Assessing desertification sensitivity map under climate change and agricultural practices scenarios: the island of Crete case study
G. Morianou, N. N. Kourgialas, V. Pisinaras, G. Psarras and G. Arambatzis

ABSTRACT

The aim of this study is the assessment of desertification risk for a typical Mediterranean island, in the frame of climate change and the application of good agricultural practices. Based on the MEDALUS Environmentally Sensitive Area Index (ESAI) approach, the sensitivity in desertification is estimated by employing 15 quantitative parameters divided into four main quality indices: climate, vegetation, soil, and management quality. The methodology applied for a baseline scenario (current conditions), two future climate change scenarios (RCP 4.5 and RCP 8.5) and a soil quality improvement scenario. According to the results, more than 13% of the island’s area is characterized as critically sensitive to desertification in the current conditions. This percentage will increase in the future under both the RCP 4.5 and the RCP 8.5 climate scenarios, where the critical areas will rise above to 15%. By applying the soil quality improvement scenario simultaneously with the climate change scenarios, a slight mitigation of desertification risk in the future could be achieved. The methodology developed in this study may be used to assess desertification process under various climate, soil, and land use management scenarios in regions of the Mediterranean Sea.

Key words | agricultural practices, climate change, Crete, desertification, ESAI, GIS

HIGHLIGHTS

- This study investigates, using GIS, the effects of all the above approaches on the sensitivity of desertification risk for the Mediterranean island of Crete (Greece) for the period 2031–2060. This study also highlights the results of the comparison of the future desertification scenarios under the application of GAPs and the maintenance of the traditional-conventional agricultural practices.
INTRODUCTION

Land degradation is the ‘reduction or loss in the biological or economic productive capacity of the land caused by human activities and often magnified by the impacts of climate change’ (UNCCD 1994). Desertification is a type of land degradation that occurs mainly in arid, semi-arid, and dry sub-humid environments, where water is the main limiting factor of land use performance in ecosystems. Environmental systems are generally in a state of dynamic equilibrium, thus a small change in climate or at the land use intensity can affect the desertification risk of an area (Kosmas et al. 1999; Baartman et al. 2007).

In the Mediterranean region, the desertification risk in combination with the expected climate changes pose a significant threat. Several research studies, support that large areas of the Mediterranean region have been recognized as vulnerable to desertification (Drake & Vafeidis 2004; Kepner et al. 2006; Sommer et al. 2011; Kourgialas et al. 2016a; Symeonakis et al. 2016; Morianou et al. 2018). In the Mediterranean region, desertification is mainly an outcome of the climatic conditions and the intensity of human activity on land (Conacher & Sala 1998; Geist & Lambin 2004; Reynolds et al. 2007). The Eastern Mediterranean area is particularly considered as one of the main ‘hot spots for climate change’ at a global scale, meaning that climatic factors in this region are especially susceptible to climate change, a fact that may increase the desertification risk (Türkeş 1999; Kourgialas 2021). In line with this, the establishment of simple modeling tools for assessing the spatiotemporal variability of such risks is very important (Eris et al. 2020). Overgrazing and deforestation are two of the main causes of land degradation. In arid regions, vegetation cover is particularly necessary to prevent soil erosion and nutrient loss. In addition, improper agricultural practices such as the long-term conservation tillage may also lead to land that is more vulnerable to desertification. Recent studies have suggested that global climate change will have a significant impact on both local and extended scale territories (Mickley et al. 2004; Weaver et al. 2009; Kourgialas et al. 2016b). The results of many climate model simulations, under various CO2 emission scenarios, also showed that temperatures in the Mediterranean are projected to rise significantly, while precipitation is projected to decrease. These trends could significantly affect the risk of desertification at specific areas in the Mediterranean region (Giorgi & Bi 2005; Giorgi & Lionello 2008; Zanis et al. 2009). Furthermore, organic matter and erosion by water are two important factors in terms of soil quality and desertification risk. Organic matter affects both the chemical and physical properties of the soil (soil structure, moisture, and nutrient holding capacity and activity of soil...
organisms) (Montanaro et al. 2012). On the other hand, soil erosion, especially in arid and semi-arid lands, contributes to soil degradation, which in turn affects the sustainable agricultural land use and productivity (Lal 2003).

Over the past decades, various models and methodologies have been proposed to assess the desertification sensitivity of an area (Oldeman & GWJ 1997; Babaev & Kharin 1999; Kosmas et al. 1999; Brandt et al. 2003; DESERTLINKS 2004). The most commonly used methodology in the Mediterranean region is an indicator-based approach proposed by Kosmas et al. (1999), the Environmental Sensitivity Area Index (ESAI) methodology. The Environmental Sensitivity Area (ESA) is a simple and flexible model that uses a wide variety of indicators. In this system, four main factors of climate, soil, vegetation, and land management are produced and combined in a synthetic way to make the so-called ESAI (Kosmas et al. 1999; Basso et al. 2000). ESA methodology has been applied to quite a few case studies in Mediterranean region: Italy (Basso et al. 2000; SORRISO-VALVO 2005; Salvati & Zitti 2009; Ladisa et al. 2012; Salvati et al. 2013), Spain (Contador et al. 2009), Iran (Sepehr et al. 2007), Egypt (Bakr et al. 2012), and Algeria (Boudjemline & Semar 2018). In Greece, the methodology has been applied in Lesvos island by Kosmas et al. (1999) and Symeonakis et al. (2016) and in Crete by Morianou et al. (2018). The majority of the aforementioned studies assess the desertification risk in a one-time-step static system. Symeonakis et al. (2016) noted that the land degradation process is dynamic due to the time dimension and the indicators should, therefore, derive from a sequence of temporal steps. To fill in this gap, they developed a continuous monitoring system of environmental sensitivity to desertification of the island of Lesvos (Greece) and they examined two different time periods, one during 1990 and one during 2000. However, up to now, no studies have assessed the risk of desertification under future climate change scenarios.

This study tries to fill this gap by incorporating the desertification risk assessment methodology for the RCP 4.5 and RCP 8.5 climate change scenarios. More specifically, the main purpose of this work was to assess the environmentally sensitive areas to desertification of a typical Mediterranean island (Crete) under two future climate change scenarios and under the application of good agricultural practices (GAPs). Many studies have shown that soil quality improvement can be achieved by applying GAPs (Hernández et al. 2005; Moreno et al. 2009; Koubouris et al. 2017; Kavvadias et al. 2018; Michalopoulos et al. 2020). For instance, cover crops and the maintenance of weeds during winter contribute as good practices to protection of land from erosion and increase soil water infiltration and carbon storage (Xiloyannis et al. 2008). In addition, the application of organic matter from composted byproducts and tree pruning residues can increase organic carbon in the soil in the long-term (Montanaro et al. 2010, 2012). Thus, for the first time, this study investigates, using GIS, the effects of all the above approaches on the sensitivity of the desertification risk for the Mediterranean island of Crete (Greece) for the period 2051–2060. This study also compares future desertification scenarios under GAPs and the maintenance of the traditional-conventional agricultural practices.

MATERIALS AND METHODS

Case study

Crete, the study area, is an island in the Mediterranean Sea and is the largest island in Greece (55:20:27 N, 25:07:46 E). Crete is an island of the Mediterranean Sea with a total area of about 8,265 km². The western part of Crete includes the Chania and Rethymnon prefectures, while the eastern includes the prefectures of Heraklion and Lassithi. The elevations in Crete range from 0 m to 2,400 m mean sea level. In Crete, lowlands (<200 m) cover an area of 2,165 km², 26% of the total area, semi-mountainous areas (200–800 m) cover an area of 4,627 km² which is 56% of the total area, while the mountainous area (>800 m) is approximately equal to 1,473 km² which is 18% of the total area.

The climate of Crete is sub-humid Mediterranean with humid and relatively cold winters, and dry and warm summers. The annual rainfall ranges from 300 to 700 mm/year in the lowlands, from 700 to 1,000 mm/year in the semi-mountainous areas, while in the mountainous areas it reaches 2,000 mm/year. Significant rainfall differences are recorded between the western and eastern areas of the island during the wet seasons (Kourgialas et al. 2018).
According to Panagos et al. (2014), soils in Crete are generally characterized as poorly developed and shallow. The biggest part of the island consists of fine soils (clay, sandy-clay, clay-loam, silty-clay & silty-clay-loam) and medium soils (sandy-clay-loam, loam, silt-loam & silt). Coarse soils (sand, loamy-sand & sandy-loam) occur mainly in the western part of the island.

According to the CORINE Land Cover maps (2012), Crete is mostly covered by natural grasslands and pastures. Evergreen forests, coniferous forests, and Mediterranean maquis cover less than 5% of the island. The agricultural areas of the island cover about 3,205 km². These areas are mainly dominated by tree crops (olive, citrus, avocado), vineyards, and greenhouse vegetation cultivations. Tree crops cover about 72% of the total agricultural area in Crete (OPEKEPE 2017). Olive, avocado, and citrus trees thrive at the western part of the island due to the local climate conditions. On the other hand, the agricultural areas at the eastern part of the island are characterized by drier climate conditions and the dominant cultivations are olive trees and vineyards.

ESAI methodology

The areas environmentally sensitive to desertification can be assessed in relation to various parameters such as landscape, soil, geology, erosion, vegetation, climate, and human action (Kosmas et al. 1999). Each of these parameters is reclassified according to its behavior on desertification and weighting factors are assigned in each class.

In this study, the modified ESAI methodology proposed by Morianou et al. (2018) is used. This modification of the MEDALUS approach includes two additional parameters related to soil quality (water erosion and soil organic matter) compared to the original one. Fifteen layers belonging to four main sensitivity groups (climate, soil, vegetation management, and land management) were collected from various sources and their values were standardized between 1 (low sensitivity) and 2 (high sensitivity) (Tables 1–4). The four sensitivity groups were estimated using the following formula (Equation (1)):

$$\text{Sensitivity}_x = (\text{layer}_1 \times \text{layer}_2 \times \text{layer}_3 \times \ldots \times \text{layer}_n)^{1/n}$$

where: sensitivity$_x$, represents the computed value of each sensitivity and n represents the number of sub-indicators (layers) used to calculate each Sensitivity Index (SI).

Also, in this study, climate change scenarios (RCP 4.5 and RCP 8.5) as well as GAP scenarios were incorporated into climate and soil main sensitivity groups to investigate their effects on the final desertification sensitivity map. A flow chart of the proposed methodology is presented in Figure 1. In the following sections, analytical information for each involved sensitivity group index/parameter is given.

Climate sensitivity

In this study, the Climate Sensitivity Index was calculated from three climate indicators: rainfall, evapotranspiration, and aspect. Rainfall amount and its spatial distribution as well as the hydrological extreme events in the semi-arid and arid zones of the Mediterranean are the main climatic

| Table 1 | Main indicators adopted classification scheme- scores and methods used in the GIS to estimate the Climate Sensitivity Index |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **Parameter** | **Classes** | **Index** | **Data/source** |
|----------------|---------------|------------|-----------------|
| Climate sensitivity | Rainfall (mm) | >650 | 1 | Data from meteorological stations of the island |
| | | 280–650 | 1.5 | |
| | | <280 | 2 | |
| Aridity = Precipitation/PET | >0.65 | 1 | PET: FAO-56 Penman–Monteith equation (Allen et al. (1998)), mean monthly min and max temperature from the meteorological stations of the island |
| | 0.5–0.65 | 1.5 | |
| | <0.5 | 2 | |
| Aspect | N, NE, NW | 1 | 25 m – pixel DEM EU-DEM v1.1 |
| | S, SE, SW | 2 | |
attributes that contribute to the degradation of land (Kosmas et al. 1999). Annual precipitation was classified in three classes considering that annual precipitation of 280 mm is a critical threshold for plant growth (Sepehr et al. 2010). The aridity index was also used in this study. According to Allen et al. (2005), the aridity index is the ratio of the annual precipitation divided by the annual potential evapotranspiration (P/PET). Precipitation and evapotranspiration data were collected from 56 meteorological stations distributed all over the island providing sufficient coverage. Figure 2 depicts the spatial distribution of these stations. Monthly data has been collected during the last 40 years, provided by the Department of Water Resources Management of the Region of Crete, the National Observatory of Athens and the Hellenic Agricultural Organization – National Agricultural Research Foundation. Data gaps were filled using values from the nearby stations, while a data quality check was applied to ensure the homogeneity of the time-series data. Aspect was calculated from a Digital Elevation Model (EU-DEM v1.1) at 25 m resolution scale. The input data that were used in the climate sensitivity group index are presented in Table 1.

**Vegetation sensitivity**

Vegetation cover is a very crucial factor affecting desertification and land degradation. The key indicators of desertification related to the existing natural or agricultural vegetation can be considered in relation to: (i) fire risk and ability to recover, (ii) erosion protection offered to the soil, (iii) drought resistance, and (iv) percentage plant cover. The vegetation sensitivity map was produced using the vegetation cover data according to the CORINE Land Cover (CLC) 2012 (CLC 2012). The input data that were used in the vegetation sensitivity group index are presented in Table 2.

### Table 2: Main indicators adopted classification scheme - scores and methods used in the GIS to estimate the Vegetation Sensitivity Index

| Parameter | Classes                                                                 | Index | Data/source |
|-----------|-------------------------------------------------------------------------|-------|-------------|
| Vegetation sensitivity | Drought resistance | Evergreen forests (except coniferous), mixed Mediterranean maquis-evergreen forests | 1 | Corine Land Cover (CLC) for the year (2012), source: http://www.data.gov.gr/dataset/xartes-kalypshs-ghs-corine-land-cover-gia-ta-eth-2006-and-2012 |
|          |                                                                          | Conifer forests, deciduous forests, and olives | 1.2 |
|          |                                                                          | Almonds, orchards, and vines | 1.4 |
|          |                                                                          | Perennial grasslands, pastures, and shrubland | 1.7 |
|          |                                                                          | Annual crops (annual grassland, cereals, maize, and sunflower), horticulture, and very low vegetated | 2 |
| Erosion protection | Evergreen forest (except conifers), mixed Mediterranean maquis-evergreen forest | 1 |
|          | Mediterranean maquis, conifer forests, perennial grasslands, pastures, olives, and shrubs | 1.3 |
|          | Deciduous forests (oak and mixed) | 1.6 |
|          | Almonds and orchards | 1.8 |
|          | Vines, horticulture, annual crops, very low vegetated, and bare soils | 2 |
| Fire risk | Almonds, orchards, vines, olives, irrigated annual crops, and horticulture | 1 |
|          | Perennial grasslands, pastures, cereals, annual grasslands, deciduous forests (oak and mixed), mixed Mediterranean maquis evergreen forests, very low vegetated, and shrublands | 1.3 |
|          | Mediterranean maquis | 1.6 |
|          | Pines and other conifer forests | 2 |
| Plant cover (%) | >40 | 1 |
|          | 10–40 | 1.8 |
|          | <10  | 2 |
### Table 3 | Main indicators adopted classification scheme – scores and methods used in the GIS to estimate the Soil Sensitivity Index

| Parameter                  | Classes                                                                 | Index | Data/source                                                                 |
|----------------------------|-------------------------------------------------------------------------|-------|-----------------------------------------------------------------------------|
| Soil sensitivity           | Parent material                                                        |       |                                                                             |
|                            | Shale, schist, basic, ultra-basic, conglomerates, unconsolidated, clays, and marl (with natural vegetation) | 1     | Geological maps were bought from the Institute of Geology & Mineral Exploration |
|                            | Limestone, marble, granite, rhyolite, ignimbrite, gneiss, siltstone, sandstone, and Dolomite | 1.7   |                                                                             |
|                            | Marl and pyroclastics                                                  | 2     |                                                                             |
| Texture                    | LSCL, SL, LS, and CL                                                   | 1     | The map produced by the Institute of Geology and Mineral Exploration was downloaded from the European Soil Data Centre (ESDAC) [http://esdac.jrc.ec.europa.eu/content/soilmap-greece-edafologikos-xartis-ellados](http://esdac.jrc.ec.europa.eu/content/soilmap-greece-edafologikos-xartis-ellados) |
|                            | SC, SIl, and SiCL                                                        | 1.2   |                                                                             |
|                            | S                                                                        | 1.6   |                                                                             |
|                            |                                                                          | 2     |                                                                             |
| Soil depth (cm)            | >75                                                                     | 1     |                                                                             |
|                            | 30–75                                                                   | 1.3   |                                                                             |
|                            | 15–30                                                                   | 1.6   |                                                                             |
|                            | <15                                                                     | 2     |                                                                             |
| Soil organic matter (%)    | <0.5                                                                    | 2     | The map downloaded from [https://esdac.jrc.europa.eu/content/octop-topsoil-organic-carbon-content-europe](https://esdac.jrc.europa.eu/content/octop-topsoil-organic-carbon-content-europe) |
|                            | 0.5–1                                                                  | 1.7   |                                                                             |
|                            | 1–2                                                                     | 1.5   |                                                                             |
|                            | 2–3                                                                     | 1.2   |                                                                             |
|                            | >3                                                                      | 1     |                                                                             |
| Water erosion (tn/ha/yr)   | <1                                                                      | 1     | A map was produced by [Panagos et al. 2012](https://esdac.jrc.europa.eu/content/g2-soil-erosion-model-data-crete-greece-and-strymonas-greecebulgaria-ishmi-erzeni-albania) |
|                            | 1–5                                                                     | 1.3   |                                                                             |
|                            | >2                                                                      | 1.7   |                                                                             |
|                            |                                                                          | 2     |                                                                             |
| Slope gradient             | <6                                                                      | 1     | 20X20 m – pixel DEM Hellenic Military Geographical Service                   |
|                            | 6–18                                                                    | 1.2   |                                                                             |
|                            | 18–35                                                                   | 1.5   |                                                                             |
|                            | >35                                                                     | 2     |                                                                             |

### Table 4 | Main indicators adopted classification scheme – scores and methods used in the GIS to estimate the Management Sensitivity Index

| Parameter                  | Classes                                                                 | Index | Data/source                                                                 |
|----------------------------|-------------------------------------------------------------------------|-------|-----------------------------------------------------------------------------|
| Management sensitivity     | Intensity of land use                                                  | 1     | CORINE Land Cover (CLC) 2012                                               |
|                            | Woodlands, semi-natural areas, and natural grasslands                  | 1.5   |                                                                             |
|                            | Irrigated and non-irrigated vineyards, irrigated and non-irrigated fruit trees, irrigated and non-irrigated olive groves, annual crops associated with permanent crops, complex cultivation patterns, land principally occupied by agriculture with significant areas of natural vegetation, non-irrigated arable land | 2     |                                                                             |
|                            | Open field herbaceous with spring–summer cycle, horticultures with spring–summer cycle, horticultures with spring–summer–autumn cycle, greenhouses | 2     |                                                                             |
| Protection policies        | Reserves, parks, and archaeological areas                              | 1     | Sites of Community Importance (SCI) and Special Protected Areas (SPA) according to the EU Directive 92/43. Source: [http://www.ypeka.gr/?tabid=504](http://www.ypeka.gr/?tabid=504) |
|                            | Woodlands, semi-natural, and coastal areas Areas not subject to restrictions | 1.5   |                                                                             |
|                            |                                                                          | 2     |                                                                             |
Soil sensitivity

The soil sensitivity map was produced using the following soil data: texture, slope, parent material, soil depth, organic, and soil erosion caused by water. For the purpose of this study, soil data was derived from the European Soil Database (ESDAC). Soil erosion caused by water were derived from the study of seasonal and annual erosion assessments in Mediterranean agricultural areas using the G2 model (Panagos et al. 2017). The input data that were used in the soil sensitivity group index are presented in Table 3.

Management sensitivity

The definition of ESAs to desertification requires key indicators related to the physical environment and to the human-induced stress. The intensity of land use factor was produced according to the CORINE Land Cover 2012 (CLC 2012) and the protection policies factor that was produced using data from EU Directive 92/43 (NATURA 2000). The combination of these two parameters gives the final Management Sensitivity map. The input data that were used in the management sensitivity group index are presented in Table 4.

Climate change scenarios

Regarding the two studied climate change scenarios, RCP 8.5 scenario is characterized by increasing greenhouse gas emissions over time. The underlying scenario drivers and resulting development path are based on the A2 scenario detailed in Moss et al. (2008). This can be considered as a
non-mitigation business-as-usual scenario with high emissions. The RCP 8.5 (Moss et al. 2008) is developed by the MESSAGE modelling team and the Integrated Assessment Framework at the International Institute for Applied Systems Analysis, Austria. On the other hand, RCP 4.5 scenario is similar to the lowest-emission scenarios (B1) assessed in the Intergovernmental Panel on Climate Change AR4. It is a stabilization scenario where total radiative forcing is stabilized by around 2050 by using a range of technologies and strategies for reducing greenhouse gas emissions. This can be considered as a weak climate change mitigation scenario. The RCP 4.5 (Clarke et al. 2007; Moss et al. 2010) is developed by the MiniCAM modelling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute.

A lot of effort has been given by the scientific community in the last decades to produce high-resolution data from Regional Climate Models (RCMs) that are widely used to support climate change impact assessment studies. Nevertheless, and in the context of small-scale studies, these data are usually further processed with bias-correction methodologies to reduce the incorporated biases. This procedure requires adequate time-series of observed data. Due to data availability restrictions, RCM data that represents the climate conditions of the study had to be chosen. According to LIFE ADAPT2-CLIMA (2017), such data for Crete comes from the RCA4 RCM developed by the Swedish Meteorological and Hydrological Institute (Strandberg et al. 2015), driven by the Global Circulation Model named Hadley Centre Global Environmental Model, version 2 Earth System (Martin et al. 2010; Collins et al. 2013), which was developed by the Met Office Hadley Centre, hereafter referred as RCA4_MOHC.
Spatial downscaling can improve the resolution of climate data from RCMs and therefore produce a better representation of the climate conditions. RCA4_MOHC data (precipitation, and minimum and maximum air temperature) were downscaled from 0.11° to 100 m using a bilinear approach that was suggested and implemented in previous studies (Marke et al. 2011; Herrmann et al. 2016). Minimum and maximum air temperature data from RCA4_MOHC was used to calculate reference evapotranspiration (ETo) using the Hargreaves method (Hargreaves & Samani 1985). This method has been proposed by Allen et al. (1998) to be implemented as an alternative to Penman–Monteith when temperature data is the only input available. The period used in the context of the present study is 2031–2060, which is considered as representative of the near- to medium-distant future.

Agricultural practices scenarios

In terms of the desertification risk assessment, the factors that could be affected by the applied GAPs are related to soil sensitivity (soil organic matter and soil erosion). More specifically, a set of GAPs for improving soil conservation in tree crops areas includes: (i) application of organic matter by composted olive mill byproducts and olive tree pruning residue and (ii) reduction of water erosion using cover crops and/or introducing natural barriers in sloppy tree crops areas, also for this purpose, no tillage is strongly recommended. The above practices, as part of LIFE AgroClimaWater project, were applied in two pilot river basins in Crete, one in the western side and one at the eastern side of the island during the period 2017–2019. It is important to mention that for each of the two studied river basins, 20 experimental sites/tree crop parcels were selected to apply the GAPs. These experimental sites were selected based on different criteria (geomorphology, soil characteristics, climate data, water availability, management regime of the parcels, as well as the already applied agricultural practices) to capture a wide range of alternative agricultural ecosystems on Crete, including climatic, soil, and cropping systems heterogeneity. The results of the above applied GAPs, as well as the results from other related studies and research projects in Crete (Kavvadias et al. 2018; Kavvadias & Koubouris 2009), indicate that organic matter in agricultural areas of the island can be increased up to 14% until 2060 by the application of organic matter by composted olive mill byproducts, tree pruning, and weed mowing residue application. In addition, the findings of the above studies/projects indicate that by establishing means of physical reduction of surface runoff along the contour lines in orchards located in sloppy areas (slope >10%), the water erosion could be reduced up to 40%. For simulating the effects of the above GAPs, in the proposed methodology, the tree crops areas in Crete were isolated with a mask in GIS environment and the percentage of organic matter was increased by 14% (the baseline soil organic matter content was obtained from ESDAC database). In the same way, water erosion, in the agricultural areas with a slope of more than 10%, was reduced by 40%. The new map indicators of erosion and organic matter were then evaluated according to the ESA methodology and combined with the other soil factors to provide a new soil sensitivity map that incorporates GAPs implementation in tree crops areas of Crete.

Final desertification sensitivity map

After the combination of the environmental and land use parameters into the four sensitivity groups maps (climate, soil, vegetation management, and land management), the quantitative results of each factor are classified into three qualitative classes (low, moderate, and high quality) according to the scheme suggested by Sepehr et al. 2007 (Table 5).

Analytically, in the last ESAI stage, the final sensitivity to desertification of an area is evaluated from the

| Sensitivity index       | Range       | Sensitivity class |
|-------------------------|-------------|-------------------|
| Climate Sensitivity Index| 1           | Low               |
|                         | 1.1–1.5     | Moderate          |
|                         | 1.5–2       | High              |
| Vegetation Sensitivity Index| <1.13     | Low               |
|                         | 1.13–1.38   | Moderate          |
|                         | >1.38       | High              |
| Soil Sensitivity Index  | <1.13       | Low               |
|                         | 1.13–1.45   | Moderate          |
|                         | >1.45       | High              |
| Management Sensitivity Index| 1–1.3      | Low               |
|                         | 1.3–1.5     | Moderate          |
|                         | >1.5        | High              |
combination of the above mentioned four sensitivity maps in Equation (2) in a linear way:

\[
\text{ESAI} = (\text{Sensitivity}_1 \times \text{Sensitivity}_2 \times \text{Sensitivity}_3 \times \ldots \text{Sensitivity}_n)^{1/n}
\]  

(2)

The ESAI assigns equal weights to layer \( n \), within each SI, as well as equal weights to each SI when computing the overall environmental sensitivity (ESAI). This way, the computations in Equation (2) are unaffected by the number of layers used in every SI, which means that a SI is not considered of less importance because less layers are used for its computations (Basso et al. 2000).

According to Kosmas et al. (1999), four general types of Environmentally Sensitive Areas (ESAs) to desertification can be distinguished based on the stage of land degradation.

Not Affected: Areas not affected by desertification are usually areas with deep to very deep, well-drained, coarse-textured or finer soils, under semi-arid or wetter climatic conditions, independent of vegetation.

Potential ESAs: Areas with nearly flat to gently sloping (slope <12%), moderately fine-textured, deep and mainly well-drained. The climate is mainly characterized as dry sub-humid with rainfall greater than 650 mm. The dominant vegetation of these areas is usually olives and pines and, in some cases, evergreen oaks or annuals, with usually low fire risk (olives) or high fire risk (pines), high to moderate erosion protection, and mainly high resistance to drought. These areas are mainly under moderate land use intensity.

Fragile ESAs: Areas in which any change in the delicate balance of natural and human activity is likely to bring about desertification. For example, the impact of predicted climate change is likely to enhance reduction in the biological potential due to drought, causing areas to lose their vegetation cover and are subject to greater erosion.

Critical ESAs: Areas already highly degraded through past misuse, presenting a threat to the environment of the surrounding areas. For example, badly eroded areas subject to high runoff and sediment loss.

RESULTS AND DISCUSSION

The results/maps for the four sensitivity groups are shown in Figures 3–6. In terms of climate sensitivity (Figure 3), the majority of the island was mapped as having low to moderate climatic sensitivity, except for a part of the eastern island that was mapped as having high sensitivity under the current conditions (Figure 3(a)). This could be attributed to the fact that eastern areas (south Heraklion and Lasithi prefecture) receive less precipitation than the western part of the island (Koutroulis et al. 2011). Comparing the climate maps of the current situation (Figure 3(a)) with the two climate scenarios, RCP 4.5 (Figure 3(b)) and RCP 8.5 (Figure 3(c)), a significant part of the island seems to become more sensitive to desertification in terms of climate. It can also be noted that under the climate scenario RCP 4.5, there is higher sensitivity than under the scenario RCP 8.5. This is due to the fact that the climate model used gives less rain under the scenario RCP 4.5 compared to RCP 8.5 for the period 2031–2060. Since RCP 8.5 is a no-mitigation scenario, while RCP 4.5 is an average mitigation scenario, it is considered that, in general, the amount of rainfall for the Mediterranean region under the RCP 8.5 scenario is higher compared to the RCP 4.5. Nevertheless, this corresponds to an average trend which can differentiate depending on the RCM used and the specific area under study.

The amount of precipitation also affects the aridity index (precipitation/evapotranspiration), which gives lower values under climate scenario RCP 4.5. Specifically, at the eastern part of the island, in contrast to the general depiction presented by the climate maps, there seems to be an improvement in terms of climate sensitivity under both future climate scenarios. This is because, in recent years, the region of eastern Crete has long periods of drought, and in both climatic scenarios this region shows an increase in precipitation amounts.

Regarding the Vegetation Sensitivity Index, the areas with low drought resistance (e.g. agricultural areas), high fire risk (e.g. pine forests), and low percentage of vegetation cover are identified as highly sensitive. As Figure 4 indicates, the largest part of the island is characterized by moderate vegetation sensitivity except for some areas of Heraklion prefecture, which are characterized by high vegetation sensitivity. This is due to the fact that Heraklion prefecture includes large urbanization areas in the north and areas with intensive agricultural activity across the prefecture. Considering also that vegetation cover is a crucial factor for soil erosion control in sloppy areas, a considerable part
Figure 3  (a) Climate sensitivity map of Crete (Greece) in the current conditions, (b) climate sensitivity map under the scenario RCP 4.5 and (c) climate sensitivity map under the scenario RCP 8.5.
Figure 4 | Vegetation sensitivity map of Crete (Greece).

Figure 5 | (a) Soil sensitivity map of Crete (Greece) in the current conditions and (b) soil sensitivity map of Crete after the application of GAPs for the next 40 years.
of the island’s natural lands are subject to very high erosion risk due to the animal breeding activities (overgrazing).

Figure 5(a) shows the resulting soil sensitivity map of Crete under current conditions. The areas with the most sensitive soils are found at the southwest part of the island, in the major part of Heraklion prefecture and in the eastern part of Lasithi prefecture. The rest of the island has moderate soil sensitivity. This is due to the presence of large areas with slopes greater than 18%, a high presence of soils with a depth of less than 30 cm, and an important presence of fine texture soils. The results of soil quality are also related to soil erosion from water and the poor soil organic content in agricultural areas.

Comparing the soil result maps, in the current condition (Figure 5(a)) and after the application of GAPs for 40 years (Figure 5(b)), a reduction of high sensitivity areas and an increase of the moderate sensitivity areas is observed. This is due to the increase of organic content in agricultural areas and the reduction of water erosion in areas with a slope of more than 10%. Therefore, it is observed that by the improvement of even two of the six soil sensitivity factors, a slight improvement in soil quality could be achieved.

In terms of the management policies dimension, Figure 6 shows that the north-western part of the island and the major part of Heraklion prefecture are considered very sensitive regarding land management. The two largest cities of Crete (Chania and Heraklion) are located here and therefore the human activity is more intense. The southern areas of Chania prefecture and the mountainous areas in the eastern part of the island are covered by pine or oak forests and are considered environmentally protected (low sensitivity). Large parts of these areas are also managed by environmental protection policies (e.g. NATURA 2000 areas and Important Bird Areas).

The environmental sensitivity to desertification of the Crete island according to the ESA approach in the current conditions (baseline scenario) is shown in Figure 7(a). According to these results and Table 6, the vast majority of the island is considered as fragile or critical for desertification. The most environmentally sensitive areas (critical areas) of Crete, in the current conditions, are found mainly in the southern and eastern parts of the island. More specifically, the results show that 29% of the island is fragile or critical to desertification (fragile: 16.24% and critical: 13.15%) (Figure 8). According to Morianou et al. (2018), these areas have badly degraded shallow soils, are poorly vegetated, and are very sensitive in terms of climate due to low rainfall and high air temperatures. The management policies are also quite poor in these areas. The Not Affected areas and the Potential ESAs are mainly located in the western and in the middle parts of the island (Figure 7(a)), in areas characterized by favorable climate (high annual rainfall) and efficient land management.

By applying the ESAI methodology under two climate change scenarios, this study indicates that, in the future, a greater extent of the island will be characterized as critical to desertification rather than fragile and potential. This
seems likely to occur under both the average mitigation scenario (RCP 4.5) and the no-mitigation scenario (RCP 8.5), where the critical areas will rise to 15.76% and 15.09%, respectively, versus 13.15% for the baseline scenario (Figure 8). Unlike the general trend, some regions of eastern Crete show an improvement in terms of the desertification risk. This happens due to the potential increase in precipitation in the future and therefore the local increase of climate quality.

Comparing the effects on desertification risk between the two future climate change scenarios (RCP 4.5 and RCP 8.5), it is observed that under the climate scenario RCP 4.5 more areas are characterized as critical (15.76% vs 15.09%) and less as non-affected and potential to desertification than under the scenario RCP 8.5 (3.97% vs 4.28% and 8.60% vs 9.05%, respectively) (Figure 8). This is because the estimated amount of precipitation is lower in scenario RCP 4.5 compared to RCP 8.5.

Finally, the results obtained by the incorporation of the soil improvement scenario with the climate change scenarios showed that with the application of GAPs, the risk of desertification is slightly reduced. More specifically, the critical to desertification areas are reduced and, correspondingly, the percentage of areas not affected by desertification has increased with the application of GAPs. The fragile areas remain at the

![Figure 7](image-url)
same percentages with or without application of GAPs (Figures 7(b2), 7(c2) and 8).

The results of this study indicate that in the frame of climate change the desertification risk in the Mediterranean island of Crete could be higher. It also shows that by applying GAPs in cultivated areas a slight mitigation of desertification risk can be achieved. This is because GAPs affect only two of the 15 factors of ESAI methodology. These findings should alert local authorities considering measures to prevent or mitigate desertification in terms of land management and protection policies. In addition, the produced ESAI maps could become a valuable tool for the local authorities to inform farmers and convince them on the measures to be taken for the mitigation of desertification in their area.

This study, using the ESAI methodology, aims to assess the desertification risk on Crete and includes, as a new approach, the RCP 4.5 and RCP 8.5 climate change scenarios as well as the effects of the applied GAPs in tree crops, which cover about 72% of the total agricultural area on the island. Although ESAI methodology has been widely used and numerous scientific studies have been published based on it, the main limitations are the coarse assessments and the uncertainty in evaluating the final desertification map. In our case, apart from the model’s inherent uncertainty, including the applied climate change scenarios, the uncertainty for some of the four main sensitivity groups/maps that are involved, such as soil and the scenario of how GAPs could affect it, can be significant. The uncertainty for the others (climate, vegetation management, and land management) is usually low, provided that the map information is accurate and up-to-date. Concerning the soil sensitivity group, there is uncertainty about soil organic matter stocks and trends because long-term soil monitoring networks, with a sufficient number of sampling sites across Europe, note contrasting soil organic matter trends and several assumptions on their relationship with soil type, geomorphology, land use, and climate (Panagos et al. 2013; Stolte et al. 2016). These sources of uncertainty could be reduced for small-scale field measurements, capturing as far as possible the heterogeneity of the studied system, as well as detailed climatological information. These approaches are included in the present study and contribute to overcoming the limitations of the proposed method.

CONCLUSIONS

The present study is an application of the MEDALUS – ESAI methodology in a typical Mediterranean island (Crete) for the assessment of the desertification risk under different climate and agricultural practices scenarios. As a step forward from the previous desertification study in Crete by Morianou et al. (2018), two future climate change scenarios were used to dynamically study the evolution of desertification sensitivity in the future. Going one step further, a scenario of soil quality improvement using GAPs is incorporated for the mitigation of the phenomenon.

In the current conditions (baseline scenario), a significant part of the island is characterized as fragile or critically sensitive to desertification. Human activities are
the main cause – the non-proper changes of land use, overgrazing and deforestation are only some of these activities. The eastern part of Crete is more sensitive to desertification than the western part mainly due to the drier climate conditions.

By applying the ESAI methodology for two climate change scenarios, this study shows that the desertification risk of the island warrants attention for the future. The sensitivity of the island will increase greatly due to the increasing temperature and decreasing precipitation. Therefore, in this study a soil quality improvement scenario was also applied in combination with the two future scenarios. The scenario was based on the results of GAPs applied in the frame of LIFE + AgroClimaWater, to reduce the desertification sensitive areas in Crete. The results of this scenario show a slight mitigation of desertification risk in the future. However, it seems that good agricultural practices, individually, are not enough to mitigate the risk of desertification in the context of climate change. Therefore, the problem of land degradation must be addressed comprehensively by the authorities by applying policies for the prevention and mitigation of desertification in the Mediterranean region.

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REFERENCES

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

Allen, R. G., Pereira, L. S., Raes, D. & Wright, J. L. 2005 FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. *Journal of Irrigation and Drainage Engineering* **131** (1), 2–13.

Baartman, J. E., van Lynden, G. W., Reed, M., Ritsema, C. & Hessel, R. 2007 Desertification and Land Degradation: Origins, Processes and Solutions. *DESIRE Report Series: Scientific Report*, Wageningen: DESIRE.

Babaev, A. & Kharin, N. (eds) 1999 The monitoring and forecast of desertification processes. In: *Desert Problems and Desertification in Central Asia*. Springer, Berlin, pp. 59–75.

Bakr, N., Weindorf, D. C., Bahmasy, M. H. & El-Badawi, M. M. 2012 Multi-temporal assessment of land sensitivity to desertification in a fragile agro-ecosystem: environmental indicators. *Ecological Indicators* **15** (1), 271–280.

Basso, F., Bove, E., Dumontet, S., Ferrara, A., Pisante, M., Quaranta, G. & Taberner, M. 2000 Evaluating environmental sensitivity at the basin scale through the use of geographic information systems and remotely sensed data: an example covering the Agri basin (Southern Italy). *Catena* **40** (1), 19–35.

Boudjemline, F. & Semar, A. 2018 Assessment and mapping of desertification sensitivity with MEDALUS model and GIS-Case study: basin of Hodna, Algeria. *Journal of Water and Land Development* **36** (1), 17–26.

Brandt, J., Geeson, N. & Imeson, A. 2005 A Desertification Indicator System for Mediterranean Europe. DESERTLINKS Project. Available from: www.kcl.ac.uk/desertlinks.

Clarke, L., Lurz, J., Wise, M., Edmonds, J., Kim, S., Smith, S. & Pitcher, H. 2007 Model Documentation for the Minicam Climate Change Science Program Stabilization Scenarios: Ccsp Product 2.1. Pacific Northwest National Laboratory, PNNL-16735.

CLC 2012 CORINE Land Cover. Available from: https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T. & Krinner, G. 2013 Long-term climate change: projections, commitments and irreversibility. In: *Climate Change 2013: The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp. 1029–1136.

Conacher, A. J. & Sala, M. 1998 *Land Degradation in Mediterranean Environments of the World: Nature and Extent, Causes and Solutions*. John Wiley and Sons Ltd, Chichester.

Costa, J. L., Schnabel, S., Gutierrez, A. G. & Fernandez, M. P. 2009 Mapping sensitivity to land degradation in Extremadura, SW Spain. *Land Degradation & Development* **20** (2), 129–144.

DESERTLINKS 2004 *Desertification Indicator System for Mediterranean Europe*. Available from: http://www.desire-his.eu/en/assessment-with-indicators/related-sites/thematicmenu-277/204-desertifi.

Drake, N. & Vafeidis, A. 2004 A review of European Union funded research into the monitoring and mapping of Mediterranean

Downloaded from http://iwaponline.com/ws/article-pdf/21/6/2916/933438/ws021062916.pdf by guest
desertification. *Advances in Environmental Monitoring and Modelling* 1 (4), 1–51.

Eris, E., Cavus, Y., Aksoy, H., Burgan, H. I., Aksu, H. & Boyacioglu, H. 2020 Spatiotemporal analysis of meteorological drought over Kucuk Menderes River Basin in the Aegean Region of Turkey. *Theoretical and Applied Climatology* 123 (3), 1515–1530.

Geist, H. J. & Lambin, E. F. 2004 Dynamic causal patterns of desertification. *BioScience* 54 (9), 817–829.

Giorghi, F. & Bi, X. 2005 Regional changes in surface climate interannual variability for the 21st century from ensembles of global model simulations. *Geophysical Research Letters* 32 (13), L13701.

Giorghi, F. & Lionello, P. 2008 Climate change projections for the Mediterranean region. *Global and Planetary Change* 65 (2–3), 90–104.

Hargreaves, G. H. & Samani, Z. A. 1985 Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture* 1 (2), 96–99.

Hernández, A. J., Lacasta, C. & Pastor, J. 2005 Effects of different management practices on soil conservation and soil water in a rainfed olive orchard. *Agricultural Water Management* 77 (1–3), 232–248.

Herrmann, F., Kunkel, R., Ostermann, U., Vereecken, H. & Wendland, F. 2016 Projected impact of climate change on irrigation needs and groundwater resources in the metropolitan area of Hamburg (Germany). *Environmental Earth Sciences* 75 (14), 1104.

Kavvadias, V. & Kourbousis, G. 2009 Sustainable soil management practices in olive groves. In: *Soil Fertility Management for Sustainable Development* (D. G. Panpatte & Y. K. Jhala, eds). Springer Singapore, Singapore, pp. 167–188.

Kavvadias, V., Papadopoulou, M., Vavoulidou, E., Theocharopoulos, S., Repas, S., Kourbousis, G., Psarras, G. & Kokkinos, G. 2018 Effect of addition of organic materials and irrigation practices on soil quality in olive Groves. *Journal of Water and Climate Change* 9 (4), 775–785.

Kepner, W. G., Rubio, J. L., Mouat, D. A. & Pedrazzini, F. 2006 Desertification in the Mediterranean Region. In: *In A Security Issue: Proceedings of the NATO Mediterranean Dialogue Workshop, Held in Valencia*, 2–5 December 2003, Spain. Springer Science & Business Media.

Kosmas, C., Ferrara, A., Brasiosul, H. & Imeson, A. 1999 Methodology for mapping environmentally sensitive areas (ESAs) to desertification. In: *The Medalus Project Mediterranean Desertification and Land Use. Manual on Key Indicators of Desertification and Mapping Environmentally Sensitive Areas to Desertification* (K. Kosmas, M. Kirkby & N. Geeson, eds.). European Commission, pp. 31–47.

Koubouris, G., Kourgialas, N., Kavvadias, V., Digalaki, N. & Psarras, G. 2017 Sustainable agricultural practices for improving soil carbon and nitrogen content in relation to water availability—an adapted approach to Mediterranean olive groves. *Communications in Soil Science and Plant Analysis* 48 (22), 2687–2700.

Kourgialas, N. N. 2021 A critical review of water resources in Greece: the key role of agricultural adaptation to climate-water effects. *Science of The Total Environment* 775, 145857.

Kourgialas, N. N., Dokou, Z., Karatzas, G. P., Panagopoulos, G., Soupios, P., Vafidis, A., Manoutsoglou, E. & Schafmeister, M. 2016a Saltwater intrusion in an irrigated agricultural area: combining density-dependent modeling and geophysical methods. *Environmental Earth Science* 17 (1), 1–15,15.

Kourgialas, N. N., Koubouris, G. C., Karatzas, G. P. & Metzidakis, I. 2016b Assessing water erosion in Mediterranean tree crops using geoinformatic techniques and field measurements: the effect of climate change. *Natural Hazards* 83, 65–81. doi: 10.1007/s11069-016-2354-5.

Kourgialas, N. N., Anyfanti, I., Karatzas, G. P. & Dokou, Z. 2018 An integrated method for assessing drought prone areas – water efficiency practices for a climate resilient Mediterranean agriculture. *Science of the Total Environment* 625, 1290–1300.

Koutoulis, A. G., Vrohidou, A.-E. K. & Tsanis, I. K. 2011 Spatiotemporal characteristics of meteorological drought for the island of Crete. *Journal of Hydro meteorology* 12 (2), 206–226.

Ladisa, G., Todorovic, M. & Liuzzi, G. T. 2012 A GIS-based approach for desertification risk assessment in Apulia region, SE Italy. *Physics and Chemistry of the Earth, Parts A/B/C* 49, 103–113.

Lal, R. 2001 Soil degradation by erosion. *Land Degradation & Development* 12 (6), 519–539.

LIJE ADAPT2CLIMA 2017 Deliverable C3: Future Projections on Climatic Indices with Particular Relevance to Agriculture for the Three Islands (Coarse Resolution) and for Each Agricultural Pilot Area (Fine Resolution) Project ADAPT2CLIMA LIFE14 CCA/GR/000928. Available from: http://adapt2clima.eu/uploads/2017/ADAPT2CLIMA_DEL_C3_Final_3.pdf (accessed 1 April 2020).

Marke, T., Mauser, W., Pfeiffer, A. & Zängl, G. 2011 A pragmatic approach for the downscaling and bias correction of regional climate simulations: evaluation in hydrological modeling. *Geoscientific Model Development* 4 (3), 759.

Martin, G., Milton, S., Senior, C., Brooks, M., Ineson, S., Reichler, T. & Kim, J. 2010 Analysis and reduction of systematic errors through a seamless approach to modeling weather and climate. *Journal of Climate* 23 (22), 5933–5957.

Michalopoulos, G., Kasapi, K., Kourbousis, G., Psarras, G., Arampatzis, G., Hatzigiannakis, E., Kavvadias, V., Xiloyannis, C., Montanaro, G. & Malliaraki, S. 2020 Adaptation of Mediterranean olive groves to climate change through sustainable cultivation practices. *Climate* 8 (4), 54.

Mickley, L. J., Jacob, D. J., Field, B. & Rind, D. 2004 Effects of future climate change on regional air pollution episodes in the United States. *Geophysical Research Letters* 31 (24), L24103.

Montanaro, G., Celano, G., Dichio, B. & Xiloyannis, C. 2010 Effects of soil-protecting agricultural practices on soil organic
carbon and productivity in fruit tree orchards. *Land Degradation & Development* 21 (2), 132–138.

Montanaro, G., Dichio, B., Bati, C. B. & Xiloyannis, C. 2012 Soil management affects carbon dynamics and yield in a Mediterranean peach orchard. *Agriculture, Ecosystems & Environment* 161, 46–54.

Moreno, B., Garcia-Rodriguez, S., Cañizares, R., Castro, J. & Benítez, E. 2009 Rainfed olive farming in south-eastern Spain: long-term effect of soil management on biological indicators of soil quality. *Agriculture, Ecosystems & Environment* 131 (3–4), 333–339.

Morianou, G., Kourgialas, N., Psarras, G. & Koubouris, G. 2018 Mapping sensitivity to desertification in Crete (Greece), the risk for agricultural areas. *Journal of Water and Climate Change* 9 (4), 691–702.

Moss, R., Babiker, W., Brinkman, S., Calvo, E., Carter, T., Edmonds, J., Elgizouli, I., Emori, S., Erda, L. & Hibbard, K. 2008 Towards New Scenarios for the Analysis of Emissions: Change, Impacts and Response Strategies. IPCC Expert Meeting Report, 19 September, Noordwijkerhout, The Netherlands.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M. & Kram, T. 2010 The next generation of scenarios for climate change research and assessment. *Nature* 463 (7282), 747–756.

NATURA 2000 *Natura 2000 Data and Maps*. Available from: http://ec.europa.eu/environment/nature/natura2000/data/index_en.htm.

Oldeman L. & GWJ v. L. 1997 Assessment of the status of human-induced soil degradation in China. *Proceedings Workshop Wageningen-China* (P. W. J. Uithol & J. J. R. Groot, eds.), Wageningen, December 1997, Report 84 (8), 101–111.

OPEKEPE 2017 *Greek Payment Authority of Common Agricultural Policy (C.A.P.) Aid Schemes*. Available from: http://www.opekepe.gr/

Panagos, P., Metzburger, K., Alewell, C. & Montanarella, L. 2012 Soil erodibility estimation using LUCAS point survey data of Europe. *Environmental Modelling & Software* 30 (2012), 143–145.

Panagos, P., Hiederer, R., Van Liedekerke, M. & Bampa, F. 2013 Estimating soil organic carbon in Europe based on data collected through a European network. *Ecological Indicators* 24, 439–450.

Panagos, P., Christos, K., Cristiano, B. & Ioannis, G. 2014 Seasonal monitoring of soil erosion at regional scale: an application of the G2 model in Crete focusing on agricultural land uses. *International Journal of Applied Earth Observation and Geoinformation* 27, 147–155.

Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B., Mortimore, M., Batterbury, S. P., Downing, T. E., Dowlatabadi, H., Fernández, R. J. & Herrick, J. E. 2007 Global desertification: building a science for dryland development. *Science* 316 (5826), 847–851.

Salvati, L. & Zitti, M. 2009 Convergence or divergence in desertification risk? scale-based assessment and policy implications in a Mediterranean country. *Journal of Environmental Planning and Management* 52 (7), 957–971.

Salvati, L., Ferrara, C. & Corona, P. 2015 Indirect validation of the environmental sensitive area index using soil degradation indicators: a country-scale approach. *Ecological Indicators* 57, 360–365.

Sepehr, A., Hassanli, A., Elkhtesasi, M. & Jamali, J. 2007 Quantitative assessment of desertification in south of Iran using MEDALUS method. *Environmental Monitoring and Assessment* 134 (1–3), 243.

Sommer, S., Zucca, C., Grainger, A., Cherlet, M., Zougmore, R., Sokona, Y., Hill, J., Della Peruta, R., Roehrig, J. & Wang, G. 2011 Application of indicator systems for monitoring and assessment of desertification from national to global scales. *Land Degradation & Development* 22 (2), 184–197.

Sorriso-Valvo, M. 2005 To desertification: an application to the Calabrian territory (Italy). *Geomorphological Processes and Human Impacts in River Basins* 23, 299.

Stolte, J., Tesfai, M., Ogarden, L., Kwaerno, S., Keizer, J., Verheijen, F. & Hessel, R. 2016 Soil Threats in Europe: Status, Methods, Drivers and Effects on Ecosystem Services: Deliverable 2.1 RECARe Project. European Commission DG Joint Research Centre.

Strandberg, G., Bärring, L., Hansson, U., Jansson, C., Jones, C., Kjellström, E., Kupiainen, M., Nikulin, G., Samuelsson, P. & Ullerstig, A. 2015 CORDEX Scenarios for Europe From the Rossby Centre Regional Climate Model RCA4. 116 SMHI. SE-60176, Norrköping, Sweden.

Symeonakis, E., Karathanasis, N., Koukoulas, S. & Panagopoulos, G. 2016 Monitoring sensitivity to land degradation and desertification with the environmentally sensitive area index: the case of lesvos island. *Land Degradation & Development* 27 (6), 1562–1573.

Türkeş, M. 1999 Vulnerability of Turkey to desertification with respect to precipitation and aridity conditions. *Turkish Journal of Engineering and Environmental Sciences* 25 (5), 363–380.

UNCCD 1994 *United Nations Convention to Combat Desertification, Elaboration of an International Convention to Combat Desertification in Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa (U.N. Doc. A/AC.241/27, 33 I.L.M. 1328. United Nations, New York.

Vicente-Serrano, S. M., Beguería, S., López-Moreno, J. I., García-Vera, M. A. & Steppe, P. 2010 A complete daily precipitation database for northeast Spain: reconstruction, quality control, and homogeneity. *International Journal of Climatology* 30 (8), 1146–1163.

Weaver, C., Liang, X.-Z., Zhu, J., Adams, P., Amar, P., Avise, J., Caughhey, M., Chen, J., Cohen, R. & Cooter, E. 2009 A preliminary synthesis of modeled climate change impacts on US regional ozone concentrations. *Bulletin of the American Meteorological Society* 90 (12), 1843–1864.

Xiloyannis, C., Martínez Raya, A., Kosmas, C. & Favia, M. 2008 Semi-intensive olive orchards on slopes of good quality. *Agriculture, Ecosystems & Environment* 128 (3–4), 206–214.
land husbandry for future development. *Journal of Environmental Management* **89**(2), 110–119.
Zanis, P., Kapsomenakis, I., Philandras, C., Douvis, K., Nikolakis, D., Kanellopoulou, E., Zerefos, C. & Repapis, C. 2009

Analysis of an ensemble of present day and future regional climate simulations for Greece. *International Journal of Climatology: A Journal of the Royal Meteorological Society* **29**(11), 1614–1633.

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