly in France and Spain (Yves et al., 2020). This reflects the strong susceptibility of the region to droughts, owing to its climate conditions (Orth and Destouni, 2018) and to human activities and their influences on the regional hydrological cycle (e.g. Ferreira et al., 2016; Kalantari et al., 2017; Destouni and Prieto, 2018). Depletion of stored water reserves is affecting surface and subsurface reservoirs, driven by increasing abstraction and overexploitation of groundwater (Miranda et al., 2018), the main water resource in the region (Yves et al., 2020). In the hydrological Mediterranean Basin, unsustainable water management with agricultural crops estimated to be over-irrigated by 30-49%, is aggravating water scarcity (Katerji et al., 2008). Over-irrigation is needed in salinized areas to ensure percolation below the rootzone (leaching fraction) and avoid salt accumulation in soils (Corwin and Grattan, 2018).

Increasing numbers of large dams (>15 m dam height) are being constructed in the European Mediterranean region, particularly Spain and southern France, for water storage, flood control, navigation, recreation and hydropower generation (NASA, 2020). Although relevant for water management, dams increase consumptive evaporation losses of water from the landscape (Jaramillo and Destouni, 2015) and have numerous physical and ecological impacts on freshwater, terrestrial and marine ecosystems (Lehner et al., 2011).

2.3. Soils

Over time, different soil geological origins (parent material) along with topography, the climate settings, and several biological factors determined by vegetation, animals, microorganisms and human activities (e.g. massive deforestation, urbanisation) have resulted in a wide diversity of soil types within the Mediterranean region (Fig. 3). The influence of soil forming factors on different Mediterranean soil types and their main properties is presented by Verheye and Rosa (2005).

Different physical, chemical, mineralogical and biological properties of the soils determine their natural capital and ability to provide ecosystem services (FAO, 2015). Monitoring spatial heterogeneity in soil properties within the region is difficult but necessary to detect changes and identify appropriate land uses and management regimes. Local studies have mapped soil heterogeneity and degradation based on monitoring sites and long-term experiments at relatively small scale (e.g. Ferreira et al., 2015; Barão et al., 2019), but this information is rarely collected and inventoried (FAO, 2015). All EU countries must produce state-of-the-environment reports, but most countries in the Mediterranean region do not produce regular assessments of their soil resources (Solomun et al., 2020).

The first regional maps of European soils were produced in the early 1960s (FAO/UNESCO, 1962). Since then, organisations such as the Forum of European Geological Surveys (FOREGS), the Joint Research Centre (JRC) of the European Commission and the United States Department of Agriculture (USDA) have provided regional soil updates. According to the European Digital Archive of Soil Maps (EuDASM), few Mediterranean countries have soil maps with detailed resolution (≤1:50000), and some may not cover the entire territory (Table 1).

In 2006, design and planning began for a soil grid of the world (GlobalSoilMap) (ISRIC, 2020). The Land Use and Coverage Area Frame Survey (LUCAS) is the most comprehensive harmonised soil database for EU. It includes records of topsoil characteristics, focusing

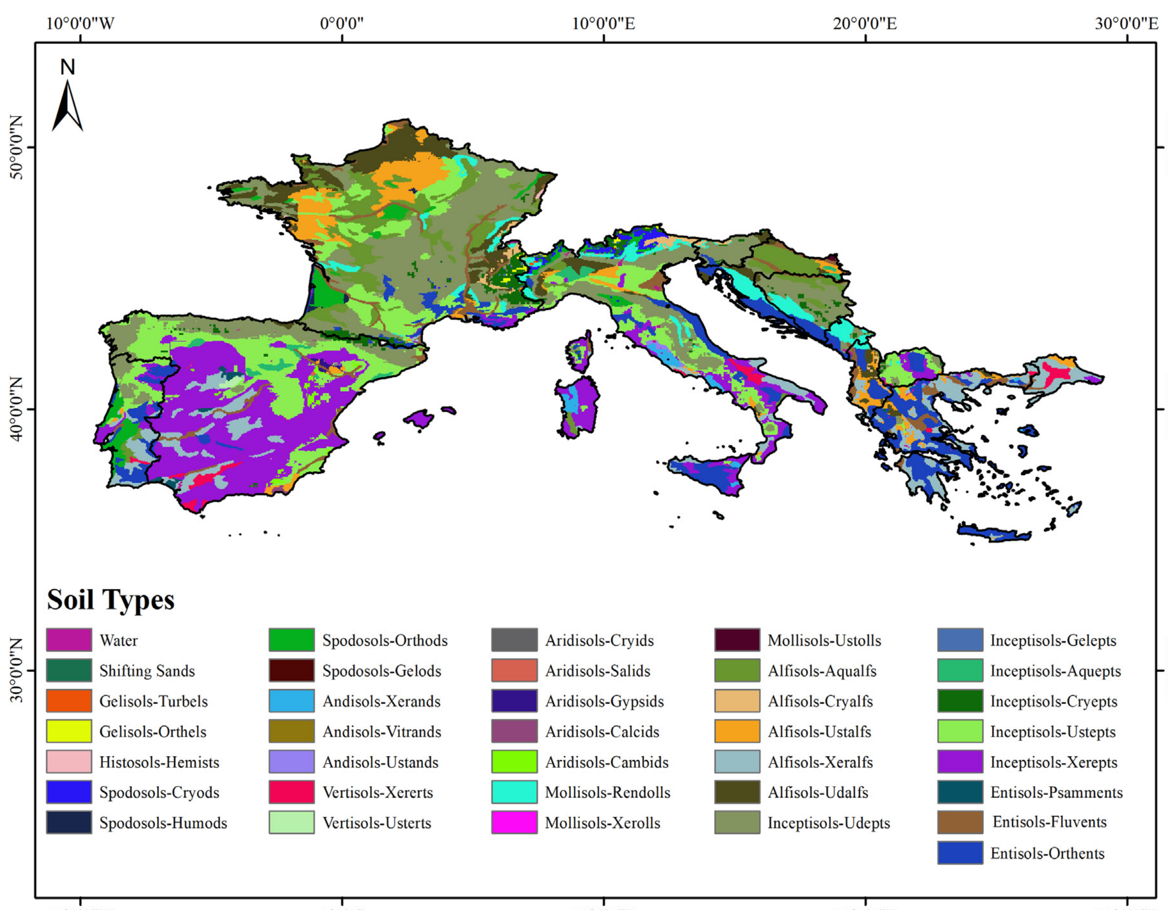

Fig. 3. Major soil types in the EU Mediterranean countries.
(Adapted from USDA Global Soil Region Map: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/?cid=nrcs142p2_054013.)

Table 1
Available maps of soil type and associated resolution in Southern European Mediterranean countries, based on the EuDASM database (https://esdac.jrc.ec.europa.eu/resource-type/national-soil-maps-eudasm).

Country	Portugal	Spain	France	Italy	Slovenia	Croatia	Bosnia and Herzegovina	Montenegro	Albania	Macedonia	Greece
Map resolution	1:50000	1:100000	1:25000	1:25000	–	1:50000	–	–	–	–	1:100000

on 13 categories of physical and chemical properties (e.g. silt content, bulk density, pH, soil organic carbon, nitrogen), and analysis of 12 heavy metals in more than 21,000 soil samples collected in 27 EU Member States (excluding Croatia) (JRC, 2008). Soil surveys in 2009, 2015 and 2018 allowed detection of trends (Orgiazzi et al., 2016). Although LUCAS is a very important database, soil data on national and European scale are limited (Yigini and Pangos, 2016). There is a particular lack of soil information for the Mediterranean region, with countries like Bosnia and Herzegovina being absent from most European databases (Solomun et al., 2020).

3. Major soil threats in the Mediterranean region

Soil degradation processes (physical, chemical and biological) are linked with major soil threats in the Mediterranean countries (EC, 2006).

3.1. Physical degradation

3.1.1. Soil sealing

Soil sealing refers to permanently covering the soil with impermeable artificial materials such as asphalt or concrete (e.g. roads and buildings), and may involve physical soil removal to construct strong foundations in the subsoil (Ferreira et al., 2018a). It is an irreversible process that results in loss of all soil services and functions, such as: (i) production of food and biomass, especially when fertile soils are sealed; (ii) infiltration and storage of water, generating surface runoff with associated flood hazard (e.g. Kalantari et al., 2017); (iii) local climate regulation, through reduced evapotranspiration by loss of vegetation and variations in albedo (e.g. Früh et al., 2011) and higher surface temperatures associated with urban heat island effects (Ferreira et al., 2018a); (iv) filtration, immobilisation and purification capacity to cope with organic and inorganic contaminants (EEA, 2019a); (v) carbon sequestration and carbon storage (Stolte et al., 2016); and (vi) provision of habitats for soil organisms and other animals and plants, through habitat destruction and fragmentation (affecting the stability and resilience of habitats), and loss of soil biodiversity (e.g. Jato-Espino, 2019). Soil sealing also often diminishes landscape and cultural heritage (FAO, 2015).

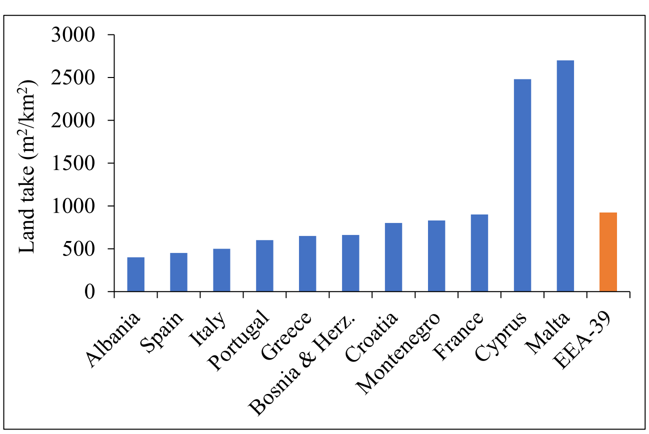

Fig. 4. Land take in the European Mediterranean countries, 2012-2018. (Adapted from EEA, 2019b.)

In 2012, the average soil-sealing index (rate of soil sealing as a result of urbanisation) compared with 2006 was higher within the Mediterranean countries (3.02%) than in all European countries (2.87%) (EEA, 2020). In 2012-2018, most Mediterranean countries showed land-take per unit available area below the EEA-39 average, but Malta and Cyprus were well above (Fig. 4). The percentage of sealed area varies considerably between and within Mediterranean countries (Fig. 5), depending on dominant settlement structures. Mediterranean coastal soils are among the most widely sealed, particularly in Portugal and some areas of Italy (Stolte et al., 2016).

Soil sealing also has implications for other soil threats. Soil organic matter content is reduced by urbanisation, through topsoil removal or disruption of mineralisation rates caused by sealing (Lu et al., 2020). Use of heavy machinery at construction sites causes soil compaction (Ferreira et al., 2018a). Increasing surface runoff driven by sealing may accelerate the risk of soil erosion and landslides, with associated loss of natural vegetation and decreasing slope stability (Lei et al., 2021). Urbanisation is also often associated with increasing soil contamination, directly from human activities (e.g. industrial activities, waste deposits) and indirectly through air contamination and subsequent atmospheric deposition (Stolte et al., 2016).

To mitigate the effect of current urban sprawl, the Seventh Environment Action Program and EU Roadmap to a Resource-efficient Europe promote 'no net land-take' ('no urbanisation') in the EU by 2050 (EEA, 2019b). However, this target is unlikely to be met unless annual rates of land-take are reduced (EEA, 2019b), a particular concern in the Mediterranean region given the rural exodus. Land recycling, i.e. construction between existing buildings (densification) and on brownfield sites, is one way to cope with a growing urban population while consuming less land per capita, but is constrained by the lack of a legal framework or incentives to recycle urban land in the EU. There is also no specific EU legislation to protect rural soils suitable for cropping (e.g. fertile soils) from being urbanised.

3.1.2. Soil compaction

Soil compaction involves densification and distortion of soil under stresses exceeding its strength, exerted by machinery (e.g. wheels, tracks, rollers) and/or livestock (Alaoui and Diserens, 2018). Depending on the intensity and frequency of the stress, compaction can affect topsoil and/or subsoil at depths >30 cm (JRC, 2008). Soil compaction is usually a function of soil properties (e.g. particle size distribution, organic matter, bulk density). Soils vary from being sufficiently strong to resist all likely applied loads to being naturally compacted by climate change (FAO, 2015). Soil water content and land management (e.g. tillage practices, grazing intensity, forest harvesting, and construction activities) also play an important role in soil compaction (Stolte et al., 2016; Alaoui and Diserens, 2018).

Compaction disrupts soil structure, including aggregates and their stability, reducing porosity (especially macroporosity) and permeability, and lowering water infiltration capacity (Ferreira et al., 2012). Loss of soil structure increases resistance to root penetration, and also affects nutrient and gaseous exchanges and water fluxes, impairing soil biodiversity (Schjønning et al., 2015; Yin et al., 2020). Crop yield reductions in Europe due to soil compaction are reported to range from 2.5-15% (EEA, 2019b) to 25-50% (Eswaran et al., 2001), but limited information is available for the Mediterranean countries.

Soil compaction is a major threat to soil quality and health (Stolte et al., 2016), as its impacts may be long-lasting or even permanent, particularly in the subsoil. Upper subsoil (0.25-0.7 m) compaction is a great

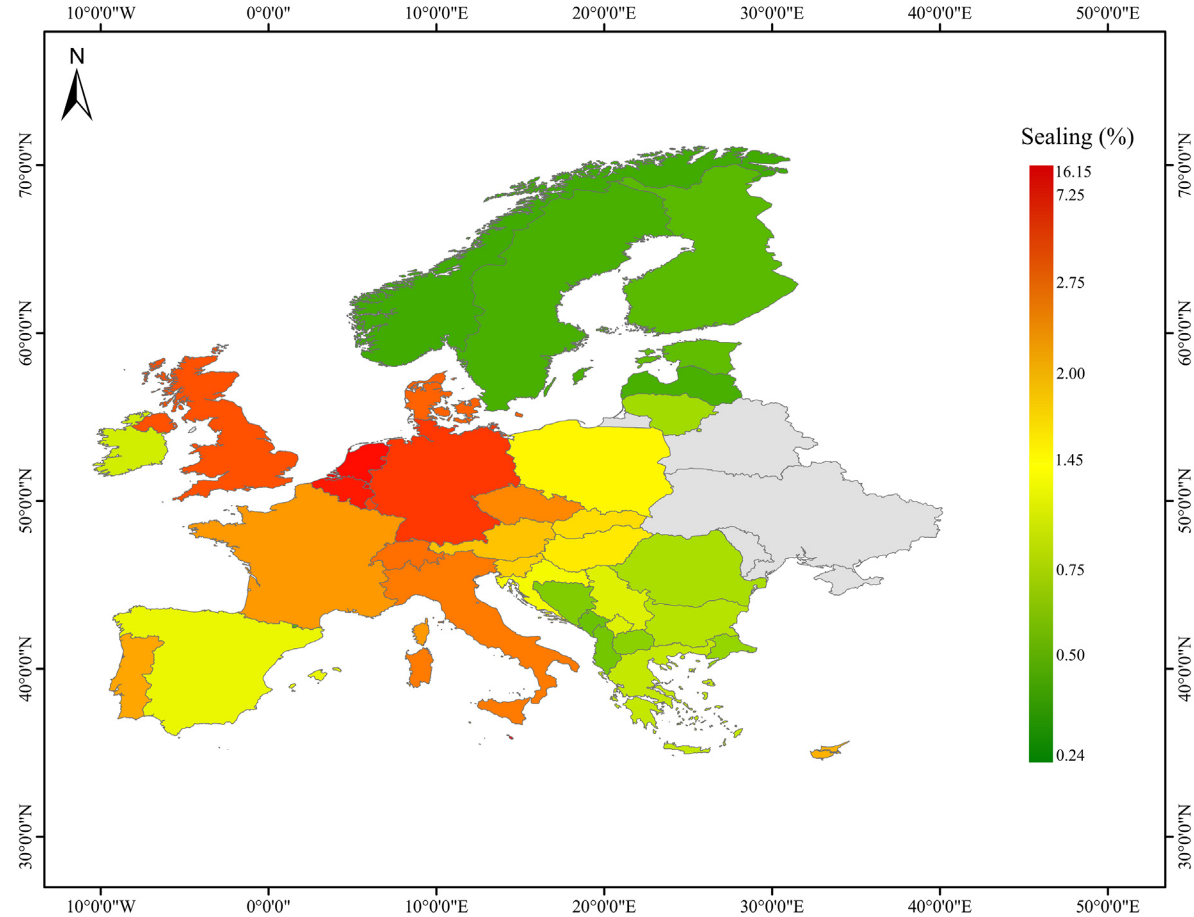

Fig. 5. Percentage soil sealing in different European countries in 2015.
(Based on EEA: https://www.eea.europa.eu/data-and-maps/daviz/percentage-sealing-by-country-1#tab-chart_5.)

concern across the Mediterranean region (Koue et al., 2008), with some regions of Greece, Portugal, Spain and Italy displaying critically high densities (JRC, 2008). However, current databases on compaction, developed by JRC (2008) and Koue et al. (2008) do not include data for some eastern Mediterranean countries. Furthermore, these databases are focused on natural susceptibility of agricultural soils to compaction, estimated mainly from soil parameters (e.g. type and texture) and water regime at a coarse scale (1 Km grid).

Some studies across the Mediterranean countries have considered local status of soil compaction driven by management practices, mainly associated with machinery traffic, different tillage operations, and distinct irrigation systems. Most of these studies have focused on specific crops, including vineyards (e.g. Bogunovic et al., 2016; Ferreira et al., 2020), orchards (e.g. Moradi et al., 2020; Telak et al., 2020), citrus plantations (Cerdà et al., 2021) and sunflower (Panettieri et al., 2020), or grazing fields (e.g. Pulido et al., 2017). Although soil compaction represents a major concern in agriculture areas, some studies in the Mediterranean countries have also shown the relevance of soil compaction on soil degradation in forest areas due to terracing, post-fire salvage logging, and the exposure of burned soils to rainfall (e.g. Stoof et al., 2015; García-Orenes et al., 2017). A few studies with local focus have investigated soil compaction status in the urban areas of Mediterranean countries (e.g. Ferreira et al., 2012; Ferrara et al., 2015). Besides focusing predominantly on local spatial scales, most of the studies investigating soil compaction in the Mediterranean countries also consider limited time periods (up to few years), and do not provide knowledge on temporal change trends. Overall, available studies have thus used different methodological approaches, and considered different relatively small spatial locations and time periods, which makes difficult to compare results and provide a relevant problem overview. By enhancing soil bulk density and reducing infiltration, compaction increases surface runoff and contributes to waterlogging during precipitation events, reducing soil trafficability and number of workable days (Ferreira et al., 2012; Alaoui and Diserens, 2018). It also enhances erosion rates and, in extreme precipitation events, may trigger landslides and flooding (FAO, 2015). High water content and reduced aeration in compacted soils increase the risk of anaerobic conditions, changing biogeochemical cycles and enhancing greenhouse gas emissions (e.g. nitrous oxide) (Yin et al., 2020). Compaction also decreases saturated hydraulic conductivity and increases the risk of cracks and other soil openings with fast preferential through-flow allowing contaminants to bypass the soil matrix and quickly move to lower soil layers (Schjønning et al., 2015). Given the large number of soil functions affected, soil compaction should be monitored routinely in order to adapt soil management practices appropriately.

However, without proper knowledge of the wider status and temporal trends of soil compaction in the Mediterranean countries, it is difficult to manage the problem, adapt management practices, and mitigate or prevent degradation. Thus, additional research focus should be devoted to this soil threat.

3.1.3. Soil erosion

Soil erosion is defined as accelerated removal of topsoil from the land surface (FAO, 2015). It involves: (i) detachment of soil particles by external forces (e.g. rainsplash), and (ii) subsequent downslope transport of particles, mainly by water or wind (Shakesby, 2011). The main causes of soil erosion are human driven, e.g. changes in land use and management (e.g. Borrelli et al., 2017). These changes include removal or disturbance of surface cover, e.g. by cultivation, intensive tillage and ploughing (e.g. Panagos et al., 2019) and fire (Shakesby et al., 2015), loss of vegetation cover and lack of adequate soil conservation practices (Borrelli et al., 2017). Climate change resulting in more intense storms may also be an important driver of soil erosion (Borrelli et al., 2020).

Erosion is one of the main soil degradation processes (FAO and ITPS, 2015; Panagos et al., 2019). Erosion rates in 24% of the EU exceed the rate of soil renewal through weathering and pedogenesis (Panagos et al., 2015), which is estimated to be ~1.4 t ha^{-1} yr^{-1} (Verheijen et al., 2009). Very high soil erosion rates (>2 t ha^{-1}) occur widely from agricultural land in the Mediterranean countries (Fig. 6a), the most affected area within the EU (EC, 2020b). For example, severe erosion affects up to 41% of the agricultural land in Slovenia (Fig. 6b).

According to Borrelli et al. (2017), the Mediterranean region saw a slight soil erosion decrease between 2001 and 2012, due to increased vegetation cover. However, Panagos et al. (2020) detected increases in soil erosion between 2010 and 2016 in most Mediterranean countries, e.g. >3% in Greece and Italy and 1-3% in Spain. This disturbing trend is mostly explained by unsustainable land management in those countries (Robinson et al., 2017). However, soil conservation practices applied in France, Malta and Portugal have reduced erosion rates from arable land by at least 3.5% (Panagos et al., 2020).

The ESDAC database (https://esdac.jrc.ec.europa.eu/resource-type/soil-data-maps) provides relevant information about net erosion and soil erosion by water and by wind across Europe, but lacks information for some of the eastern European Mediterranean countries (e.g. Croatia, Bosnia & Herzegovina, Albania, Macedonia). However, some global soil erosion assessments provide data for these countries (Borrelli et al., 2017) and, although dispersed in a large body of literature, several local field studies have been carried out, using distinct methodologies (e.g. sediment fences, runoff plots, erosion pins, rainfall simulations), to measure soil erosion in various European Mediterranean countries (e.g. Ferreira et al., 2012; Shakesby et al., 2015; Prosdocimi et al., 2016). Most of these studies have focused on water erosion, since water is the most relevant eroding agent in the Mediterranean region, as sheet, rill and pipe erosion (Fig. 7), depending on soil properties, topography and climate (Stanchi et al., 2012). Some attempts have also been made to synthesize studies on soil erosion across the Mediterranean countries, with focus on vineyards (Prosdocimi et al., 2016), abandoned agricultural fields (Rodrigo-Comino et al., 2018), badlands (Martínez-Murillo et al., 2013), and wildfire affected areas (Shakesby, 2011; Girona-García et al., 2021).

Based on plot measurements, erosion from bare surfaces is twice as high in the Mediterranean countries (~32 t ha^{-1} yr^{-1}) as in the rest of Europe (~17 t ha^{-1} yr^{-1}) due to the rainfall regime (Cerdan et al., 2006). Field measurements across the European Mediterranean region have shown variable erosion rates, revealing that it is particularly problematic for agricultural land (Ferreira et al., 2018b) and in wildfire-affected areas (Shakesby et al., 2015), but also in urban areas (Ferreira et al., 2018a). Gully erosion, the most severe form of erosion, is particularly common in Spain, Italy and Greece (Verheijen et al., 2009), leading to erosion rates of up to 455 t ha^{-1} yr^{-1} (Poesen et al., 2006).

On agricultural land, soil losses during crop harvesting due to particles adhering to root and tuber crops (e.g. potatoes, sugar beet) may also be considerable, depending on soil texture, structure and moisture, type of crop, dropping intensity and harvesting technique (technology, harvester effectiveness and velocity) (Panagos et al., 2019). It can comprise 1.5-28% of total soil losses by water and wind in Europe, and even more in some regions of Greece and Italy due to the extent of tuber crops (Panagos et al., 2019). Wind erosion, caused by strong winds over loose, dry soil with insufficient surface protection, mainly affects semi-arid areas of the Mediterranean region with patchy vegetation (Borrelli et al., 2014).

Soil erosion has multiple environmental impacts due to on-site soil losses and off-site sediment transfer and deposition, with significant negative effects over time (Borrelli et al., 2018). This has implications for biogeochemical processes, such as soil carbon cycling, by increasing CO_2 emissions through enhanced mineralisation and decreasing carbon sinks and sediment burial (Borrelli et al., 2017; Lugato et al., 2018). However, changes in soil carbon stocks driven by erosion are poorly quantified, particularly in the Mediterranean region (Borrelli et al., 2018).

Topsoil loss reduces soil capacity to provide rooting space and store water, with 4% yield decline per 0.1 m of soil loss (FAO, 2015). This may have serious impacts in Mediterranean forests, where soils are thin and poor, particularly in mountainous areas (Shakesby et al., 2015; Miranda et al., 2018). Soil erosion also leads to loss of organic matter and nutrients, and thus represents the greatest threat to soil fertility, long-term productivity and overall biodiversity (Panagos et al., 2018b; Alewell et al., 2020). This can compromise food security and impede achievement of the UN Sustainable Development Goals (SDGs), particularly SDG2: Zero hunger (UN, 2015). Severe soil erosion in the EU leads to annual foregone production of 3 million tonnes of wheat and 0.6 million tonnes of maize, with the highest losses in the Mediterranean countries (Italy, Spain, Greece), where these crops are dominate (Panagos et al., 2018b). In 2010, severe erosion led to total economic losses in the EU agriculture sector of €1257 million, or 0.43% of the sector's contribution to GDP (Panagos et al., 2018b). But the economic losses are considerably higher in the Mediterranean region, with impacts on GDP of up to -36.8%, -17.1% and -16.8% in Italy, Spain and France (Fig. 6b).

Soil erosion has off-site impacts, such as damage to recreational facilities and destruction of roads, railways and other public assets. It also causes siltation of reservoirs (reducing the storage capacity and drinking water quality) and streams, resulting in ecological disturbance

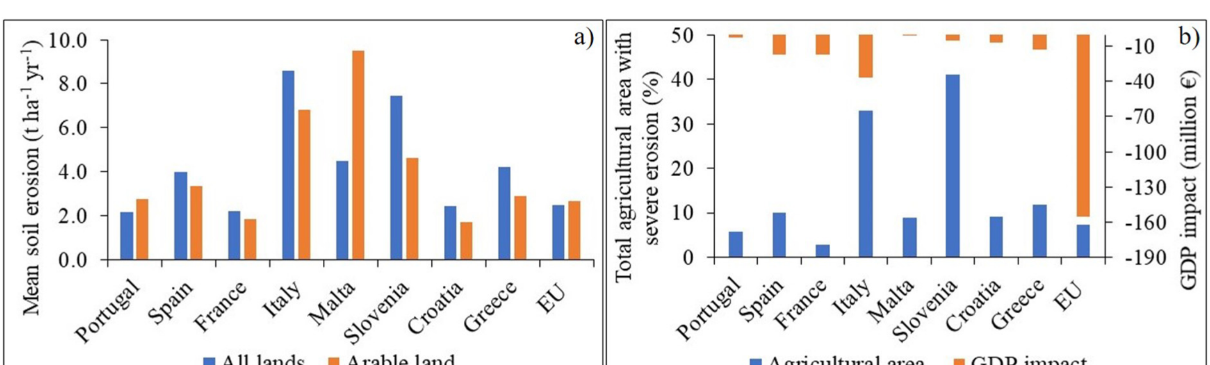

Fig. 6. a) Mean soil erosion in the EU Mediterranean countries (adapted from Panagos et al., 2020); and b) percentage of total agricultural land suffering severe soil erosion (>2 t ha^{-1} yr^{-1}) and impact on GDP due to productivity loss (adapted from Panagos et al., 2018b).

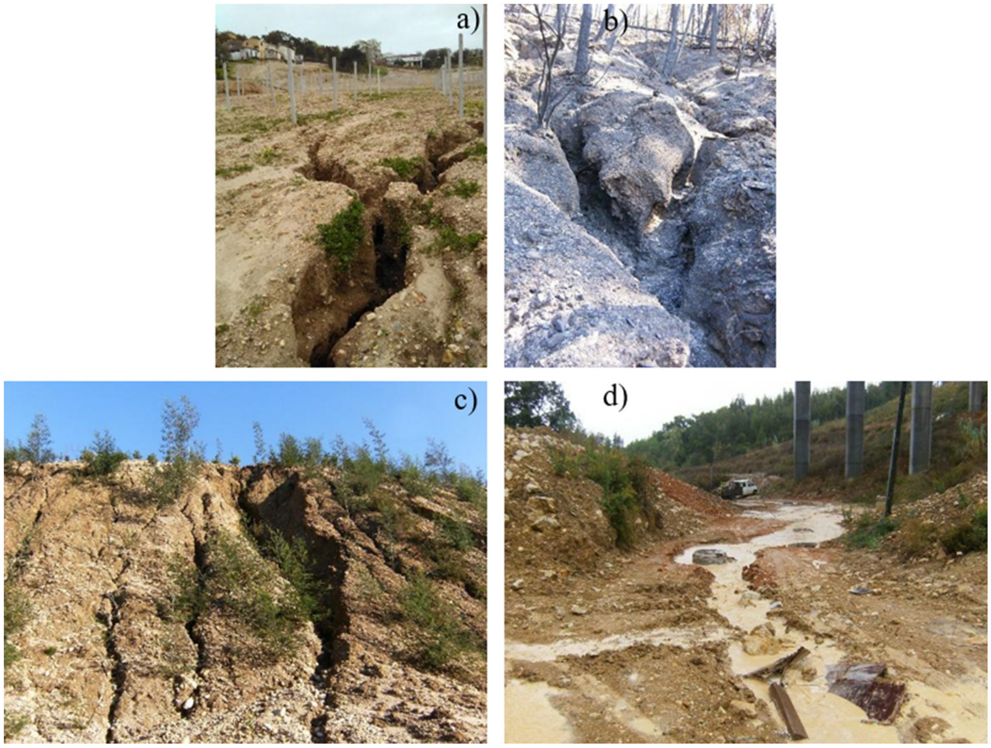

Fig. 7. Examples of water-driven erosion on soils in central Portugal under: a) agriculture (early-stage kiwifruit plantation), b) fire-affected forest, c) abandoned farmland, and d) urban construction.

to aquatic ecosystems and increased risk of flooding (Kalantari et al., 2019; Borrelli et al., 2020). Water quality impairment due to sediment transport usually involves nutrients, particularly from agricultural areas, but also heavy metals and polycyclic aromatic hydrocarbons (PAHs) from urban areas (Ferreira et al., 2017; Stolte et al., 2016). These off-site impacts can affect achievement of SDG6: Clean water and sanitation, SDG14: Life below water, and SDG15: Life on land (UN, 2015). The EU Soil Thematic Strategy alerts policy-makers to the need to include soil erosion as a key priority for action (CEC, 2006), which is particularly relevant for the Mediterranean region given the high erosion rates in most of the countries in this region. To better support decision-making processes, however, it is important to understand how eroded soil is redistributed over the landscape and how much is lost to surface waters (Robinson et al., 2017). Future research should focus on soil formation rates within the Mediterranean region and the transport of sediments across the landscape, so that the soil erosion threat can be appropriately assessed. Mapping the hotspots of soil erosion within the Mediterranean countries, based on field data and appropriate modelling, is also needed to support targeted restoration and mitigation measures and practices, and the achievement of land degradation neutrality targets.

3.2. Chemical degradation

3.2.1. Soil organic matter

Soil organic matter (SOM) is composed of residual plant and animal materials (e.g. litter), transformed (humified) by microbes and decomposed under the influence of soil conditions (e.g. temperature and moisture) (FAO, 2015). SOM has major impacts on multiple soil properties and functions, such as enhancing water-holding capacity and infiltration, improving soil structure and stability, reducing soil bulk density and decreasing water runoff and soil erosion (Ghorbani et al., 2008). SOM also plays an important role in biological activities, as the main source of energy for decomposing organisms and an important pool of nutrients (nitrogen, phosphorus, micronutrients), influencing crop performance and supporting biodiversity and ecosystem functions (Haddaway et al., 2017).

SOM contributes to carbon cycling in terrestrial ecosystems (Yigini and Pangos, 2016), since soil organic carbon (SOC) comprises 48-58% of SOM by weight (Stolte et al., 2016). SOM and SOC dynamics are affected by soil properties (e.g. lithology and texture), biomass production and microbial abundance, climate, anthropogenic activities defining land-use and land-cover changes (Yigini and Pangos, 2016) and fire (Girona-García et al., 2019).

In the Mediterranean region, conversion of natural vegetation, grasslands and forests to cultivated land has generated considerable losses of SOC (Aguilera et al., 2013). Agricultural practices such as deep ploughing, intensive tillage, drainage and fertiliser use cause major decreases in SOM, through influences on microbial degradation and mineralisation (Kibblewhite et al., 2005; Haddaway et al., 2017). In the Mediterranean region, vineyards tend to have the lowest SOM and have received considerable research attention (e.g. Novara et al., 2018; Ferreira et al., 2020). More complex cropping systems involving e.g. introduction of cover crops or biomass incorporation (e.g. crop residues, straw, manure) can favour SOM accumulation (Barão et al., 2019). Land-use changes associated with afforestation after abandonment of cropland can also enhance soil carbon and nutrients (FAO, 2015). SOM responds quickly to human-induced changes, but organic matter may remain in the soil for a relatively short time (days to a few years) (FAO, 2015). Wildfires are often associated with rapid losses of SOM, driven by thermal decomposition (Shakesby et al., 2015). However, prescribed burning, with lower fire temperatures than wildfires, used to control biomass loads in forest, shrublands and grassland can lead to increases in SOM, due to temporary soil enrichment with ash and charred material and a reduction in soil biological activity, depending on fire temperature and residence time (Girona-García et al., 2019).

The Mediterranean region has low SOM content (<2%) (FAO, 2015), as its high soil temperatures and moisture conditions accelerate soil respiration and mineralisation (Brito et al., 2005). Mediterranean soils also have low SOC content, often below 40 t C ha^{-1}, whereas soils in north-eastern Europe have on average 80-250 t C ha^{-1} (Panagos et al., 2013a). This is because SOM has a positive correlation with precipitation, and a negative correlation with temperature (Stolte et al., 2016). There has been a SOC stock decrease in global Mediterranean soils over the last 50 years, due to accelerated mineralisation (two-thirds of the decrease) and soil degradation (one-third), enhanced by anthropogenic disturbance (Lal, 2004). However, there is a great uncertainty regarding SOM and SOC stocks and trends, particularly in the European Mediterranean countries (Panagos et al., 2013b). Estimates of SOC stocks are typically based on modelling exercises with considerable uncertainty, depending on model and input data (Novara et al., 2018). The data in most EU policy documents may overestimate SOC levels, based on the LUCAS 2009 Topsoil Survey performed by the JRC (Stolte et al., 2016).

The ESDAC database has available SOC stock data for agricultural topsoils, but as mentioned for other soil threats, soil data for some eastern European Mediterranean countries is lacking. Several studies have investigated local SOM and SOC in different European Mediterranean countries, mostly to assess impacts of different agricultural management practices (e.g. Ferreira et al., 2020; Payen et al., 2021), post-fire management treatments (e.g. Juan-Ovejero et al., 2021), abandonment of agricultural lands (e.g. Djuma et al., 2020; Bell et al., 2021), livestock grazing (Oggioni et al., 2020), and afforestation of pastures (Hoogmoed et al., 2012). These findings need to be synthesized to get a more comprehensive problem overview, but this is challenging due to the different spatial-temporal scales considered and methodological approaches used in the various available studies.

Decreases in SOM negatively affect soil physical, chemical and biological functions and enhance degradation. SOM depletion can also decrease filtering and biodegradation of pollutants, such as heavy metals and xenobiotics (e.g. polychlorinated biphenyls) (Ahmed et al., 2015). In addition, SOM affects soil erosion, with erodibility peaks in European soils with 1-2% SOM and with wind erosion decreasing by up to 15% per 1-5% increase in SOM (Stolte et al., 2016). Soil erosion and reduced SOM can induce a vicious cycle of soil degradation, exacerbated by associated biomass production decline (Lal, 2004). Declining SOM favours soil compaction, since it decreases porosity and pore size distribution, which may inhibit root growth by reducing rooting volume, soil aeration and drainage (Alaoui and Diserens, 2018). Through impacts on water retention capacity and soil structure, SOM losses also enable desertification (Stolte et al., 2016). Given the environmental consequences of SOM losses, better assessments and trend evaluations are required to understand SOM dynamics and support policy and decision-making, namely in the European Mediterranean countries with typically low SOM.

3.2.2. Soil contamination

Soil contamination is defined as occurrence of a contaminant (physical, chemical, or biological) that, above a certain level, causes deterioration or loss of soil functions (FAO, 2015). It is one of the greatest threats to soil resources globally (Ballabio et al., 2018), driven by human activities (Stolte et al., 2016). In Europe, municipal and industrial waste disposal contributes most to soil contamination (37%), followed by industrial/commercial activities (33%) (Panagos et al., 2013a), with e.g. mining and military activities also introducing excessive amounts of contaminants (Solomun et al., 2020). These sources cause local and diffuse soil contamination, with the latter involving accumulation in soil (e.g., from atmospheric deposition, agriculture, and flooding), with further emission, transformation, and spreading of contaminants to other media, including as dominant legacy sources for ongoing water pollution (Destouni et al., 2021; Chen et al., 2021).

In Europe, common contaminants include metallic trace elements, radionuclides and xenobiotic molecules, with more than 700 substances recognised as soil pollutants (harming soil functions) (EC, 2020b). Recent attention has focused on 'chemicals of emerging concern' (CECs), e.g. pharmaceuticals, antibiotics, hormones and microplastics (EEA, 2019b). In the EU, 2.8 million potentially CEC-contaminated sites have been identified already and the number is expected to increase (EC, 2020b). Many of these contaminated sites are in the Mediterranean countries (Ballabio et al., 2018), with France reported to have a particularly high number of contaminated sites per thousand inhabitants (Panagos et al., 2013b).

Overuse of fertilisers is a major driver of soil contamination, particularly in irrigated cropping systems (e.g. Sanz-Cobena et al., 2017). Nitrogen inputs through mineral fertiliser, organic amendments (e.g. manure, biosolids) and nitrogen-fixing crops are currently exceeding critical values, leading to eutrophication and acidification in 65-75% of European agricultural areas (EC, 2020b). In some Mediterranean countries (Portugal, Spain), intensive livestock production (e.g. pigs) and application of large quantities of manure and synthetic fertilisers to cropland have led to environmental problems such as groundwater contamination with nitrates (Cameira et al., 2021). In fact, the Iberian Peninsula and most eastern Mediterranean countries are reported to be overusing agricultural fertilisers (Riccaboni et al., 2020). Atmospheric deposition also causes nitrogen accumulation in and contamination of soils, with estimated total annual values in the Mediterranean region exceeding levels causing adverse environmental effects (Doblas-Miranda et al., 2017).

Heavy metals and mineral oils are the most frequent soil contaminants in the European Mediterranean countries, causing around 60% of soil contamination (Panagos et al., 2013b). Heavy metal contamination of agricultural soils is a particularly pressing concern since heavy metals are toxic, have a long biological half-life for elimination and tend to accumulate in living organisms (e.g. plant tissues) and enter the trophic web, affecting food safety and security (Guittonny-Philippe et al., 2014).

The European Mediterranean countries have high soil copper concentrations (Table 2), especially in Greece and Portugal, in part driven by extensive use of copper-based fungicides (Ballabio et al., 2018; Ferreira et al., 2020), particularly in olive and wine-producing regions (EC, 2020c), and by application of sewage sludge (Panagos et al., 2018a). Cyprus has the highest average soil copper concentrations of all EU countries, due to historic mining activities (Panagos et al., 2018a). Cadmium, mainly originating from mineral phosphorus fertilisers, accumulates in agricultural soils in the Mediterranean countries because leaching rates are low due to low precipitation surplus (EC, 2020b). Soils in France, Italy and Spain have high concentrations of arsenic (Table 2). High concentrations of chromium and nickel, linked to seismic activity, are found in soils in central Greece, northern Italy, the central Pyrenees and Croatia (Lado et al., 2008). High concentrations of cobalt are reported in some regions of France, Greece and Italy (Tóth et al., 2016). High levels of lead and mercury are found at former mining sites, such as central Italy (Tóth et al., 2016). Generally, central Italy and Greece have high heavy metal contamination (Table 2). As for other soil threats, the ESDAC database provides information on spatial concentration distributions for several heavy metals in European countries, but does not distinguish natural background concentrations in soils, and thus inferences about soil contamination must be made carefully. Additional studies of the temporal trends of soil contamination in the Mediterranean countries are also required.

Pesticides are currently attracting research attention due to their high persistence, toxicity and accumulation of residues and metabolites in agricultural soils (Silva et al., 2019). It is estimated that $<$0.1% of pesticides applied to European crops reach the target pest, resulting in pollution depending on the capacity of soils to store, immobilise and degrade contaminants (Silva et al., 2019). Based on LUCAS soil surveys, 83% of European soils are contaminated with pesticide residues (EC, 2020b). However, the available data regarda relatively small number of soil samples taken in a few cropping systems. Glyphosate, the main herbicide used in Europe, is present in high concentrations in soils across the Mediterranean region (Silva et al., 2018). Pesticide sales in the Mediterranean countries represented 60% of all EU sales in 2017 and 2018 (Eurostat, 2020). This may be linked to pest and disease

Table 2
Mean (minimum - maximum) baseline concentrations (mg/kg) of heavy metals in soil in Mediterranean countries, based on pan-European studies.
(Adapted from ESDA database: esdac.jrc.ec.europa.eu.)

Country	Arsenic	Cadmium	Chromium	Copper	Mercury	Nickel	Lead	Zinc
Albania	10 (6-17)	0.3 (0.1-0.7)	35 (5-84)	21 (5-55)	0.05 (0.02-0.19)	39 (3-115)	23 (10-46)	68 (25-143)
Bosnia & Herzegovina	8 (3−12)	0.2 (0.1-0.4)	29 (10-74)	15 (6-30)	0.06 (0.03-0.12)	29 (5-87)	19 (9-39)	57 (25-99)
Greece	10 (1-34)	0.3 (0.1-1.4)	47 (5-172)	27 (6-104)	0.05 (0.01-0.27)	56 (6-391)	25 (3−103)	72 (18-241)
Croatia	7 (1-17)	0.3 (0.1-0.6)	26 (9-68)	15 (5-42)	0.06 (0.01-0.28)	21 (5-87)	19 (3-39)	57 (17-196)
Italy	9 (2-25)	0.3 (0.0-1.0)	29 (6-106)	20 (3-87)	0.06 (0.01-0.29)	27 (4-125)	22 (5-57)	67 (11-189)
Malta	5 (4-5)	–	28 (27-30)	21 (8-26)	0.03 (0.02-0.04)	17 (10−20)	–	46 (42-52)
Montenegro	11 (8-15)	0.4 (0.4-0.5)	25 (25-25)	17 (14-22)	0.07 (0.06-0.09)	32 (21-45)	28 (28-28)	84 (72-103)
Slovenia	8 (4-16)	0.2 (0.1-0.8)	26 (12-77)	16 (8-48)	0.06 (0.02-0.11)	26 (10-81)	23 (8-54)	68 (28-150)
France	9 (1−30)	0.3 (0.1-1.2)	26 (7-84)	16 (3-71)	0.06 (0.01-0.30)	19 (3−120)	22 (5-83)	64 (14-192)
Portugal	13 (4-40)	0.2 (0.1-1.0)	26 (11-86)	22 (7-67)	0.05 (0.02-0.25)	20 (7-77)	32 (9-118)	71 (25-251)
Spain	8 (1-25)	0.2 (0.0-0.7)	21 (7-85)	17 (4-67)	0.04 (0.01-0.24)	18 (4-95)	17 (4-78)	49 (18-179)
Europe	*7 (1-40)*	*0.1 (0.0-0.7)*	*27 (4-172)*	*15 (3-104)*	*0.05 (0.00-0.31)*	*20 (3-391)*	*19 (1-118)*	*59 (9-291)*

outbreaks, a recurring issue in Mediterranean agriculture due to climate conditions (FAO, 2011). In eastern Spain, herbicide application has increased in the last years following conversion of rainfed olive plantations (or scrubland) to citrus orchards (Panagos et al., 2016).

Persistent organic pollutants (POPs), characterised by high toxicity, persistence and bioaccumulation potential (e.g. polychlorinated biphenyls (PCBs) and PAHs), are other important soil contaminations (FAO, 2015). Soil contamination by POPs in the Mediterranean region is the result of intensive atmospheric deposition driven by industrialisation, with soils in Italy, France and Spain being particularly polluted (Merhaby et al., 2019). However, only a few studies have investigated soil contamination by POPs, with the main focus being devoted to aquatic ecosystems (e.g. Nadal et al., 2015), and thus the real extent of the problem in the European Mediterranean soils is largely unknown.

Depending on contaminant type and concentration and soil properties, soils may lose their capacity to filter and buffer contaminants (EEA, 2019b), posing risks to human health and terrestrial and aquatic ecosystems (FAO, 2011; Panagos et al., 2013b). In contaminated soils, biogeochemical equilibria altered, which may change physical, chemical and biological soil properties (Stolte et al., 2016). Soil contamination lowers the activity of soil biota, affecting community structure and reducing biodiversity (Santorufo et al., 2014). These impacts have negative effects on SOM and aggregate stability, enhancing erodibility and erosion risks, with associated transport and spread of contaminants to downslope areas (Silva et al., 2019). Landslides and flooding can also cause major off-site transport of polluted soils (Stolte et al., 2016).

The UN Resolution on Soil Pollution (UNEP, 2017) requires countries to set norms and standards to prevent, reduce and manage soil pollution. The Thematic Strategy on Soil Protection (CEC, 2006) established the aim of remediation of contaminated soils, but only 24% of contaminated sites in the EU have been inventoried (EC, 2020b). Various EU directives refer to the need for data on soil pollution sources (e.g. Water Framework Directive), but there is no statutory requirement for EU countries to publish data on polluted sites (EEA, 2019b).

Soil contamination is difficult to manage. Local contamination can be managed by site investigations and surveys to determine the actual extent of the problem and its environmental impacts, but diffuse contamination is more difficult to assess, control and mitigate (Destouni and Jarsjö, 2018), yet may cover large areas and dominate ongoing water pollution (Destouni et al., 2021; Chen et al., 2021), and thus represent a substantial environmental threat (FAO, 2015). Little progress has been made to date in assessing and managing contaminated soils (EEA, 2019b) and their further water and ecosystem pollution impacts, including in the Mediterranean region.

3.2.3. Soil salinisation and sodification

Soil accumulation of water-soluble salts is referred to as salinisation when involving potassium, magnesium, calcium, chlorine, sulphate carbonate or bicarbonate, or as sodification when involving sodium (Katerji et al., 2008). A soil is considered saline if the electrical conductivity of its saturation extract exceeds 4 dS m^{-1} (FAO, 2015). The threshold value above which environmental and economic impacts are apparent depends on e.g. soil water regime, climate conditions and type of vegetation (Stolte et al., 2016). Soils are considered sodic if the exchangeable sodium percentage is 5-40%, depending on different factors such as terrain characteristics (Sentís, 2014). Accumulation of salts may (i) occur naturally (e.g. Calcisols, Durisols), due to rock weathering, soil formation from sediments and marine parent materials, and atmospheric deposition of marine salts; or (ii) be driven by human-induced processes associated with mismanagement of soil and water resources. These include over-exploitation of groundwater and associated intrusion of seawater in coastal areas (Mazi et al., 2014), crop irrigation without adequate drainage or with poor-quality water, intensive fertilisation and replacement of deep-rooted perennial vegetation with shallower-rooted annual crops and pastures that use less water, leading to a rise in saline groundwater levels (Katerji et al., 2008; Singh, 2021). Irrigated cropland area has doubled over the past 50 years and irrigation currently accounts for 70% of global water use (FAO, 2015), which increases the risk of human-induced soil salinisation and sodification. Waterlogging also contributes, since it prevents leaching of salts accumulated at the soil surface (Stolte et al., 2016). Sodification has received less attention and is less understood than salinisation (Sentís, 2014).

Salinisation and sodification problems occur widely, affecting 20% of irrigated land world-wide (UN, 2017), but are most common in arid and semi-arid regions, where the annual rainfall surplus, after plant evapotranspiration, is insufficient for leaching salts out of the rootzone (Eswaran et al., 2001). The extent of salt accumulation is still uncertain, but it is estimated that Mediterranean countries contain only ~1% of affected land in Europe, although the Mediterranean coastline stands out at European scale (EC, 2020b). Naturally saline soils occur in Spain, Greece, Serbia and Croatia (Tóth et al., 2008). Combined climate and human-driven increase in seawater intrusion is a major concern in coastal areas of Greece, Spain, Italy, Cyprus and Portugal (Mazi et al., 2014; Daliakopoulos et al., 2016). Moreover, agriculture-induced salinisation is a serious form of soil degradation in some areas, with 25% of irrigated global Mediterranean cropland being affected by moderate to high salinisation (Mateo-Sagasta and Burke, 2011; IPBES, 2018). Such salinisation affects parts of Spain (southeast areas, the Ebro Valley), Italy (Sicily, Campania), Greece, Portugal (coastal areas), France (west coast) and Cyprus (FAO, 2015). According to Daliakopoulos et al. (2016), some soils in northern Portugal and Spain, southern France, and some parts of Greece and Albania also constrain agriculture due to high salinity and sodicity levels. These areas, however, are not always coincident with those identified in the saline and sodic soil map of the ESDAC database, which shows potentially affected areas, and this implies a limited level of reliability with recommended use mainly for orientation purposes (Tóth et al., 2008). Distinct saline and sodic areas identified by different data sources highlight a need for additional studies and improved methodologies to properly assess the spatial extent of the problem within the European Mediterranean countries.

Only a few field experiments have been performed to quantify the impact of irrigated agriculture on soil salinity and sodicity in European Mediterranean countries (e.g. Aragués et al., 2011; Kourialas and Dokou, 2021). Although no systematic data are available on trends in soil salinisation, studies have shown that this problem is increasing in Spain and Italy due to large irrigated areas and inappropriate drainage systems, in Portugal due to increased risk of saline intrusion in coastal areas driven by groundwater abstraction and sea-level rise (EC, 2020b), and in Cyprus due to mining activities (Stolte et al., 2016). Long term salinity trends are only reported as monitored in Aragón agriculture areas of Spain (Herrero and Pérez-Coveta, 2005). The high annual rate of mineral fertilisation in some Mediterranean countries, such as France, Greece and Italy (248, 166 and 134 kg ha^{-1}, respectively), is also an important driver of salinisation in agricultural soils (Katerji et al., 2008).

Excessive accumulation of soluble salts affects the metabolism of soil organisms, thus impacting important soil processes such as respiration, residue decomposition and nutrient cycling (Eswaran et al., 2001). It also affects plants by causing imbalances in their nutrition and disturbing several regulation mechanisms, such as increasing osmotic pressure and plant toxicity due to saline ion action, and impaired uptake of soil water, thereby modifying plant water status and gas exchange and impairing plant growth (Singh, 2021). Most salt-affected soils exert moderate to severe limitations on crop yield (FAO, 2015). With advanced salinisation, fertile soils may become barren as vegetation can no longer survive (Tóth et al., 2008).

Accumulation of salts may also have adverse consequences for soil structure, due to changes in the proportion of exchangeable cations attached to clay minerals affecting the bonds between soil particles, leading to collapse of soil aggregates (Das et al., 2020). Depending on soil texture, clay mineralogy, exchangeable sodium content and soil moisture content, salt accumulation may promote soil crusting, which impedes seedling emergence (Lo'ay and El-Ezz, 2021). The effect of poor soil conditions associated with salinity and sodicity on various mechanisms of vegetation growth and reproduction, and subsequent loss of vegetation cover, enhances soil vulnerability to erosion, decreases SOM and accelerates desertification (Stolte et al., 2016).

Despite being identified as a major soil threat in the Soil Thematic Strategy, salinisation is not addressed in specific EU policies. However, the 7th Environment Action Programme considers productive land as "natural capital" and stresses the need to protect and manage soils. Salinisation can pose compromise the long-term objectives of the EU Common Agricultural Policy, regarding sustainable management of soil and viable food production, achievement of SDG2 and the land degradation neutrality target. Thus, the EU needs to develop policy (e.g., directive, regulations), setting limits on soil salinisation, and requiring monitoring of trends, including also for the threats to coastal areas posed by enhanced seawater intrusion due to climate, sea level, and inland land- and water-use changes (Mazi et al., 2016).

3.3. Biological degradation

Soils host most of the terrestrial biosphere and are a major reservoir of global biodiversity (FAO, 2020). They include heterogeneous habitats supporting an essential pool of organisms, ranging from microbes (bacteria and fungi) to macro-fauna (e.g. collembola, nematodes) (Geisen et al., 2019). Soils vary in species richness (number of taxa per m^2) and abundance (number of individuals per m^2), and it is estimated that 1 g of soil contains around 10,000 bacterial species (Gans et al., 2005). Soil biodiversity and biomass positively affect ecosystem functions and services, including soil health and crop productivity (Jackson et al., 2019).

Fauna communities break up soil organic matter (e.g. litter), digesting some, facilitating the decomposition by microorganisms and invertebrates. Thus, soil macrofauna control the dynamics of SOM, while bacteria and fungi are mainly responsible for nutrient cycling (Santorufo et al., 2014), nutrient availability and soil carbon sequestration (FAO, 2020; Geisen et al., 2019). Invertebrate soil communities such as ants and earthworms have been identified as key species regulating soil nutrients and diversity and dynamics within plant communities (Almeida et al., 2020). Through their moving and feeding activities, soil organisms play an important role in improving soil physical structure (e.g. porosity and aggregate stability), supporting soil water regimes (e.g. infiltration and water storage capacity) and reducing soil erosion (Orgiazzi and Panagos, 2017). Ants play an important role as seed dispersers, supporting the restoration of vegetation and soil in Mediterranean grassland ecosystems, which are currently severely affected by land degradation (Almeida et al., 2020).

Soil biota is affected by land-use type, with forests usually associated with more fungi and fungivores and more structured fauna communities than grasslands and meadows, while arable systems have lower soil biodiversity and abundance than undisturbed ecosystems (Jackson et al., 2019). However, intensive human land use and soil exploitation, along with climate change, alter physical and chemical soil properties, leading to different assemblages of soil communities (Santorufo et al., 2014). For example, forest management activities (e.g. tree harvesting, prescribed fires) can strongly affect the composition and biomass of soil communities, and associated soil functions (Castano et al., 2020). Agricultural intensification, associated with monoculture cropping, intensive tillage and fertilisation, application of phytopharmaceuticals and increasing incidence of pests and diseases, leads to soil disturbance and can reduce soil biodiversity by decreasing food-web complexity and functional groups (FAO, 2020; Preece et al., 2020). Although there is no overall consensus within the scientific community on the effects of phytopharmaceuticals on soil biodiversity, previous studies have shown that insecticide application has a much greater effect on soil biota than pesticides, leading to major changes in microbial community composition, decreasing collembola abundance and affecting earthworm reproduction (Jeffery et al., 2010). Soil microbial processes (e.g. carbon and nitrogen fluxes) are also affected by differences in soil conditions between irrigated and rain-fed cropland (Sanz-Cobena et al., 2017). Research studies in Italy have quantified the impacts of soil salinity gradients on microbial activity (Canfora et al., 2015). Moreover, recent studies in European Mediterranean countries have addressed the impacts on soil biodiversity of livestock grazing abandonment (Oggioni et al., 2020), and of restoration measures used in agricultural areas (e.g. Tosini et al., 2020) and forest areas (e.g. Bonari et al., 2019).

Other soil threats, such as organic matter depletion, sealing, pollution (e.g. fertilisers, pesticides, urban and industrial pollutants), compaction and erosion, also alter the abundance of individual species and soil biodiversity (Gardi et al., 2013). Based on estimated abundance of soil organisms and considering the active range of movement of soil bacteria (~1 m^{-6}), short-distance displacement of soil through erosion may have profound consequences for soil communities (Orgiazzi and Panagos, 2017). Declining soil biodiversity has negative impacts on soil resistance and resilience to perturbations (Stolte et al., 2016).

Soil biology is a fairly young field of research, but the European Atlas of Soil Biodiversity compiles available information, e.g. on the spatial distribution of eight groups of soil organisms (tardigrades, rotifers, nematodes, collembola, acari, diplurans, annelids and myriapods) within Europe. The existing data indicate relatively limited numbers of species in some organism groups (collembola, diplurans) in some Mediterranean countries and a lack of information particularly for south-eastern countries (e.g. Montenegro) (Jeffery et al., 2010). According to Orgiazzi et al. (2016), risks for soil biodiversity are particularly high in large areas of Spain, and moderate to high in several areas of Greece and Italy, with no information available for several eastern European Mediterranean countries. There are no data available on changes in soil biodiversity (EC, 2020b), so a coordinated network is needed to study and monitor soil biodiversity in the Mediterranean region and throughout Europe (Plexida et al., 2018). A better understanding of soil biodiversity and the role of soil biota can promote crop production, carbon sequestration and biotechnological and medical innovations (EC, 2020b).

4. Concluding remarks

Soil is an important, non-renewable resource sustaining life on Earth by supporting food production and water scarcity, but human pressures and climate are reducing this natural capital. The shallow soils of the Mediterranean region are suffering from sealing, compaction, high erosion rates, and low organic matter content. Some are also contaminated, by e.g. heavy metals and pesticides, and are experiencing ongoing salinisation from inappropriate irrigation practices and seawater intrusion. Soil degradation by erosion has received much research attention, but processes such as loss of biodiversity have still remained poorly investigated, with limited and sparse data availability.

Mediterranean soils face multiple threats, with changes in soil properties driven by degradation increasing soil susceptibility to other degradation processes and hampering soil ecosystem services (Fig. 8). Loss of ecosystem services through soil degradation will affect economic growth and ultimately societal health and sustainability.

Initiatives on collecting soil data have had limited uptake at regional, national, and local level, particularly in eastern Mediterranean countries. While soil sealing has been relatively well mapped across the Mediterranean region, other degradation processes, such as soil compaction have not and further investigations are needed to identify affected areas and trends. Soil erosion has been well studied in some respects, but temporal trends and the spatial extent of affected areas, particularly in eastern Mediterranean countries, need further clarification. Further research and establishment of systematic monitoring are also needed to reduce uncertainties about SOM stock modelling and trends, and the extent of salt-affected areas. Moreover, despite efforts by the European Commission to map soil contamination, identification of contaminated sites is quite limited and there is a lack of soil quality guidelines on chemical concentrations, which also requires further research.

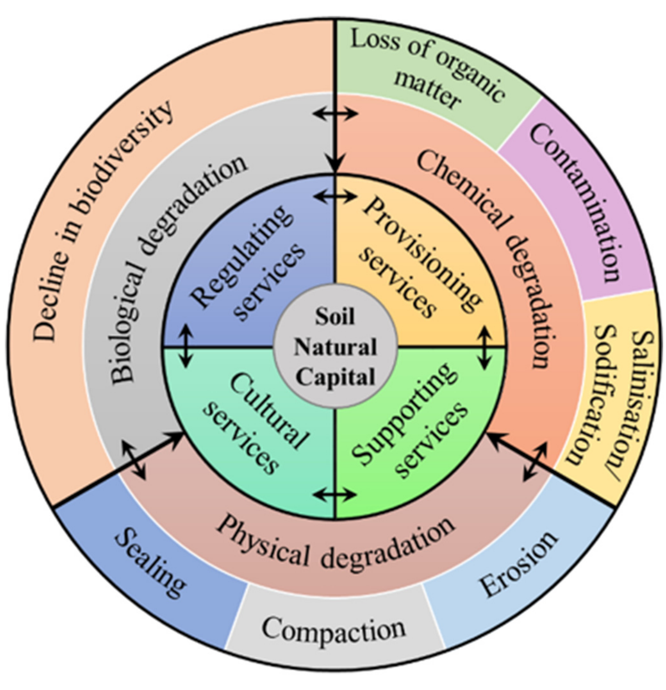

Fig. 8. Major soil threats and potential impacts on ecosystem services (supporting, regulating, provisioning, cultural) provided by soil natural capital.
(Adapted from Robinson et al., 2017)

Overall, there is a general lack of regular systematic assessments of Mediterranean soils, and of a formal authority to compile and synthesize available information. Soil assessments within a harmonised, continuous monitoring system would provide comparable datasets and help reveal the spatial extent of soil degradation and its spatial and temporal trends. A coordinated network is also needed to investigate soil biodiversity and assess its spatial and temporal trends as means for preventing future degradation in the Mediterranean region. While some studies have investigated economic impacts of declines in crop yields caused by soil erosion, economic assessments of the impacts of other soil degradation processes are currently lacking for the Mediterranean region.

In conclusion, systematic, synthesized, and accurate information about soil degradation status and trends, and their environmental, societal and economic implications are of critical importance but lacking in various important aspects for the Mediterranean region. Bridging the gaps for these lacking aspects, as outlined above, is essential for guiding policy and decision-making to improve soil management, protect this natural resource, and safeguard its long-lasting delivery of ecosystem services in this region.

Declaration of competing interest

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

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