Agricultural Land Degradation in Portugal and Greece

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Contents

Abstract Agricultural land degradation is a global problem affecting food production and other ecosystem services worldwide such as water regulation. It is driven by unsustainable land use and management practices (e.g. intensive tillage, overuse of agrochemicals) and can be aggravated by future climate change. Land degradation is particularly problematic in arid and semi-arid areas of southern Europe, and distinct soil degradation processes impair agricultural areas in Portugal and Greece. This chapter aims to improve understanding of various degradation processes affecting agricultural land, including soil erosion, compaction, contamination, and salinity and sodicity. It summarises the scientific literature on the current status of these degradation processes in agricultural areas of Portugal and Greece and their main causes and consequences. Moreover, it provides examples of best management practices implemented to mitigate agricultural land degradation. Some degradation processes are relatively well documented (e.g. erosion), while knowledge of the spatial extent of others such as soil compaction is still limited. A better understanding of soil degradation processes and of the counter-impacts of improved agricultural management practices is critical to support decision-making and ensure long-term fertility and productivity, thereby maintaining the sustainability of agriculture.

Keywords Agricultural land degradation, Compaction, Contamination, Greece, Portugal, Salinity and sodicity, Soil erosion

1 Introduction

Agricultural land supports crop and livestock production, as well as multiple ecosystem services of vital importance for local and global societies, and thus sustainable management of agricultural land is of paramount importance [1]. However, the importance of agricultural land for food security and the multitude of environmental services it provides are not always recognised by the public, while many stakeholders (e.g. policy-makers, land managers) are poorly involved in management strategies [2]. This is leading to diversified forms of land degradation, which are often ignored due to their gradual development over time and impacts on soil resources that are often neglected [3]. Land degradation encompasses an array of biophysical processes which result in reductions in land quality and is defined by loss of production [4]. In recent decades, it has been exacerbated by various factors including human activities and climate change [5]. Land degradation is an active process in arid, semi-arid and dry sub-humid areas [6], such as those found in Portugal and Greece.

Soils in southern Europe have been identified as particularly vulnerable to soil degradation [7], and at high or very high risk of desertification [8], in part favoured by the abundance of shallow soils [9]. Typically, these soils have high erosion rates [10], low levels of soil organic matter [11] and salinisation problems [12] and are threatened by compaction, contamination and loss of biodiversity [13, 14]. Such degradation processes are particularly problematic for agricultural land, given the negative impacts on soil fertility and crop yields [15]. It is estimated that land degradation leads to annual losses of six million ha of productive land globally [16]. On agricultural land, degradation has been aggravated in recent decades by rapid land use changes and intensive management practices [2]. The negative impacts on production often lead to land abandonment or are partly overcome by compensation through artificial provision of nutrients and increased use of irrigation [17].

Portugal, in the western European Mediterranean region, occupies an area of about 92,212 km^2 and has a population of 12 million [18]. Like many other countries, Portugal has experienced negative changes in its cropping systems over recent decades. Rainfed cereal, the main land use until the middle of the twentieth century, gradually became unprofitable in most marginal areas of Portugal due to decreasing crop prices driven by opening up to international markets [19]. This contributed to abandonment of marginal, mountainous or semi-mountainous areas and a decrease in the area of arable land where low-intensity management practices were used [20]. Implementation of the European Union (EU) Common Agricultural Policy (CAP) in 1992 led to afforestation of former agricultural land, intensification of production practices in more fertile areas (mainly lowlands), accelerated abandonment of marginal land and the collapse of traditional farming systems [20]. From 1999 to 2009, the area of total arable land in mainland Portugal decreased by 30% (from 1.7 to 1.2 million ha), associated with a similar area increase in pasture land (from 1.3 to 1.7 million ha) [21]. Utilised Agricultural Area (UAA) in Portugal is currently 3.641.680 ha [22], mainly comprising permanent grassland (52%), followed by arable land (29%) and permanent crops (19%) [23]. Between 2010 and 2020, the most relevant harvested crops in Portugal were grapes, permanent crops, olives, cereals and maize [24]. The agriculture sector represents 5% of total employment [22].

Greece, in the eastern European Mediterranean, occupies an area of about 132,000 km^2 and has a population of 11 million, mainly residing in coastal regions and on the islands [25]. Agriculture in Greece is a vital sector in terms of economic activity and employment (11% of total employment), contributing one-third of total national exports [22]. The agriculture system is characterised by small or average-sized farms [26], mainly located in lowlands (57%) but also extending into mountainous or semi-mountainous areas (43%) [27]. The UUA in Greece is 3591.42 million ha, comprising 39% arable land, 41% permanent grassland and 20% permanent crops [23]. Nearly 45% of the total cultivated area in Greece is irrigated [27]. A significant part of the arable land is intensively cultivated with tree and/or annual crops [26] and the dominant crops include olive, permanent crops, grapes, cereal, wheat and spelt [24].

This chapter describes the current status of agricultural land degradation in Portugal and Greece, focusing on soil erosion, compaction, contamination and salinity and sodicity degradation processes as well as their causes, environmental consequences and possible solutions to mitigate these processes. Although land degradation is an age-old problem, there is a new urgency in addressing and managing it in order to guarantee food security and safety for a growing global population and to ensure sustainable development of the agriculture sector.

2 Soil Erosion

Soil erosion is one of the most widespread forms of soil degradation in Europe [28]. Although a natural process, it has been largely accelerated by human activities, especially those associated with land use and management and in particular those linked with intensive tillage and ploughing in agricultural areas [29]. In the EU, 24% of soils are affected by erosion rates higher than the soil formation rate, driven by weathering and pedogenesis, which is estimated to be on average 1.4 t ha^{-1} $year^{-1}$ [30]. Higher erosion rates (>2 t ha^{-1} $year^{-1}$) occur on most of Greece's territory and on a significant proportion of Portugal's territory (Fig. 1). The rainfall regime, associated with short but intensive storm events, is an important driver of soil erosion in both countries and across the Mediterranean region [31]. In Portugal, the main causes of soil erosion include inappropriate management practices, overgrazing, deforestation, land abandonment, wildfires and construction activities, but agricultural land uses are reported to generate the highest soil erosion rates [20]. In Greece, the high susceptibility to soil erosion is driven by the combined impact of agriculture and site-specific conditions such as high susceptibility of most soils to erosion, the predominance of mountains and hilly landscapes (80%, one of

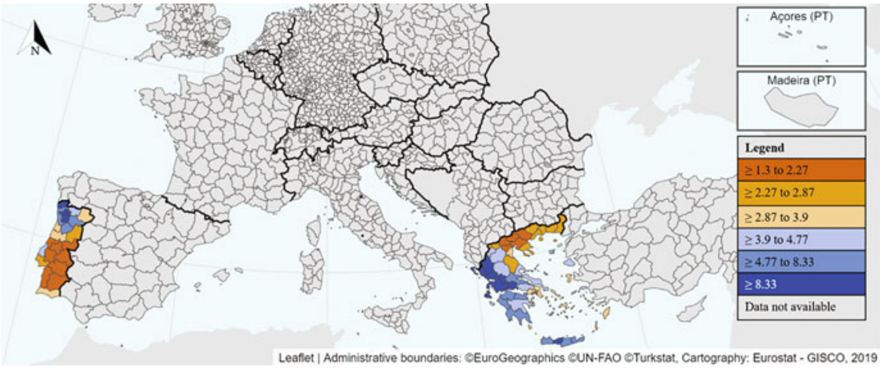

Fig. 1 Estimated water-driven soil erosion rates (t ha^{-1} year^{-1}) in NUTS 3 level administrative areas in Greek and Portuguese territories, 2016. Values based on the Revised Universal Soil Loss Equation (RUSLE) (adapted from [34])

the highest rates in Europe), erodible bedrock characterised by low permeability material favouring runoff (e.g. limestone, volcanic and transformed formation) and climate conditions [32, 33].

Between 2001 and 2012, there was a slight decrease in soil erosion in both Portugal and Greece, due to increased vegetation cover associated with farm abandonment caused by the global economic crisis [29]. This tendency became stronger in Portugal in 2010–2016, due to increasing use of soil conservation practices on arable land, but was reversed in Greece, where an increasing proportion of farmland is affected by high erosion rates due to unsustainable management practices [10].

2.1 State of the Problem for Agricultural Land in Portugal and Greece

Agricultural land is generally characterised by the highest erosion rates, due to intensive management practices and typical lack of vegetation cover [1, 20]. Intensive management is practised on about one-third of UAA in Europe and on a slightly higher percentage area in Portugal than Greece (Fig. 2). The average soil erosion rate for arable land in Portugal and Greece is ~2.75 t ha^{-1} year^{-1} and ~ 2.90 t ha^{-1} year^{-1}, respectively [10]. The Portuguese rate for farmland is higher than the average soil erosion rate for all Portuguese land (~2.17 t ha^{-1} year^{-1}), but the Greek rate for farmland is lower than the Greek national average (~4.19 t ha^{-1} year^{-1}) [10]. It is estimated that severe soil erosion affects 5.8% and 11.8% of total agricultural area in Portugal and Greece, respectively [35].

Agricultural mechanisation has enabled great advances in crop management and productivity, but locally it can trigger soil compaction and decrease infiltration, favouring runoff and soil erosion [36]. To reduce soil compaction and improve

Fig. 2 Share of Utilised Agricultural Area (UAA) under low-, medium- and high-intensity management in Portugal (PT) and Greece (GR) in 2019, and average values for the 28 countries belonging to the European Union (EU28) [51]

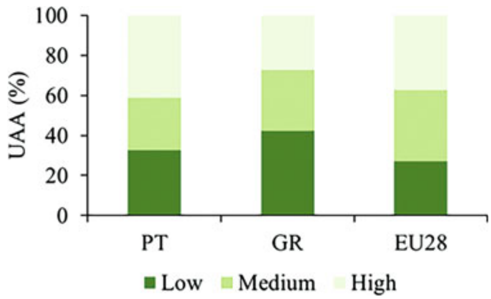

Fig. 3 Soil erosion caused by the first rainstorms in a newly established kiwi plantation in central Portugal: (**a**) rill erosion in the upper part of the field, and (**b**) gully erosion in a downslope area (photo by Ferreira 2012)

soil conditions for root development, tillage and particularly ploughing (a highly intense form of tillage since it involves inverting the soil) has been intensively used in Portugal and Greece [37]. Studies performed in Portuguese vineyards report high sediment yields after tillage, even when little runoff is generated, since disturbed sediments are readily available to be transported [38]. Water is the most prevalent eroding agent, with sheet, rill and pipe erosion found in many farm fields in both Portugal and Greece. These can evolve into more severe forms such as gully erosion when fragile and bare soils are subject to intensive rainfall. Figure 3 shows the magnitude of soil erosion recorded in a small Portuguese kiwi plantation (1 ha) during the first storms after field preparation, which left the soil surface bare and totally exposed to erosive agents [39]. Other studies examining different land uses in Portugal have shown that soil transport by runoff peaks during autumn/winter coincides with the highest and most erosive rainfall [20]. This is associated with the typical seasonal pattern of the Mediterranean region, characterised by intense rainfall after a dry summer, with rainfall being concentrated in the autumn and winter months [40]. Gully erosion is particularly common in Greece and is responsible for erosion rates of up to 455 t ha^{-1} $year^{-1}$ [41].

Soil erosion on Portuguese and Greek farmland is also driven by other inappropriate farming techniques such as monoculture (which favours depletion of nutrients), limited use of organic fertilisers (which accelerates depletion of already limited organic matter), burning of crop residues (which leaves the soil surface bare and unprotected), cultivation on mountain slopes (e.g. for vineyards) and overgrazing [14, 33]. In intensively grazed areas, there is a significant reduction in vegetation cover and soil compaction due to trampling, which accelerates soil erosion [6]. Overgrazing is of particular importance in Greece since grazing land now comprises more than 40% of total land use in that country, following an increase in the number of grazing animals from 0.78 million in 1960 to 2.51 million in 2010, despite the estimated pasture carrying capacity being only ~0.65 million [6]. The increasing grazing pressure in Greece emerged particularly after the mid-1980s, driven by farm subsidies [6]. Around 71% of grassland in Greece is grazed for more than 10 months, so Greece has one of the highest grazing intensities in the EU in terms of duration and proportion [42].

Crop harvesting may also trigger soil losses, due to particles adhering to roots and tuber crops (e.g. carrots, potatoes). This form of soil loss depends on the type of crop and harvesting techniques (e.g. effectiveness and velocity of the technology used), as well as soil properties such as structure and texture and soil moisture content. Crop harvesting can make a relevant contribution to total soil losses (up to 28%), particularly in some regions of Greece due to the extent of tuber crops grown [28].

2.2 Consequences of Soil Erosion

Over time, soil erosion leads to several environmental impacts, at both on-site and off-site locations. The on-site reduction in soil depth caused by erosion restricts crop rooting space and the ability to store water. This may be particularly relevant in southern European countries typically characterised by high abundance of shallow soils [9], and in areas where water scarcity is a relevant problem during the driest periods [43]. Soil erosion affects biogeochemical processes, such as the soil carbon cycle, due to changes in nutrient mineralisation rates, and is often associated with a decreasing carbon sink [44]. These changes, coupled with losses of topsoil (the most fertile soil layer), cause on-site decreases in organic matter and nutrients and pose a threat to soil fertility and long-term productivity [45]. This can be especially relevant in southern European countries, where soils typically have low organic matter content (<2%) due to accelerated soil respiration and mineralisation driven by the regional climate (i.e. high soil temperature and moisture) [14]. Low organic matter content hinders the formation of stable soil aggregates that are resistant to the shearing forces of rainfall and runoff and reduces soil infiltration and water-holding capacity [33]. The depletion of nutrients and soil fertility caused by erosion and associated soil degradation lead to abandonment of agricultural land [20].

According to Bakker et al. [46], there is a 4.3% decline in crop yield for each 0.1 m of soil loss. Severe soil erosion in the EU is responsible for annual decreases of 3 and 0.6 million tonnes of wheat and maize, respectively, with the highest losses in countries such as Greece where extensive areas are occupied by these crops [35]. In 2010, it is estimated that the impact of soil erosion on Portuguese gross domestic product (GDP) was -€ 2.8 million but it reached -€12.6 million in Greece, based on the loss of crop productivity [35]. Apart from the relevant economic impacts of soil erosion, the loss of productivity also raises important concerns for food security and achievement of some of the United Nations Sustainable Development Goals (SDGs) [10].

Off-site impacts of soil erosion are linked to siltation of streams and reservoirs, reducing their drainage/storage capacity, which can increase the flood hazard [39]. It can also potentially impair water quality [38], leading to ecological disturbance of aquatic ecosystems and affecting recreational activities [29]. Soil erosion can also damage or destroy transportation networks such as roads and railways, and other public assets such as hydraulic infrastructure [47].

Sediments caused by erosion processes in agricultural areas may contribute to increasing concentrations of nutrients such as nitrogen [48], but also heavy metals [39] and pesticides [49] in the receiving water bodies. In Greece, several water bodies show moderate or high heavy metal contamination in sediments [26]. The impacts on water quality may impede achievement of some SDGs, e.g. SDG6: Clean water and sanitation and SDG14: Life below water.

2.3 Soil Conservation Practices

Soil erosion from agricultural land can be controlled by changing management practices and increasing the ground cover [20]. Increasing concerns regarding agricultural sustainability, partly triggered by EU guidelines and subsidies under the CAP and growing demand from consumers, have led to the adoption of improved management practices by farmers [14]. Most of these practices involve reduced-tillage intensity and/or enhanced soil cover. In 2016, arable land occupied 29% and 39% of Portuguese and Greek UAA, respectively [50]. On arable land, conventional tillage is widespread in Greece, being applied on 82% of the area, whereas in Portugal it is applied on 33% of the total area. In Portugal, 37% of arable land is managed using conservation tillage and 30% using no-tillage (Fig. 4a). In Portuguese vineyards located in the centre of the mainland, conservation tillage has led to runoff coefficients of 11–19%, which are much lower than those reported in nearby vineyards managed using conventional practices (42%) [38]. However, although conservation tillage has led to erosion rates (7–16 t ha^{-1} $year^{-1}$) of about half those recorded in conventional vineyards [38], it is not enough to prevent land degradation considering the estimated 1.4 t ha^{-1} $year^{-1}$ soil formation rate [30].

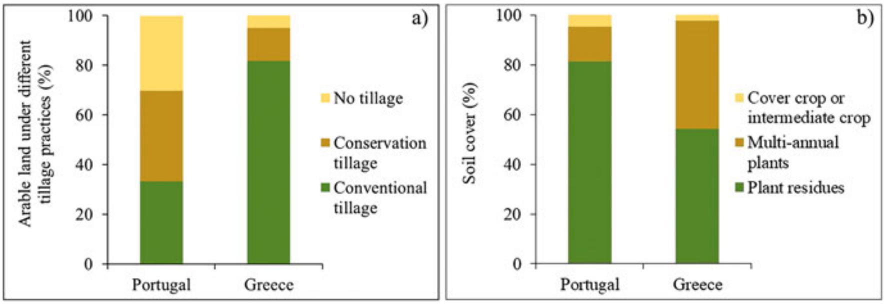

Fig. 4 Percentage cover of soil conservation practices in Portugal and Greece based on (**a**) tillage practices and (**b**) soil cover practices (data source: [51])

Soil conservation practices focusing on enhancing soil cover to protect against erosion largely involve leaving crop residues in the field (Fig. 4b). This is a widespread practice on arable land under soil conservation in Greece (81%), but less so in Portugal (44%). Grassland and intercropping (e.g. growing wheat together with clover-grass leys) are also used to reduce runoff and soil erosion, particularly in Portugal. In semi-arid areas, these measures are reported to reduce runoff by 34–89% and soil erosion by 45–94% [52]. Studies carried out in Mediterranean environments have shown that below 30% vegetation cover, soil erosion and runoff increase dramatically [53]. Unprotected soil surfaces may lead to erosion rates 100–1,000 times higher than in fields with permanent vegetation cover [20]. Vegetation protects the soil, e.g. by intercepting rainfall, which reduces the erosive power of impacting raindrops, and by reducing the volume of water reaching the soil surface, and is considered one of the basic approaches to control soil erosion [20].

Growing a cover crop is suggested to be one of the most promising measures to prevent erosion and soil degradation [54]. Cover crops are a specific form of mixed cropping in which a secondary crop is planted and grows after the main crop is harvested, thus protecting the soil between crop seasons, reducing runoff and soil erosion [37]. Field experiments performed in central Portugal have shown that leguminous cover crops reduce the risk of nutrient leaching during the rainy period and avoid groundwater pollution, by taking up and immobilising water-soluble nutrients in their roots and aerial parts [55]. Cover crops can also be used as green manure, for gradual release of nutrients to the subsequent main crop, which allows a reduction in at least 40% of nitrogen, 30% of phosphorus and 100% of potassium supplied by mineral fertilisers, while they also compete with weeds, limiting their growth [55].

Although vegetation cover can be a good strategy to prevent erosion, the dry conditions of the Mediterranean countries make it challenging to maintain soil cover. This leads to reduced vegetation cover during the summer and lower effectiveness in preventing soil erosion driven by the first autumn storms [56]. Other soil conservation practices such as application of plant residues (e.g. straw mulching, pruning wastes) can be more relevant to prevent land degradation in semi-arid and arid regions [57]. Incorporation of organic amendments (e.g. manure, green manure, compost) has been also found to improve soil properties and reduce erodibility, but it must be compliant with crop nutrient requirements and managed together with mineral fertilisation rates applied to avoid nutrient and heavy metal leaching and contamination of groundwater [58]. Widespread adoption of measures to reduce erosion and other degradation processes on agricultural land is critical for achieving food security [59].

3 Soil Compaction

Soil, a porous medium, tends to compress and increase its bulk density when subjected to pressure, and thus it can become compacted. The persistence of soil compaction, in surface and/or subsurface layers (i.e. below tillage depth, ~0.25 m), is one of the most important soil threats in Europe [60] and represents a great concern in some regions of Portugal and Greece [61].

3.1 Causes of Soil Compaction

Soil compaction is caused by exposure to pressure greater than the soil's strength, typically exerted by machinery and/or livestock [62]. The susceptibility of the soil to compaction depends on many factors, including natural and man-induced factors, or a combination of both if they occur simultaneously. Climate and soil properties such as soil texture, initial bulk density, water content and organic matter content largely determine the natural susceptibility of soil to compaction [63, 64]. Man-induced soil compaction is associated with land management [12], and tillage practices and high grazing intensity are among the land management practices with the greatest impacts on agricultural soil compaction [65]. In fire-affected areas in particular, traffic by heavy machinery is a major cause of soil compaction [66].

Although compaction is a major threat to soil quality, little has been done to reduce compaction of agricultural soils. Intensive mechanisation of crop production activities, particularly in developed countries, associated with high machine traffic in fields to perform multiple tillage operations and heavy machinery associated with powerful tractors are the main cause of soil compaction [67]. Despite the use of wider and more voluminous tyres, the changes in farm machinery have not been sufficient to compensate for the increasing weight of machinery and impacts on soil compaction [62]. Tillage, harvesting and application of chemicals and fertilisers are common operations affecting soil compaction on farms [1]. Tillage operations are widely reported to cause soil compaction at different depths [68]. In a modern drip-irrigation citric plantation located in the Mediterranean region, Cerdà et al. [69] found a rapid increase in bulk density from 1.05 to 1.33 g cm^{-3} over 13 years of machinery use. Schjønning et al. [70] reported increasing subsoil compaction, by a factor of 1.9, 3.0, 3.9 and 4.6 at 0.25, 0.50, 0.75 and 1.00 m depth in agricultural soils after 50 years of machinery use (e.g. mouldboard ploughing).

The pressure of animal traffic on the soil (overgrazing livestock) can result in soil compaction similar to that caused by machine traffic, depending on animal type, age and pressure exerted by the animals on the soil [63, 71, 72]. According to Taboada et al. [73], under the same set of soil conditions, the stress exerted by a cow in movement (98–192 kPa) can be twice the static pressure caused by a typical tractor (27–68 kPa), because of the angle of the force applied and the concentration of weight on a smaller area of hooves [71].

3.2 Current Status of the Problem in Portugal and Greece

Based on soil properties recorded in the European soil database, such as texture, relative proportion of fine particles, organic matter, level and type of aggregation, water regime and depth, and the dominant and secondary land use [74], Portuguese soils have lower susceptibility to soil compaction than Greek soils (Fig. 5). A relatively small part of mainland Portugal has high or very high susceptibility to soil compaction, whereas Greece has a large area with high susceptibility and a large area with medium susceptibility. Soils with lower susceptibility to compaction, mainly in the north of both Portugal and Greece, are mostly located in forestry and some are associated with extensive grazing systems. However, in the south of Portugal and centre and south of Greece, some regions of high and very high susceptibility of soil compaction are under intensive agricultural systems, most of them managed by conventional practices and without soil conservation measures, which can exacerbate the problem.

Increasing use of irrigation leads to higher soil moisture content, which favours compaction [12]. In Portugal, several irrigation projects (e.g. Alqueva which includes 69 dams, reservoirs and weirs over an extension of 120,000 ha, and considered the largest irrigation project in Europe) have been implemented in recent decades to enhance productivity in rainfed areas (Fig. 5b). Agricultural areas have expanded with the plantation of, e.g., new olive and almond orchards, managed under intensive practices. Thus, in the medium to long term, if improved soil management practices are not implemented, these areas can be affected by soil compaction and other soil degradation processes, with negative impacts on land resources and ecosystem sustainability. In Greece, the area under intensive farming is less extensive than in Portugal (Fig. 5b), but the soil is more susceptible to compaction than in Portugal (Fig. 5a). In Greece, around 71% of grassland is occupied by animals for 10 months of the year, which is one of the most intensive grazing rates of all European countries, both in duration and intensity [76].

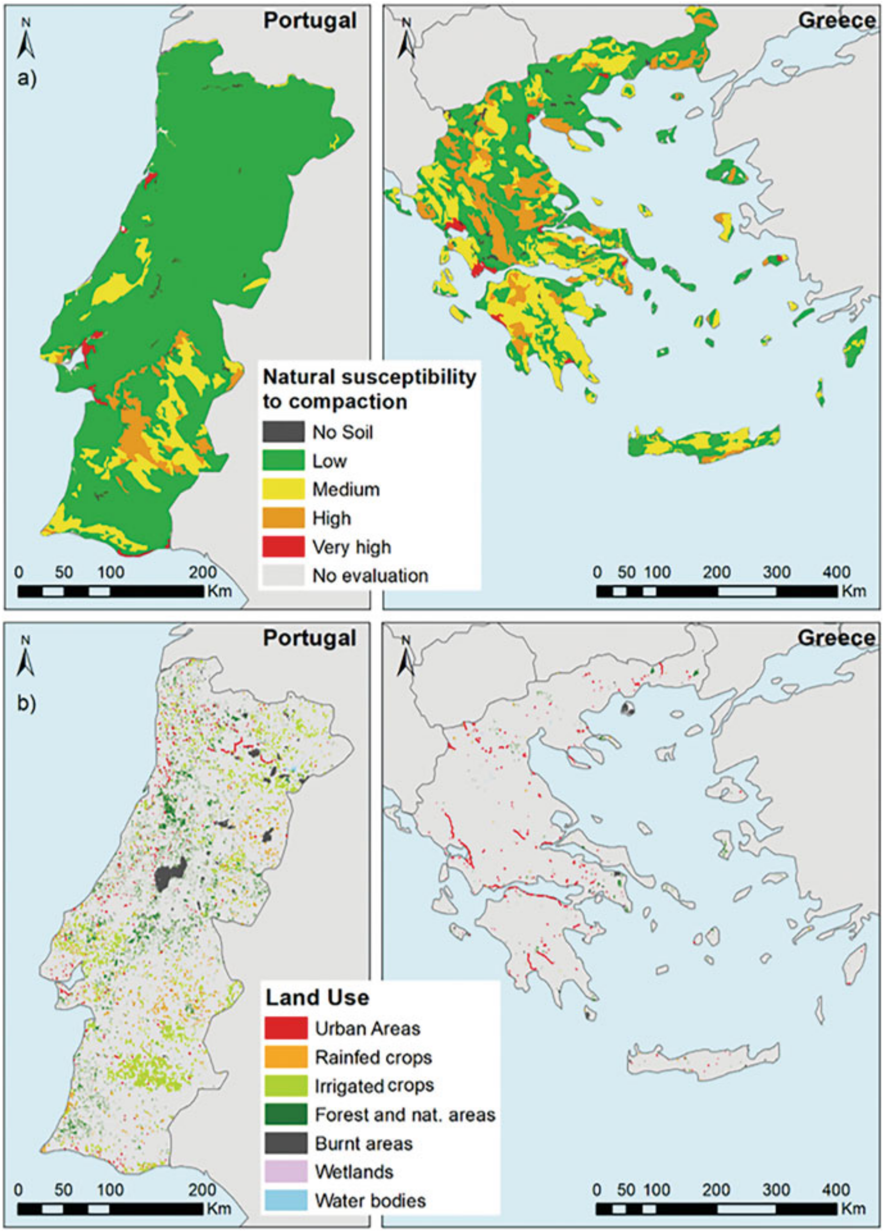

Fig. 5 (**a**) Natural susceptibility of soils in Portugal and Greece to compaction, and (**b**) change in land use between 2012 and 2018 (adapted from [74, 75])

3.3 Environmental Consequences of Soil Compaction

Soil compaction causes several environmental consequences on global farmlands, including those in Portugal and Greece. The compaction process primarily reduces the size and volume of pores, particularly macropores, decreasing the bulk density and negatively affecting several essential soil properties, such as hydraulic conductivity and infiltration capacity, which increases surface runoff and contributes to waterlogging during precipitation events [67]. With the application of compressive stress the soil can easily approach saturation. The compression of soil under saturated conditions is known as consolidation [77]. The reduction in soil water storage capacity driven by compaction also has consequences in terms of depletion of water resources [6]. In addition, increasing surface runoff from compacted soils, especially from soil surfaces lacking a protective cover, such as those where overgrazing is permitted, leads to a reduction in vegetation, increases erosion rates and, in extreme precipitation events, may trigger landslides and flooding [14]. A complete review of the effects of grazing animals on soil physical properties can be found in [78].

Some pollutants, like phosphorus and pesticides, are preferentially attached to fine soil particles and easily transported during erosion, which can have negative impacts on aquatic ecosystems, resulting, e.g., in eutrophication [79]. The transport of sediments to the natural drainage network, where the flow loses energy and deposits material, increases sedimentation effects, reducing the water storage capacity of dams and the flow capacity of natural streams (Fig. 6). This in turn increases flood susceptibility [39].

Soil compaction (in unsaturated soil) reduces diffusion of oxygen into soil, affecting microbial activity, and increases penetration resistance for roots and thus root growth [70]. The constraints imposed by soil compaction on the availability of air and water, and on uptake of nutrients by plants, lead to decreasing yield capacity [80]. In Europe, soil compaction leads to crop yield reductions ranging from 2.5–15% [15] to 25–50% [81].

3.4 Examples of Management Practices to Prevent Soil Compaction

Conservation agriculture is considered to be a good solution to prevent soil compaction. It includes a combination of several agricultural practices based on minimal soil disturbance, e.g. in seedbed preparation, retention of crop residues on the soil surface and use of combined management operations to minimise machine traffic in fields [82]. In Portugal, long-term research has shown that conservation agriculture can increase soil organic matter and improve aggregate stability and porosity throughout the soil profile, helping to prevent soil compaction [83]. Adoption of no-tillage or reduced-tillage systems, besides preventing soil compaction, also prevents mineralisation of stable components of soil organic matter and thus contributes

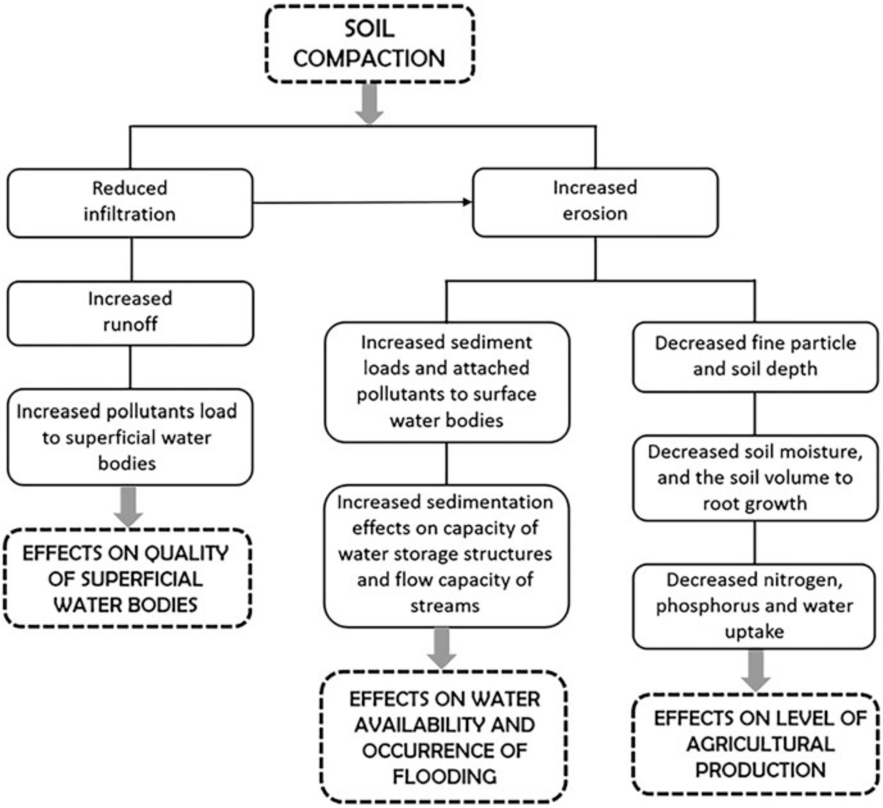

Fig. 6 Environmental impacts of soil compaction on soil on water resources, aquatic ecosystems and crop productivity

to sequestration of organic carbon in the soil [82]. As shown in Fig. 4, the Greek arable land managed under no-tillage or conservation tillage practices is nonrepresentative. In contrast, these management practices are implemented in the majority of Portuguese arable land. In fact, Portugal is the European country showing the greatest decrease in conventional tillage practices [23].

In grazing livestock systems, maintenance of vegetation cover on the soil lessens the direct impact of rainfall drops and decreases water erosion, reducing the effect of external forces on the soil. In conditions of extensive grazing, some studies report benefits of animal manure in increasing soil organic matter concentration and resilience to soil compaction [77].

4 Soil Contamination

Soil contamination refers to the presence of physical, chemical and/or biological substances causing temporary or permanent loss of one or several soil functions [64]. In recent decades, soil contamination has become one of the major concerns for developed and developing countries, particularly in agricultural soils since it impairs food safety [84]. Soil contamination affects, e.g., crop yields by lowering the activity of soil biota and reducing biodiversity, with negative impacts on nutrient cycling and soil structure. The changes in soil physical properties driven by inappropriate management practices enhance the susceptibility to degradation processes such as soil erosion, which contributes to the spread of contaminants into downslope areas [85]. Soil contamination in agricultural areas may pose threats to food safety by providing a pathway for human exposure to pollutants such as pesticides and heavy metals [84]. A study by [86] revealed that more than 29% of food samples analysed across the EU contained multiple pesticide residues. Global concerns have led more than 170 countries within the United Nations Environmental Assembly (UNEA-3) to express their willingness to reduce soil contamination [87].

4.1 Causes of Contamination in Agricultural Soils

The intensification of agricultural practices has been associated with increasing use of agrochemicals to enhance nutrient availability for crops and to control pests and diseases, in order to improve crop yields, but this is a major cause of soil contamination [49, 68].

Overuse of fertilisers, through excessive inputs of synthetic fertilisers, inappropriate management of organic amendments (e.g. manure, sewage sludge) and/or intensive livestock density, has been identified as a major driver of soil contamination [87, 88]. Nitrogen-based fertilisers are among the most widely consumed and manufactured fertilisers worldwide [51]. In Portugal and Greece, average sales of nitrogen fertilisers between 2010 and 2019 represented 67% and 74% of all fertiliser sales (nitrogen, phosphorus and potassium), respectively (Fig. 7). Although Portugal has about half the Greek level of sales of synthetic fertilisers, the rate of application of inorganic nitrogen and phosphorus fertiliser per unit area of cropland is higher, although still below the European average in both countries (Fig. 8). A decreasing tendency in the rate of fertilisation was seen from 1990 to 2009, especially in terms of phosphorus inorganic fertiliser, possibly due to increasing application restrictions and the development of the global economic crisis. However, in recent years the fertilisation rate seems to have increased slightly (Fig. 8).

Fertilisation rates higher than plant nutrient requirements can lead to nutrient imbalances in the soil, with negative impacts on the ability of plants to absorb some of the necessary nutrients (e.g. calcium and magnesium), causing nutrient deficiency in plant tissues or even toxic levels, which increases plant vulnerability to pests and

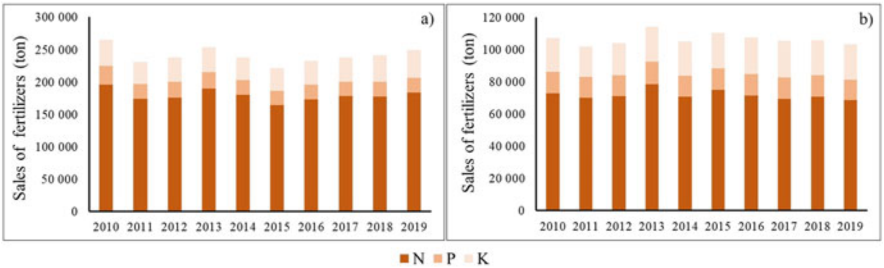

Fig. 7 Total sales of inorganic fertilisers 2010–2019 in (**a**) Portugal and (**b**) Greece (data source: [51])

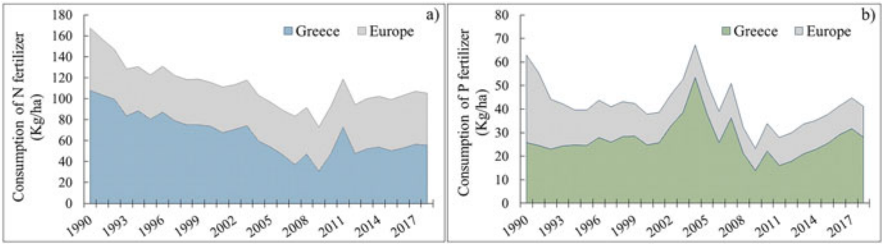

Fig. 8 Ratio of (**a**) nitrogen and (**b**) phosphorus mineral fertiliser in total fertiliser consumption and area of cropland (including arable land and permanent crops) in Portugal, Greece and Europe in the period 1990–2018 (data source: [89])

diseases and decreases crop productivity [90]. Inefficient management of nitrogen and phosphorus within agricultural fields may also lead to eutrophication and acidification of surface waters and contamination of groundwater [38, 88, 91]. In mainland Portugal, the risk of groundwater contamination driven by nitrogen fertilisation in agriculture, considering the spatial extent of the agricultural fertilisation hazard and site-specific aquifer vulnerability, increased in extent from 8,800 to 82,679 ha of the territory between 1999 and 2009 [21]. This was despite action programmes and mandatory restriction measures associated with fertilisation rates and animal stocking rates in Nitrate Vulnerable Zones delineated in 2004 (covering 4.4% of the territory), following the European Nitrates Directive, and the abandonment of grazing practices, particularly in southern regions [21].

Inappropriate management of manure and other organic amendments such as sewage sludge, which are widely used due to their potential to improve soil properties and functions, can also contribute to over-fertilisation and soil contamination [92, 93]. Soil contamination due to organic amendments has been associated with heavy metals, pathogens and veterinary antibiotic residues [94–96].

Given the positive impacts of sewage sludge on soil properties (e.g. aggregate stability, organic matter content and biodiversity) [68] and their increasing availability driven by a growing population, agricultural land can be a useful recipient of this type of solid waste. In 2016, 13.89 and 21.53 thousand tons of sewage sludge were applied to agricultural areas in Portugal and Greece, respectively, corresponding to ~12% and ~ 18% of national sludge production, respectively [97]. In order to prevent soil contamination driven by sewage sludge, the European Council Directive 86/278/EEC regulates sludge application in agriculture. The implementation of legislation regulating application of sewage sludge in Portugal, which involves regular soil monitoring and a complex permit system, led to a ~ 57% decrease in land application between 2012 and 2016, whereas in Greece a slight increasing tendency has been observed [97].

4.2 Soil Contamination with Heavy Metals and the Current Situation in Portugal and Greece

Heavy metals are among the most toxic, persistent and complex non-biodegradable contaminants reported in agricultural soils [98]. They are easily accumulated in tissues and living organisms, representing a threat to the health and well-being of animals, plants and humans [99]. Although heavy metals may occur naturally in soils, depending on bedrock properties, concentrations above background levels are likely to be found in soils receiving intensive applications of synthetic fertilisers, pesticides, manure and sewage sludge [100, 101].

In general, both Portugal and Greece have higher heavy metal concentrations in agricultural soil than the average values across Europe (Table 1). This is particularly the case in terms of copper (Cu), zinc (Zn) and lead (Pb), with concentrations about twice the European average. This may be due to the high fertiliser doses required to

Table 1 Baseline concentrations (mg kg^{-1}) of heavy metals (mean and standard deviation (STD)) in soils in Portugal, Greece and Europe, based on pan-European studies (adapted from ESDA database: esdac.jrc.ec.europa.eu)

		Portugal	Greece	Europe
As	Mean	13.45	10.18	6.89
	STD	5.05	3.41	1.68
Cd	Mean	0.20	0.29	0.11
	STD	0.10	0.11	0.66
Cr	Mean	46.73	26.30	23.77
	STD	23.21	7.42	5.17
Cu	Mean	22.20	26.97	14.83
	STD	6.06	10.29	3.70
Hg	Mean	0.05	0.05	0.05
	STD	0.02	0.01	0.01
Ni	Mean	20.38	56.31	20.43
	STD	6.78	44.22	6.95
Pb	Mean	31.66	24.78	19.06
	STD	14.96	9.18	5.16
Zn	Mean	71.28	72.37	58.88
	STD	28.95	23.86	14.26

overcome the relatively low soil organic matter content and low nutrient availability [38] and high use of pesticides to mitigate the high climate-related susceptibility to pests and diseases [102].

High soil copper concentrations are often driven by extensive use of copper-based fungicides [100], particularly in olive and wine-producing regions [75], and by application of sewage sludge [101]. In fact, vineyards in Central Portugal have been reported to have copper, lead and nickel (Ni) concentrations exceeding the legal thresholds [68]. In Greece, particularly high concentrations of nickel have been reported (Table 1) in the Atalanti [103] and Thessaloniki [104] regions. These high concentrations have been recorded on maize farms, together with high concentrations of chromium (Cr), molybdenum (Mo), selenium (Se) and antimony (Sb) [105]. Heavy metals can remain in the environment for many years, and thus impair water resources [58]. In Greece, heavy metal concentrations exceeding sediment quality guidelines have been reported in many regions since the 1970s [26].

Relatively high accumulation of heavy metals in agricultural Mediterranean soils is also favoured by relatively low leaching rates under low precipitation surplus [106]. To mitigate the impacts of high heavy metal concentrations, the FAO recommends remediation of contaminated agricultural soils and implementation of sustainable soil management practices [87].

4.3 Soil Contamination with Pesticides and the Current Situation in Portugal and Greece

In agricultural soils, contamination with pesticides is a major concern due to their high toxicity and persistence [85] and their global use [87]. In Europe, almost 500 active substances are approved for use [49] but less than 0.1% of the pesticides applied to crops reach the target pest, raising relevant environmental concerns [85]. Furthermore, pesticides may induce pest resistance and leave pesticide residues in crops, affecting food safety [49]. Within the EU, 1.7% of food samples analysed in 2015 revealed contamination with pesticides, whereas in Portugal the value reached 2.8% [107].

In Portugal, the average application rate of pesticides per unit cropland area is slightly lower than the European average, but more than twice the Greek rate (Fig. 9a). However, between 2011 and 2018 the use of pesticides in Portugal decreased by ~41%, whereas in Greece it increased by ~21% (Fig. 9b).

A study by [109] found that more than 80% of EU agricultural topsoil is contaminated with pesticide residues and that Portugal is one of the countries with more widespread contamination, whereas Greece is among the countries with the lowest contamination rates. In Portugal, the highest occurrence of pesticide residues is mostly reported in vineyards, where at least four different compounds have been detected [109]. Residues of glyphosate and their first-order metabolites are the main

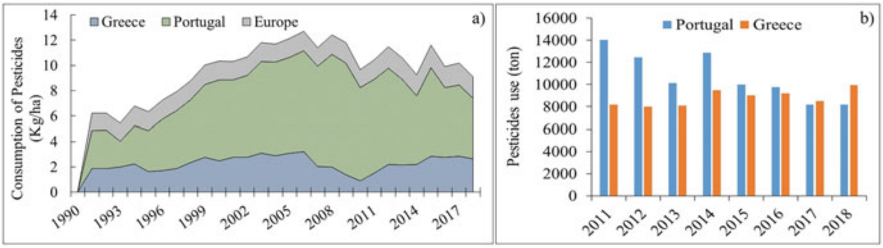

Fig. 9 a) Consumption of pesticides per unit cropland area (including arable land and land under permanent crops) in Greece, Portugal and Europe 1990–2018, and b) changes over time in the use of pesticides in Portugal and Greece during the period 2011–2018 (data source: [108])

active substances reported in Portuguese agricultural soils [110]. In Guadiana River Basin, extending over ~60 km^2 in southern Portugal, which is a biodiversity hotspot highly impacted by agriculture, the most abundant pesticides detected in soil are bentazone and 2,4-D, the most ubiquitous are terbuthylazine and terbutryn [49]. Moreover, 18 out of 38 pesticides detected are no longer approved in Europe and five of these are included in the list of priority substances for elimination. The highest concentrations of pesticides are in intensively irrigated agricultural plots such as olive groves and vineyards [49]. These results highlight the need to implement actions for sustainable use of pesticides in agricultural areas of Portugal.

In Greece, herbicide residues have been reported in soils on maize and tomato farms [111], while traceable levels of insecticides have been detected in soil samples from peach orchards [112]. The accumulation of pesticide residues and metabolites depends on their mobility in the soil, determined by pesticide chemical properties and several biophysical properties of the soil [113].

4.4 Agricultural Soil Contamination with Microplastics

Microplastics are one of the substances classified as 'chemicals of emerging concern' [15], which have been increasingly studied and widely detected in different environments [114]. In agricultural soils, small fragments of plastics have raised concerns because of their numerous and uncontrolled sources, although their distribution and abundance are affected by soil texture [115]. In general, microplastics in agricultural soils are mostly associated with practices relating to fertilisation, such as application of sewage sludge [116] and manure [117, 118], and mulching [119].

Soil contamination with microplastics has also been associated with other chemical pollution in agricultural soils. For example, polyethylene films used in agriculture may be a potential vector of several pesticide residues [119, 120]. In Greece, it is estimated that total plastic pesticide packaging waste amounts to 0.028 kg 1,000 m^{-2} farm^{-1} year^{-1} [121]. Despite increasing concern about the environmental impacts of microplastics in agriculture, there is a lack of information in the literature on the quantities of microplastics in Portuguese and Greek agricultural soils. This research gap should be filled in order to develop strategies to support farmers in mitigating the problem.

5 Soil Salinity and Sodicity

Salinisation refers to accumulation of soluble salts in the soil and comprises one of the main soil degradation processes in Europe [122]. Salinisation is associated with accumulation of salts, such as magnesium, potassium, calcium, carbonates and chorine, leading to electrical conductivity of the saturated soil extract of more than 4 dS m^{-1} at 25°C [64]. When the soil is affected by accumulation of exchangeable sodium, the problem is called sodicity. In sodic soils, the percentage of exchangeable sodium is above 15 [123]. In Europe, salinisation and soil sodisation affect about 30.7 M ha, which represents 3.3%, of all saline and sodic soils worldwide [124]. Soil salt accumulation affects most plants, leading to decreasing crop productivity and, in extreme cases, to land desertification [12].

5.1 Causes of the Problem

Salt-affected soils may occur naturally (primary salinisation) or may be caused by human-induced processes involving incorporation of highly water-soluble salts into the soil (secondary salinisation). Natural salinisation is of marine origin, driven by the direct action of the tides in coastal regions, deposition of marine salts transported by the wind, transfer of saline water to areas with limited drainage or ascending capillary flow of groundwater due to high evapotranspiration rate in arid and semi-arid areas [125]. Sodisation results mainly from the meteorisation of rocks with minerals rich in sodium [126]. The global extent of primary salinisation is estimated to be slightly under 1 billion ha and it mainly affects coastal areas [127]. This problem is particularly apparent in coastal southern Europe.

Human-induced salt accumulation is often recorded in agricultural soils receiving insufficient precipitation and/or with low hydraulic conductivity and weak drainage capacity, which restricts the leaching of salts. It is associated with inadequate management practices such as (1) intensive use of fertilisers or corrective agents, particularly in conditions of limited leaching; (2) inappropriate irrigation practices including insufficient water provisioning, overexploitation of coastal groundwater aquifers causing seawater intrusion and use of water rich in soluble salts (e.g. wastewater) and (3) application of saline products of industrial origin [128]. Secondary salinisation affects ~77 M ha globally, of which 58% are located in irrigated areas [127]. It is estimated that 20% of irrigated area worldwide is salt-affected [129]. Irrigation on drylands sustains crop production, but high evapotranspiration rates of water may lead to accumulation of salts in the root zone if not enough water is supplied to leach the salt beyond the root zone. Waterlogging without adequate drainage has also become a serious cause of soil salinisation [12].

5.2 Salinity and Sodicity Situation in Portugal and Greece

In Portugal, an area of 150,000 ha is estimated to be affected by salt accumulation, two-thirds of which is caused by primary or natural salinisation in low-lying areas affected by tides, riverbanks and estuaries in coastal areas, and only one-third is of human-related origin, associated with inadequate irrigation and drainage practices and irrigation with poor-quality water [130]. In agricultural areas, moderate or high soluble salt accumulation occurs in some soil layers during certain periods of the year, namely in summer and/or autumn. It is found in some irrigated agricultural areas located in semi-arid and arid regions in the interior of the country, such as the Alentejo. Here, the dry climate conditions co-occur with soils presenting deficient internal drainage due to low permeability of the clay B-horizon, which impedes leaching of soluble salts [130].

In Greece, salt-affected soils are found in a large variety of climatic, topographical and soil conditions, but particularly in the western coastal region, the marine Mediterranean Ionian islands and the Mediterranean mainland zone, including the south-eastern region (Aegean) and up to Thessaly [6]. Saline soils develop in particular in areas with alluvial parent material (lake or wind deposits), and thus are mainly found on plains or gentle sloping areas or in concavities (Fig. 10), and in

Fig. 10 Soil salinisation in an arable field in Messinia, Greece (photo by Maneas 2021)

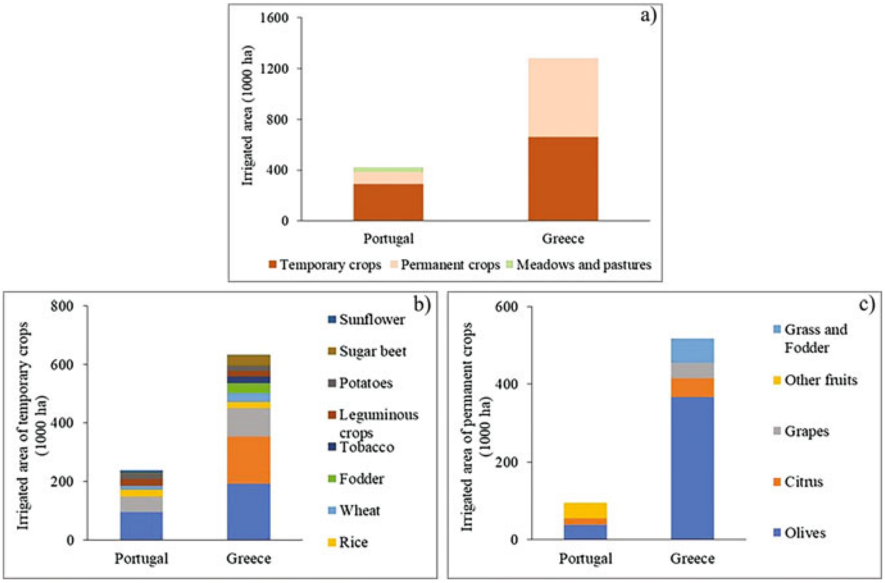

Fig. 11 (**a**) Extent of irrigated area in Portugal and Greece occupied by the main crop types in 2017, and corresponding irrigated area of (**b**) temporary and (**c**) permanent crops (data source: [102])

winter-flooded valleys surrounding by mountains. Saltwater intrusion into coastal agricultural areas and intensive agricultural activities are the main causes of the bad/poor chemical status of some water bodies in Greece [27].

Although salinisation in agricultural soils in both Portugal and Greece is not a major concern due to the relatively limited spatial extent, predicted climate change in coming decades, namely predicted increases in temperature, will increase the area requiring irrigation, and thus an increase in salt-affected areas and soil degradation can be expected. Figure 11 shows the current extent of irrigated agricultural areas and associated crops in Portugal and Greece.

5.3 Consequences for Crops

The accumulation of salts in the soil leads to imbalances in plant nutrition and may cause plant toxicity, due to excessive absorption of some ions and changes in regulatory mechanisms, such as increasing osmotic pressure driven by lower water availability in the root zone [131]. In soils with high sodium concentration, typically associated with higher pH, there is a decrease in the solubility of some macronutrient (e.g. Ca, Mg, P) and micronutrients (e.g. Fe, Mn, Zn), and in their availability to plants [130]. An excess of exchangeable sodium can also cause dispersion of clay particles, leading to disruption of aggregate stability, decreased permeability to water

Table 2 Sensitivity of different crop species to excess salt and sodium in soil. T: tolerant; MT: moderately tolerant; MS: moderately sensitive; S: sensitive (adapted from [133–136])

Crop	Salt		Sodium
Temporary crops	Maize	MS	S
	Cotton	S	S-MS
	Vegetables	MS	
	Rice	S	T
	Wheat	T-MT	MT
	Fodder	T-MT	T
	Leguminous crops	S-MS-MT	S
	Potatoes	MS	
	Sugar beet	T	T
	Sunflower	MT	
Permanent crops	Olives	MT	S
	Citrus	S	S
	Grapes	MS	S
	Other fruits	S	S
	Grass and forage crops	MT-MS	T

and air, greater resistance to root growth and greater susceptibility to surface crusting, which impedes the emergence of seedlings [126].

The impacts of salinity or sodicity on soil properties and plants are often associated with decreasing crop yields [64]. But different crops show variable tolerance to salt accumulation in the soil (Table 2). In terms of crop species, wheat and sugar beet are more tolerant than maize and vegetable crops, whereas rice and cotton are more sensitive. In terms of sodium excess tolerance, rice appears to be tolerant, wheat only moderately tolerant and legume crops such as cabbage and lentil are relatively sensitive to excess exchangeable sodium (Table 2). Besides, individual plants demonstrate variable tolerance to salt depending on the growing stage, but are generally more sensitive during germination [132].

6 Final Considerations

Land degradation, a deleterious form of disturbance driven by human-induced processes and affected by climate conditions, is a major concern worldwide. It is a particular concern in agricultural areas due to its impacts in decreasing soil fertility and productivity, threatening global food security. Land degradation affects a great area of agricultural land globally, including large areas in Portugal and Greece. In these countries, agricultural land is exposed to individual degradation processes or a combination of these. Intensive management practices and rather limited vegetation cover result in high erosion rates in both countries, although with slightly higher values recorded in Greece due to more extensive hilly terrain, higher erodibility of the soil resulting from bedrock properties and larger areas with overgrazing. Intensive grazing and mechanisation of agriculture (e.g. tillage) cause significant levels of soil compaction, aggravated by inappropriate irrigation practices (e.g. furrow irrigation), not only at the soil surface but also in the subsoil. Although the real status of the problem in Greece and Portugal is largely unknown, the natural susceptibility of the soil to compaction is considerably greater in Greece than in Portugal. However, highly and very highly susceptible areas should receive particular management attention in both countries. Intensive agricultural practices are often associated with overuse of agrochemicals, with concentrations of heavy metals (e.g. Zn, Cr and Pb) and pesticide residues in the Portuguese and Greek soils being considerably higher than average values across Europe. Although there are relatively few studies of soil contamination, some research performed in Portugal and Greece has highlighted the impact of unsuitable agricultural management practices on degradation of water resources, including groundwater and surface waters. Overuse of mineral fertilisers has also led to increasing problems with salinity and sodicity in agricultural soils, particularly in coastal areas, due to excessive groundwater abstraction. This problem is more pronounced in Greece than in Portugal due to the longer coastline in Greece. Other land degradation processes, such as loss of soil organic matter and biodiversity, are also concerns in southern European countries and should be considered when addressing agricultural land degradation in Portugal and Greece. However, these processes were outside the scope of the present review.

The degradation processes affecting agricultural land also result in several on-site and off-site problems, threatening the productivity of cropping systems and impairing the quality of the environment, with relevant consequences for society and the economy. Increasing recognition of these problems has generated awareness of the need for improved agricultural land management practices to assure the sustainability of agriculture and ensure land degradation neutrality by 2030. Some soil conservation practices have been implemented in Portugal and Greece (e.g. no-tillage, cover crops), but on a rather limited proportion of total arable land. Approaches to improve soil and crop management are required to prevent and/or mitigate soil degradation and enable water saving in agricultural fields. Building dialogue between scientists, policy-makers, decision-makers and farmers is of utmost importance to ensure effective adaptation and implementation of management practices to resolve agricultural land degradation and achieve food security.

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