# Human Impacts on Soils: Tipping Points and Knowledge Gaps

**Nikolaos P. Nikolaidis**

Department of Environmental Engineering, Technical University of Crete, 73100 Chania, Greece

Corresponding author, Tel.: +30 28210 37785; Fax: +30 28210 37846

E-mail address: nikolaos.nikolaidis@enveng.tuc.gr

**Abstract**

Soil ecosystem functions are derived from plant, animal and microorganism communities and the non-living environment interacting as a unit. Human activities have effected soil ecosystem functions and in many cases caused soil ecosystem collapse. This review provides a synthesis of current knowledge of human impacts on soil ecosystems, with a special focus on knowledge gaps regarding soil ecosystem shifts and tipping points, using the island of Crete, Greece as an example. Soil ecosystem shifts are abrupt changes that occur at "tipping points" and have long-lasting effects on the landscape and both the biotic and abiotic structure of the soil. These shifts can occur due to climate change, land use change, fertilization, or above-ground biodiversity decline. The environmental pressures in the agricultural land of Crete, place the island very close to tipping points, and make it an "ideal" area for soil ecosystem shifts. Reversing the trend of the shift while using the soil ecosystem services, means that we need to add significantly more organic matter to the soil compared to the amount added under set-aside conditions. Potential nutrient supply and demand calculations indicate that fertilizer demand in Crete can be satisfied by recycling of bio-residue and livestock excreta produced on the island. Soil fertility improves faster if, in addition to bio-fertilization, farmers use traditional agricultural practices such as crop rotations and legume row plantings within olive trees and orchards. A renewed soil fertility paradigm shift requires a "holistic" management of biotic-soil-water resources in order to provide sufficient and of appropriate type organic matter to the plant-microorganism system to maximize food production.

**Keywords:** Soil ecosystem shifts, ecosystem shift drivers, soil degradation, soil fertility restoration.

## 1. Introduction

Soil ecosystem functions (food and biomass production, biodiversity, carbon sequestration, filtering and transformation, raw material and landscape, and heritage) are derived from the dynamic actions of plant, animal and microorganism communities and the non-living environment interacting as a unit. Throughout history, humans have not integrated themselves in the soil ecosystem (i.e. interacting as a unit), but have depended on soil ecosystem services for sustenance. Human activities have affected soil ecosystem functions and in many cases caused soil ecosystem collapse. Anthropogenic forcing of the terrestrial environment has been significant for the past 5000 years resulting in land degradation (deforestation, erosion, soil fertility loss). Civilizations from Mesopotamia and Harappa (2200 BC) to Minoan-Mycenaean Greece (1200 BC) and Roman (300 AD) collapsed due to intense deforestation and ecological degradation which limited the ability of the land to overcome natural disturbances leading to extended periods of cultural stagnation and social, economic and political reorganization (Chew, 2002). Decline in soil ecosystem services brings material scarcity and significant changes in everyday life. Chew (2002) described these periods as "Dark Ages" and argued that 500 years are needed for soil biodiversity to be restored, ecosystem services to be resumed and humans to create culture again.

The story of recurrent ecological crisis throughout the ages around the globe has been recorded in historical manuscripts. Even though soil degradation is not new, it appears that there is a "historical amnesia" regarding the impacts of human practices on the land. Soil degradation spans political systems and examples of soil degradation crisis can be found from the 1930s "Dust Bowl" in the USA to the Loess Plateau in China and the "Virgin Land Project" in the USSR (1954). In all cases, significant areas of forest and grassland (sensitive and fragile ecosystems) were ploughed to cultivation and intensive agricultural practices caused soil degradation and fertility decline resulting in the "dust bowl" due to drought in the US, extensive erosion in China, and ecosystem collapse in the Aral Sea.

The situation today finds us in the midst of major climatic changes at the same time as significant stresses on ecosystem resources are exerted. Population increases have put pressure for food production that has caused fertilizer use to peak. On the other hand, climate change and energy demand (peak oil) have increased the demand for biofuel production, which has resulted in decreasing the cultivated area used for food production. Food production has increased by expansion to marginal lands causing intensified environmental impacts (soil carbon depletion, decline in biodiversity, loss of fertility, sealing, compaction, etc). Modern agricultural practices have been using a "turning oil to food" approach which is unsustainable (because it uses 10-57 times more energy to produce 1 unit of energy of a meat product and 7-10 units more energy for a plant product) and is leading to planetary ecological crisis.

The objective of this review is to provide a synthesis of current knowledge of human impacts on soil ecosystems with a special focus on knowledge gaps regarding soil ecosystem shifts and tipping points. The island of Crete, Greece, is examined in order to determine whether tipping points for soils can be detected and suggest viable alternatives to reverse soil ecosystem shift trends.

## 2. Soil ecosystem shifts and knowledge gaps

Soil ecosystem shifts are abrupt changes that have long-lasting effects on the landscape and both the biotic and abiotic structure of the soil. The point in time when the ecosystem shifts from one state to another is called "tipping point." Soil ecosystem shifts can occur due to climate change, land use change, fertilization and above-ground biodiversity decline (Nelson et. al., 2006). Fig. 1 presents the interrelationships between soil ecosystem shift drivers with soil functions and threats. A brief description of the environmental and anthropogenic pressures that can cause soil ecosystem shifts are presented in the supplementary information. The island of Crete, Greece was used as an example of a sensitive, semi-arid area where ecosystem shifts are more likely to occur.

Soil biodiversity is a key factor determining soil functions and the life-sustaining processes (Nikolaidis and Bidoglio, 2011). Even though significant progress has been made in understanding the interaction in the plant-soil-microorganism-fauna ecosystem in the past two decades (Bronick and Lal, 2005; Ehrenfeld et al. 2005; Gardenas et al., 2010), knowledge gaps remain to understanding the fundamental functioning of the system associated with ecosystem changes, soil thresholds, biota structural development traits and biota communication and interactions (Table 1).

Despite the existing knowledge gaps and the overwhelming complexity of the soil-water-plant-organism system, the fundamental question is whether we are in a position to predict the potential for ecosystem shift and forecast tipping points. The reality is that we do not have the tools to quantitatively address this question; however, we can use an indicator approach to examine potential tipping points in transitional areas like the Crete using the four drivers that can cause ecosystem shifts. There are visible impacts of variable intensity on all four factors regarding impeding soil ecosystem shift (Supplementary Information). In fact, the impacts of livestock grazing on soil ecosystem were shown to impede the nitrogen cycle by restricting mineralization and plant uptake and leaching of soluble low aromaticity organic matter (Stamati et al., 2011) suggesting a shift in soil functions. The analysis suggests that Crete is a candidate area for soil ecosystem shifts.

### 3. Future directions in reversing soil ecosystem shifts

The missing link in our cognitive understanding of soil ecosystems is that we fail to recognize it as an intelligent system that all of its components are acting as a unit and instead we consider it as part of an accounting exercise of the various elements of the periodic table. We fail to recognize plant and micro-organism intelligence in shaping their ecosystem. Above-ground vegetation provides organic litter/food to the micro-organisms below, determining in this way the taxa and structure of the microbial community. In turn, the below ground micro-organisms determine the availability and nutrition of the vegetation. Both participate in the development of soil structure and functions. Organic matter and its interrelationship to soil particle aggregation formation and turnover play a catalyzing role in soil functions. Current agricultural practices and agricultural production research is working in the opposite direction from the way soil ecosystems function. Industrial agricultural practices have interrupted the natural cycling of nutrients in the soils by depriving micro-organisms from the necessary plant input.

We need a shift in soil fertility paradigm that it is based on the "plant-microorganism-soil-organic matter" continuum. Soil is the digestive system of the plant and it cannot function without the micro-organisms (analogous to the human "Brain-Gut" relationship). The environmental pressures in the agricultural land of Crete are significant making the island an "ideal" area for soil ecosystem shifts and very close to tipping points. Historical experience suggests that soil ecosystems can be restored naturally even though the process can take centuries, unless they have passed significantly their degradation tipping point (ie. they have already been desertified). Reversing the trend of the shift while using the soil ecosystem services, means that we need to add significantly more organic matter to the soil compared to the amount added under set-aside conditions. Biomass recycling to soils is the only way towards sustainable agriculture in Crete. However, it is imperative that agricultural production research pays attention to the composition of recycled biomass (farm yard input) and the resulting taxa and structure of micro-organisms in the soil. To examine the feasibility of the recommendation, an analysis of the potential nutrient supply and demand was conducted for agriculture in Crete. Table 2 presents estimates of the potential nutrient demand and supply in Crete, Greece using a Bio-residue/Excreta calculator (Bio-REX). Bio-REX calculates the potential fertilizer demand and the biomass nutrient fluxes from the following sources: livestock extreta/manure, biosolids from wastewater treatment plants, composting of the organic fraction of municipal solid wastes, and olive mill waste water. Model assumptions are presented in the supplementary information. Recycling of biomass covers N and K fertilization needs in Crete while it falls short by 10% of the P needs. In addition, it provides 1.5 t C/ha/yr which is about 50-75% of C input to soil due to set-aside conditions. Fertilizer demand in Crete can be satisfied by the recycling of bio-residue and animal excreta. Carbon addition to set-aside levels can be achieved by recycling of crop residue, which can provide an additional 1.45 t C/ha/yr. Soil fertility improves faster if in addition to bio-fertilization, farmers use traditional agricultural practices such as crop rotations and legume row plantings within olive trees and orchards. ROTH-C, a carbon turnover in soils model (Coleman and Jenkinson, 1999) was used to assess carbon content decline due to tilling and plant litter input reductions using data from a soil survey conducted at Koiliaris Critical Zone Observatory (Fig. 2). The calibrated parameters for Greece were taken from Stamati et al. (2011). Carbon input of 1.5 t C/ha/yr is enough to maintain the carbon content of the soil, on the other hand, carbon input of 3 t C/ha/yr will restore soil carbon and thus soil fertility to previous levels in 15 years.

The renewed soil fertility paradigm shift requires a "holistic" management of biotic-soil-water resources in order to provide sufficient and of appropriate type organic matter to the plant-microorganism system to maximize food production.


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**Table 1. Significant knowledge gaps in understanding soil ecosystem functioning**

1. **Soil Ecosystem Changes:** A comprehensive understanding of how the soil ecosystem responds to climatic, land-use, fertilization and carbon input changes is still lacking.
2. **Soil Thresholds:** Plant physiological thresholds on species mortality or decline have not been determined and limit our ability to understand situations of tree mortality or plant species decline due to atmospheric nitrogen inputs.
3. **Plant-Microorganism-Fauna Structural Development Traits:** The interrelationships between the taxonomic structure of species, their function in the ecosystem and the nutrient fluxes required to maintain it have not been fully understood. A framework is required to explain the differences among crops in structural development effectiveness.
4. **Plant-Microorganism-Fauna Communication and Interactions:** The symbiotic relationship between bacteria, fungi, and plants in soils should be viewed as an intelligent living system where species communicate with each other (i.e. biochemical signaling between plants and microbes; Baker et al., 1997), build their own niche and collaborate (i.e. plant priming of microbial activity; Gardenas et al., 2010) to ensure their own survival and the survival of the system and participate fully in sustaining soil ecosystem functions. These interactions as well as rhizosphere priming have been identified as an important knowledge gaps in our understanding of carbon and nitrogen interactions in soils.

**Table 2. Nutrient supply and demand in Crete, Greece using the Bio-REX Calculator**

| **Fertilizer Demand** | | | | | |
|---|---|---|---|---|---|
| **Land use** | **Area, ha** | | **N, tn/yr** | **P, tn/yr** | **K, tn/yr** |
| Citrus plantations | 13.908 | | 1.446 | 321 | 1.200 |
| Olive plantations | 161.002 | | 19.320 | 4.293 | 16.032 |
| Crop-fodder/arable | 45.252 | | 9.050 | 2.011 | 3.755 |
| Vineyards | 37.385 | | 3.739 | 831 | 3.102 |
| **Total Demand** | **257.547** | | **33.556** | **7.457** | **24.089** |
| | | | | | |
| **Bio-Fertilizer Potential Supply** | | | | | |
| **Type** | | **C, tn/yr** | **N, tn/yr** | **P, tn/yr** | **K, tn/yr** |
| Municipal Solid Waste - Compost | | 19.016 | 3.328 | 119 | 2.219 |
| Waste Water – Biosolids | | 5.603 | 560 | 324 | 21 |
| Olive Mill Waste Water | | 22.320 | 1.395 | 605 | 3.906 |
| Animal Manure/Excreta | | 347.721 | 28.977 | 8.556 | 15.712 |
| **Total Supply** | | **394.660** | **34.260** | **9.603** | **21.858** |
| | | | | | |
| **Ratio Supply/Demand** | | | **1.02** | **1.29** | **0.91** |

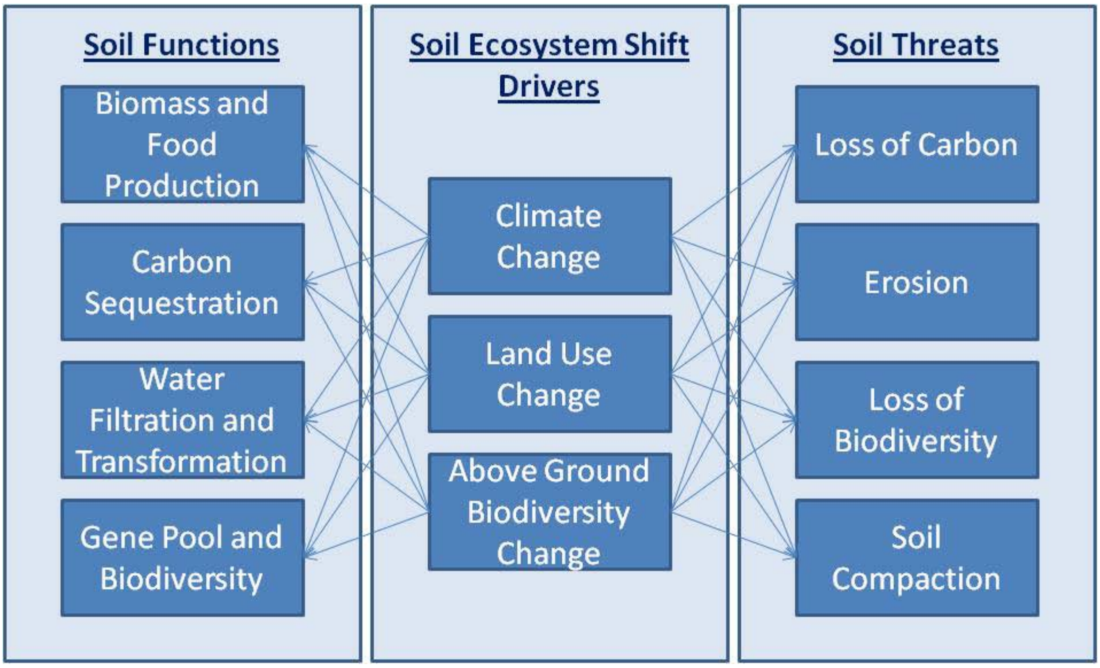


Fig. 1. Relationship between soil ecosystem shift drivers with soil functions and threats.

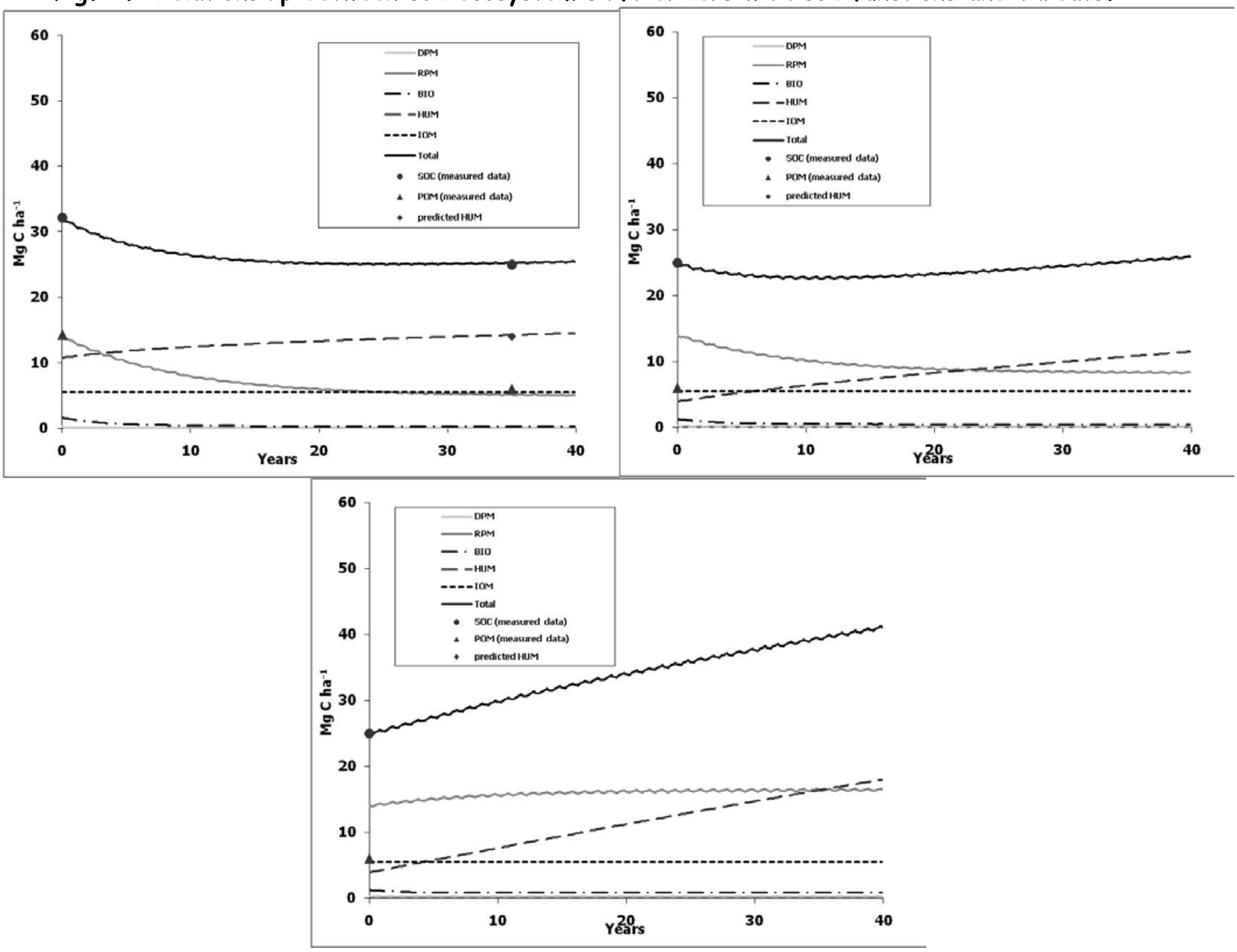


Fig. 2. Soil carbon content evolution in Olive groves of Koiliaris CZO due to tilling and plant litter input using the ROTH-C model. A) Tilling and plant input reductions reduced soil organic carbon from 4 t/ha/yr to 0.9 t/ha/yr, B) Soil carbon sequestration simulation with 1.5 t/ha/yr carbon addition and C) Soil carbon sequestration simulation with 3.0 t/ha/yr carbon addition.

## Supplementary Information

**Evidence of Soil Ecosystem Shifts in Crete:**

Soil ecosystem shift drivers affect directly and negatively soil ecosystem functions and soil threats. The relationship between soil ecosystem shift drivers with soil functions and threats is presented in Fig. 1. The figure does not include fertilization in the list of drivers because the available evidence in the scientific literature cannot be fully quantified. Table 1SI presents the factors affecting Crete's habitability during the past 8000 years which are reliable water supply, plant biodiversity and soil fertility. Soil ecosystem shift drivers are "working against" soil functions and increase the areal extent of soil threats. A summary of the evidence of soil ecosystem shift drivers in Crete is presented below.

1. **Climate change impacts:** Climate change in semi-arid areas such as the Mediterranean region is expected to cause increases in temperature, $CO_2$ concentration, water vapor evaporation and declines in rainfall. Increases in temperature and $CO_2$ and decreases in soil moisture affect significantly soil ecosystem functions and can cause ecosystem shifts. This will impact freshwater quality and quantity due to increasing irrigation demands. Crete, located within 400 km of the Sahara desert is projected to be at the center of climate change impacts according to the IPCC (2007) scenarios. Warmer and drier conditions are expected to intensify water shortages and droughts, forcing species migration at rates exceeding natural migration rates (leading to species loss), significant changes to vegetation structure resulting in loss of biodiversity and ecosystem services. Kazakis et al. (2007) studied the vascular plant diversity changes along an altitudinal gradient (1664-2339 m) and mean temperature gradient of 5° C as an indication to climate change impacts. The study recorded 70 species (20 endemic) belonging to 23 families. Cretan endemic species dominate the high altitude (the percent endemism varied between 31 and 36% at the four elevations) and species richness and turnover decreased with altitude (58 species at the 1664m elevation and decreased to 32 at 1965m and 18 and 14 species at the 2160 and 2339 m elevations). The plant cover density was 14% at the 1664m elevation and decreased to 4% at 1965m and 1% at both the 2160 and 2339 m elevations.

2. **Land use change impacts:** During the first few years after conversion from forest or grassland to crop land, rapid loss of bio-available carbon and nitrogen and deterioration of soil stability has been observed, accompanied by a significant shift in soil fertility (Olson et al., 2005). The Cretan landscape has been transformed during the past 50 years from a low intensity agrarian landscape with low impact agricultural practices, small size properties and high bio-diversity to mechanized, high intensity agriculture and larger size properties with monocultures (56% of the cultivated area

are olive and citrus plantations). Agricultural practices have been the primary cause of land degradation illustrated in Fig. 1SI (tilling, no organic matter addition to soil, high pesticide and herbicide use). Tourism and urban growth has extended soil sealing and compaction in valleys (high productivity land). Agricultural subsidies have made profitable the extension of farming to marginal, high slope, low productivity land. The sheep and goat population in Greece increased from 9 million to 11 million animals between 1960 and the present, while in Crete it increased from 0.4 to 1.8 million animals (Fig. 2SI). Crete raises 16% of the total livestock population in Greece on only 6% of the Greek land area. The average stocking density in Crete ranges from 110 to 390 animals/km$^2$, with an average of 227 animals/km$^2$. The stocking density in Crete increased by a phenomenal 460% in 40 years (from 70 thousand in 1961 to 390 thousand in 1991 in the Prefecture of Rethymnon).

3. **Fertilization impacts:** Nutrient cycles have been identified as one of the planetary boundaries that define the safe operating space for humanity because they have a narrow range of ecosystem thresholds (Rockstrom et al., 2009). Recent research suggests that inorganic nitrogen fertilization decreased soil microbial respiration rates by up to 60%. Even though fertilization with inorganic fertilizers is a common perturbation of soil systems, the cause and effect relationships to the soil ecosystem functions and resulting services have not been fully understood. Fertilizer use in Greece from 1960 (159.000 t/yr) to 1985 (710.000 t/yr) increased 4.5 fold and then it declined by 43% (405.000 t/yr) while agricultural production has leveled off (Fig. 3SI). More research is necessary in order to quantify the impacts of inorganic fertilization to ecosystems.

4. **Above-ground biodiversity decline:** Examining the symbiotic relationship between ectomycorrhizal fungi and plants in a forest, Courty et al. (2010) determined that the photosynthetic activity of the tree is a primary determinant of the mycorrhizal taxonomical structure, which in turn affects the mineral nutrition of the tree (which controls its photosynthetic activity). Decline in above-ground biodiversity will affect the composition of biota and soil functions (Allen et al., 2006; Horner-Devine et al., 2004; Kazakis and Arianoutsou, 2006). Mediterranean vegetation can be categorized into three main ecosystems: phryganic, shrub and forest ecosystems (Vogiatzakis and Griffiths, 2006; Vogiatzakis et al., 2003 and 2008). Phrygana are common woody, small shrubs extremely well adapted to dry summers by replacing their leaves with smaller ones. Maguis and garrigues are the two types of Mediterranean shrubland. Garrigues are very important to animal forage while maquis provide inferior quality forage and phrygana are not used for forage. Papanastasis (2004) reviewed the land use changes in western Crete between

1945 and 1989. He found that the decrease in population from 15 to less than 10 inhabitants/km2 was correlated to land use changes where phrygana, garriques and maquis were reduced by 17.5%, 19.7% and 13.1% respectively while the coniferous forests increased by 20.3%. The overall decline of vegetation areal cover was 3.5%. Maquis ecosystem was mostly converted to olive groves while garriques were reduced due to overgrazing and pastoral fires. The areal extent of forests increased because Samaria gorge was established as a National Park in 1962, minimizing human activity. Arianoutsou (2001) reported that from 1945 to 1989 olive groves increased by 80%, cereals decreased by 62%, and the overall decrease in total agricultural land was 39%. Cultivation of extensive areas with mono-cultures has caused decline in above-ground biodiversity, the impact of which has not been quantified. On the other hand, the impacts of livestock grazing were shown to impede the nitrogen cycle by restricting mineralization and plant uptake and leaching of organic matter suggesting a shift in soil functions. Lorent et al. (2009) studied the impact of subsidies derived from EU's Common Agricultural Policy (CAP) to livestock practices and land degradation at farm level in four communities in central Crete. They concluded that livestock subsidies increased flock size 250% in two decades, which was accompanied by intensification of livestock management and decreasing yields and profits. However, they did not find statistical changes in the plant cover that were using as a proxy to vegetation degradation. The average vegetation cover of the four communities was less than 30%. It is important to notice that the grazing density in the study area was >350 animals/km$^2$ in the 1960 and >900 animals/km$^2$ 20 years later. This suggests that the area was already degraded since the 1960s and that vegetation cover densities of 26, 23, 17 and 20 (average of 21.5%) for the four communities (Anoghia, Gergeri, Paranymfi and Sternes respectively) could correspond to limit of plant cover density of resilient high land plant species.

**Bio-residue/Excreta calculator assumptions:** A Bio-residue/Excreta calculator is an excel based nutrient fluxes model developed to calculate the potential nutrient demand and supply in Crete, Greece. The arable land of Crete amounts to 575.000 ha with 28% citrus trees, 28% olive trees, 5% vineyards and 39% crop-fodder/arable. Using typical values suggested by the Hellenic Ministry of Agricultural Development, the potential fertilizer needs are 33 kt of N, 7 kt of P and 24 kt of K. Sources and quantities of biomass in Crete include the extreta/manure from 3 million livestock (1.8 million sheeps and goats, 1.2 million poultry and 51.000 horses, cattle and pigs), biosolids from wastewater treatment plants, composting of the organic fraction of municipal solid wastes (Manios, 2004), and olive mill waste water (930.000 m3/yr). Chemical concentrations of olive mill waste water, compost and biosolids were taken from chemical analyses conducted at the Technical University of Crete while coefficients for excreta were OECD averages (OECD, 2007; Bouraoui et al., 2009; Voivontas et al., 2001). Farm residue was assumed to be a component used in the production of compost.

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**Table 1SI. Factors affecting Crete's habitability during the past 8000 years**

1. **Geomorphology:** Tectonic uplift created rugged topography and a beautiful landscape. Apart from its recognized beauty, the main geologic and geomorphologic feature of Crete is karstic formations of limestone and dolomites. The karst formations of Crete are **natural below ground reservoirs spread conveniently along the island that reliably supply water throughout the year**.

2. **Climate:** The temperate (semi-arid) in conjunction with the topography create climatic gradients (ranging from typical Mediterranean to Alpine climate) that **favor above-ground biodiversity**. In fact, Crete has been a hot spot for plant biodiversity.

3. **Soils:** The soils of the area have been formed primarily by the weathering of limestone with **high clay and iron oxide content** which are the main ingredients of **soil aggregate formation**. The potential for aggregate formation is an **indication of soil fertility, ability to filter and transform water and to sequester carbon**. It also suggests the ability of soil renewal.

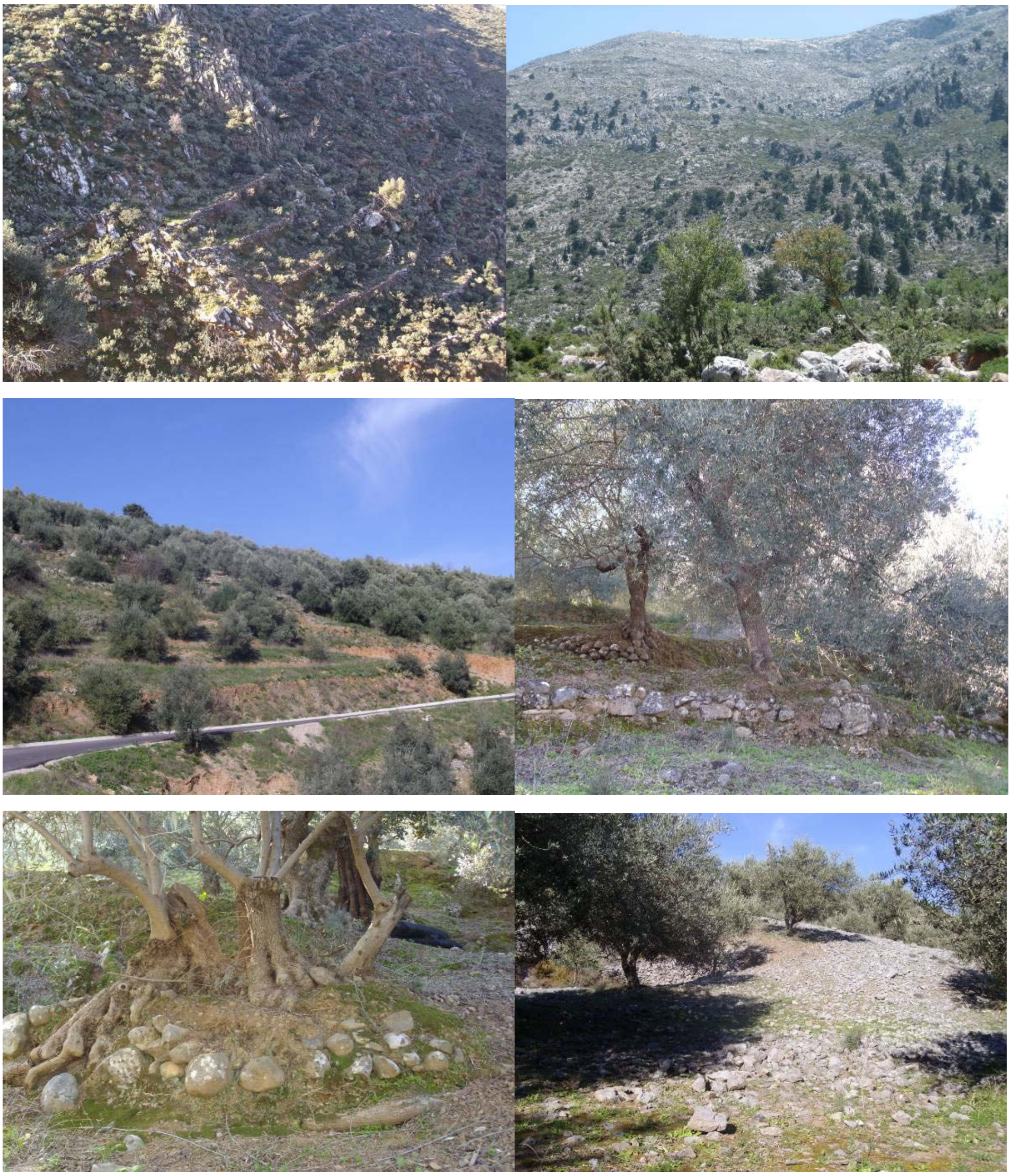

**Fig. 1SI.** **Land degradation due to abandonment of terraces, cultivation in steep slopes (marginal land), not maintaining the terrace wall and sparse vegetation. Photos from western Crete.**

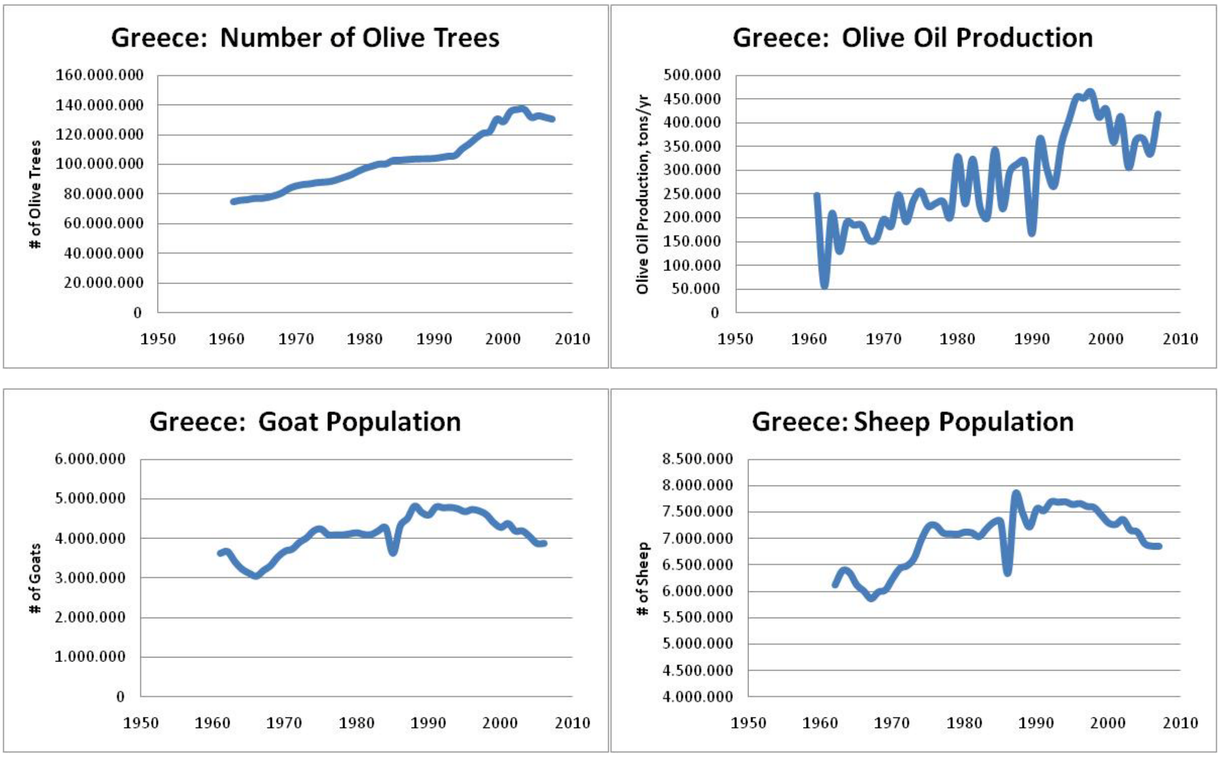


**Figure 2SI. Data from the Hellenic Statistical Service - Increases in stock densities and olive tree cultivation in Greece between 1960s to 1990s.**

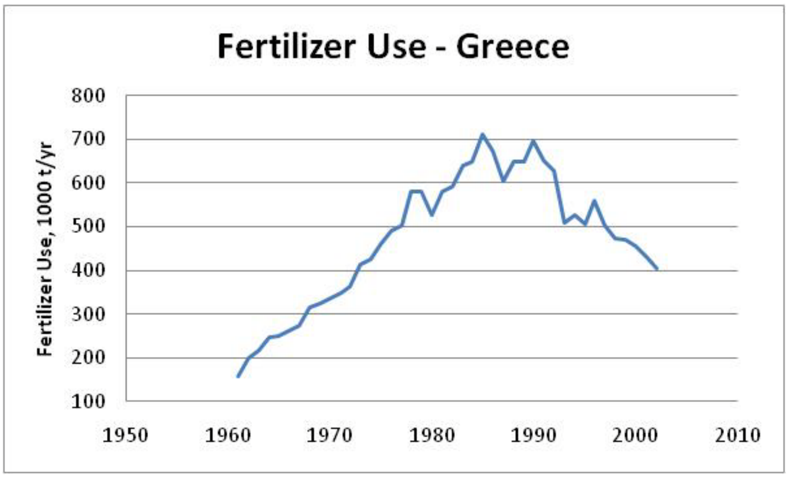


**Figure 3SI. Data from the Hellenic Statistical Service - Increases in fertilizer use in Greece between 1960s to 2000s.**