Review

A Review of Libyan Soil Databases for Use within an Ecosystem Services Framework

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Abstract: Ecosystem services (ESs) are increasingly being used by many countries around the world as a framework for addressing the United Nations (UN) Sustainable Development Goals (SDGs). This review article of the usability of Libyan soil databases for ESs and SDGs is the first of its kind for North Africa. The objectives of the article are to: describe the available soil resources of Libya in relation to an ES framework; provide examples of the usability of Libyan soil databases for ES applications (e.g., provisioning, Healthy Eating Plate), and describe some of the typical disservices in the country. Desertification, salinization, and limited freshwater resources are the largest challenges (disservices) for agriculture and future development in Libya. Seawater intrusion in coastal areas due to rising sea levels has resulted in high concentrations of salts in irrigation waters, which can lead to low soil productivity. These challenges can be addressed by integrating Libyan soil resources into a market that transforms resources into goods and services to meet human demand in a sustainable manner, with non-market institutions mediating the interactions between humans and the environment. If Libyan soil resources are taken into account by both market and non-market institutions, it will lead to more efficient use of soil resources and also should enable the implementation of innovative strategies, such as integrated farming systems, non-soil-based agricultural production (e.g., hydroponics), and alternative farming practices.

Keywords: agriculture; food security; ecosystem services; land use; mapping; soil resources; soil functions; soil properties

1. Introduction

Global development, increasing population, decreases in resource availability, and climate change have had significant impacts on many countries throughout the world. The United Nations (UN) Sustainable Development Goals (SDGs) aim to achieve a balance between using natural resources for socio-economic growth and conserving ecosystem services (ESs) that are important to human well-being and livelihoods [1]. Sustainable development is based on maintaining the sustainable use of terrestrial ecosystems, while also combating degradation and desertification of such systems. Land degradation, soil erosion, loss of soil organic matter are common deteriorations of terrestrial ecosystems around the world [2–5].

The UN adopted 17 SDGs as guidelines to improve the sustainability of global human societies [6]. Soils are at the center of the UN SDGs, and play a fundamental role in the achievement of these goals because they provide clean water and food for global societies. The UN SDGs specifically related to soil functions include: SDG 2—Zero Hunger (End hunger, achieve food security and improve nutrition and promote sustainable agriculture); SDG 3—Good Health and Well-Being (Ensure healthy lives and promote well-being for all at all ages); SDG 6—Clean Water and Sanitation (Ensure availability and sustainable management of water and sanitation for all); SDG 13—Climate Action (Take urgent action to combat climate change and its impacts); SDG 15—Life on Land (Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss) [6]. The UN SDGs are closely connected to ESs, with many ESs contributing to more than one SDG as reported by [7] (Table 1).

Table 1. Connection between ecosystem services and selected Sustainable Development Goals (SDGs) in relation to soil resources (adapted from [7]).

TEEB Ecosystem Service Categories	TEEB Typology	Sustainable Development Goals (SDGs)
Provisioning	Food; Water; Raw materials; Genetic resources; Medicinal resources; Ornamental resources	SDG 2, 3, 13, 15
Regulating	Air quality; Regulation; Waste treatment (water purification); Moderation of extreme flows; Erosion prevention; Climate regulation; Maintenance of soil fertility; Pollination; Biological control	SDG 2, 3, 6, 13, 15
Supporting	Maintenance of life cycles; Maintenance of genetic diversity	SDG 2, 3, 6, 13, 15
Cultural	Spiritual experience; Aesthetics; Information; Inspiration for art, culture, design; Recreation and tourism; Information; Cognitive development	SDG 3, 6, 13, 15

Note: The Economics of Ecosystems and Biodiversity (TEEB). SDG 2—Zero Hunger; SDG 3—Good Health and Well-Being; SDG 6—Clean Water and Sanitation; SDG 13—Climate Action; SDG 15—Life on Land.

Consumption of natural resources has been increasing worldwide, including Africa. Many African countries are trying to address challenges with food production and water shortages. Early ES studies in Africa were conducted in South Africa in 2005 [8]. A review by Wangai et al. [9] concluded that most ES studies in Africa were conducted for Sub-Saharan Africa (e.g., South Africa, Kenya, Tanzania) with a primary focus on provisioning and regulating services. Economic valuations of ES in Africa have included both monetary and non-monetary valuations [9].

Libya is a North African country covering 1,759,540 km^2 [10], which makes it the fourth largest country in Africa and one of the largest countries in the world [11]. According to the Ministry of Planning, there are four administrative territories in Libya: Tripoli (capital Tripoli), Benghazi (capital Benghazi), El-Khalij (capital Sirt), and Fezzan (capital Sabha). The territories of Tripoli and Benghazi have the highest resident populations (Figure 1). Most agricultural activities are limited to a northern strip along the Mediterranean coast, some mountainous regions, and several dispersed oases in the desert (Figure 1) [12]. Agricultural activities are an important part of the Libyan economy, employing almost 5% of the labor force and providing nearly 9% of the gross domestic product [13]. Agriculture is dependent on the private sector, with privately-owned farms producing the largest fraction of agricultural products. Some government irrigation projects have been established in the desert for cereal and forage production (Figure 1) [12].

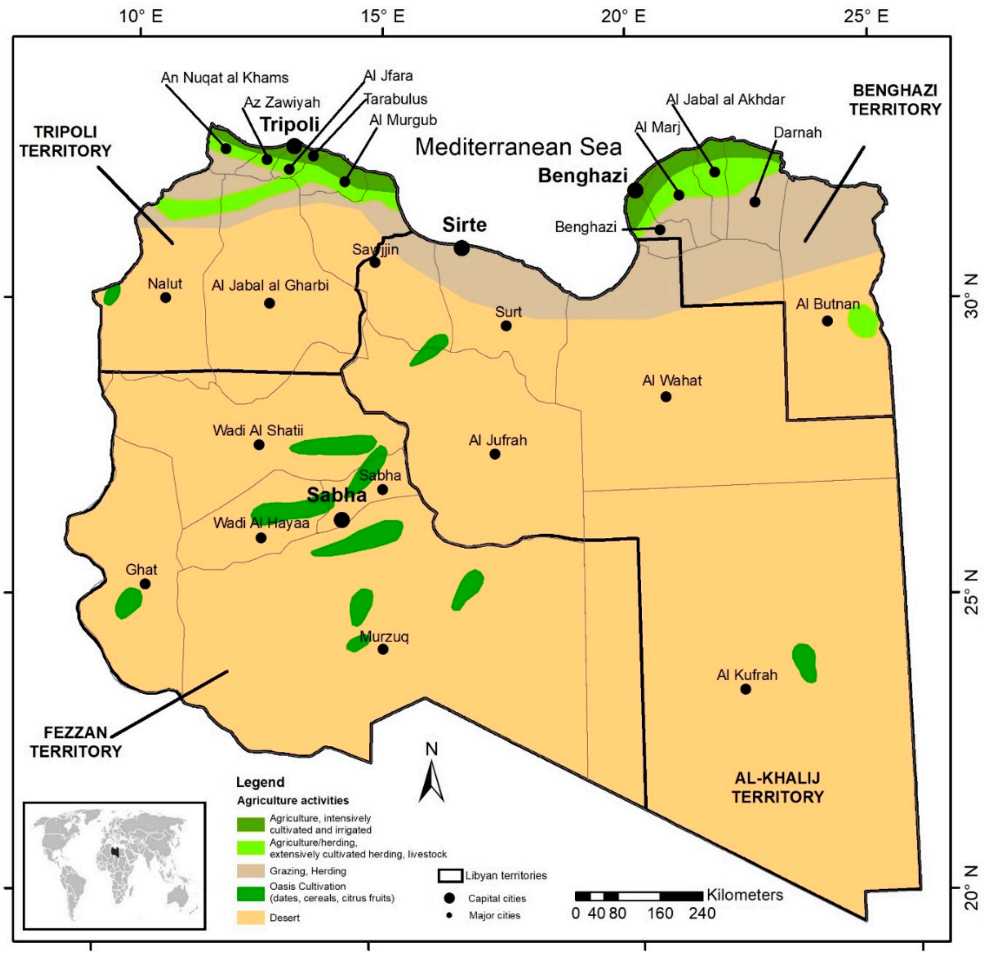


Figure 1. Locations of agricultural activities in Libya [14].

Ecosystem services (ESs) are increasingly being used by many countries throughout the world as a framework to address the UN SDGs. This review article of the usability of Libyan soil databases for ESs and SDGs is the first of its kind for North Africa, and is based on a literature review and available geospatial layers. Several questions have been considered with regard to soil resources as they relate to an ES framework: (1) What types of soils and land-uses are present in Libya to support ESs? (2) What is the potential usability of Libyan soil databases for ES applications (with selected valuation examples provided)? and (3) What are the challenges and disservices that affect both soils and ESs in Libya? Table 2 outlines subsequent sections of this article that address selected ES, disservices, and valuation examples in relation to Libyan soil resources.

Table 2. Article sections addressing selected ecosystem services, disservices, challenges, and valuation examples in relation to the soil resources of Libya.

Article Section	Ecosystem Services	Valuation Examples
3.2.	**Provisioning:**	
3.2.1.	- Food, fuel, and fiber	Healthy Eating Plate
3.3.	**Regulating:**	
3.3.1.	- Climate regulation	
3.3.2.	- Carbon sequestration	Soil inorganic carbon storage
3.3.3.	- Water purification	
3.3.4.	- Waste regulation	
3.4.	**Cultural:**	
3.4.1.	- Recreation/ecotourism	
3.4.2.	- Cultural heritage	

3.4.3.	- Education	
3.5.	**Supporting:**	
3.5.1.	- Weathering/soil formation	
3.5.2.	- Nutrient cycling	Population demand for elements
3.5.3.	- Provisioning of habitat	
Ecosystem Disservices and Human-Induced Degradation		
4.1	Challenges…	
4.2	Land Degradation…	Land degradation
4.3	Salinity	
4.4	Pollution	
4.5	Food Security	
4.6	Climate Change	

Key objectives of this review article include describing the soil resources of Libya within an ES framework, providing examples of the usability of Libyan soil databases for ES applications (e.g., provisioning, Healthy Eating Plate), and identifying some of the typical challenges/disservices in the country. Many ESs are directly or indirectly linked to, or derived from, soil. Spatial soil databases enable researchers and managers to combine soil information with other, often spatial, data (e.g., hydrology, vegetation, demographics, etc.) to understand and identify important ES within a country. Furthermore, identification of soil spatial databases that can be utilized within an existing ES framework will enable others to pursue related research.

2. Methodology

Information on the availability and usability of Libyan soil databases is limited, particularly in the peer-reviewed literature. Most of the information presented has been obtained from the Food and Agriculture Organization (FAO) of the United Nations (UN), or from other studies related to the FAO. Geospatial data, including maps of municipal boundaries, soil types, and agricultural activities were obtained from several sources and used to create geographic information system (GIS) layers in ArcGIS 10.6 (ESRI). Spatial comparisons were made using Google Earth and Google Earth Engine.

2.1. Soil Databases

Libyan soils are slightly or moderately weathered soils typical of arid areas. Figure 2 and Table 3 show the major soil classes of Libya according to the FAO Soil Classification System [13]. The most arable land in Libya occurs at two locations: Al-Jabal al Akhdar in the northeast region, and Al Jifarah Plain in the northwest region. Almost all of the country is a desert (95%) with 1.2% (2.2 million ha) being cultivated [13]. Yermosols and Xerosols are the major soil orders in the region. Soils in Libya are typically shallow, sandy in texture, low in organic matter content and water holding capacity [15].

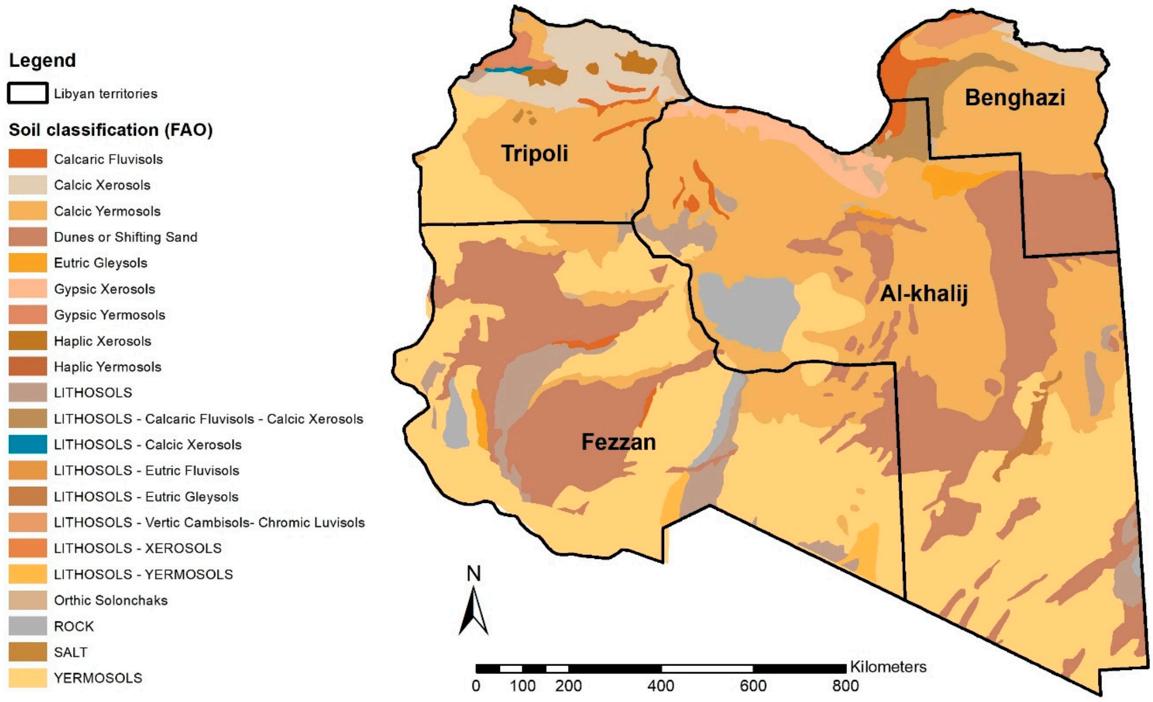


Figure 2. Soil map of Libya (adapted from [13]).

Table 3. Soils of Libyan territories based on the Food and Agriculture Organization (FAO) of the United Nations (UN) soil classification system [13].

Tripoli	Al-Khalij	Benghazi	Fezzan
Calcaric Fluvisols	Calcaric Fluvisols	Calcaric Fluvisols	Calcaric Fluvisols
Calcic Yermosols	Calcic Yermosols	Calcic Yermosols	Calcic Yermosols
Orthic Solonchaks	Orthic Solonchaks	Orthic Solonchaks	Orthic Solonchaks
Calcic Xerosols	Calcic Xerosols	Calcic Xerosols	Lithosols
Lithosols	Lithosols - Eutric Fluvisols	Lithosols—Calcaric Fluvisols—Calcic Xerosols	Lithosols—Yermosols
Yermosols	Yermosols	Haplic Yermosols	Yermosols
Gypsic Xerosols	Gypsic Xerosols	Lithosols—Vertic Cambisols—Chromic Luvisols	Eutric Gleysols
Gypsic Yermosols	Lithosols - Calcaric Fluvisols - Calcic Xerosols	Dunes or Shifting Sand	Dunes or Shifting Sand
Lithosols—Xerosols	Eutric Gleysols		Rock
Lithosols—Calcic Xerosols	Dunes or Shifting Sand		
Haplic Xerosols	Rock		
Salt			

Numerous soil studies have been carried out in Libya over the last four decades [16] with a primary emphasis on the northern part of the country and small scattered areas in the southern desert [17]. These studies are based on the U.S. taxonomy, the modern soil classification of Russia, French soil classification, and the Food and Agriculture Organization (FAO) of the United Nations (UN) soil classification system (Table 4).

Table 4. Description of soil databases available for ecosystem services studies.

Locations	Coverage Area (ha)	Soil Classification Type	Scale	Year	Project Execution
Country level	179,950,000	FAO soil (Classification System)	1:2,000,000	2002	Food and Agriculture Organization (FAO)
Northwest region*	1,600,000	Russian	1:50,000	1980	Solkhozprom Export
Northwest coast region*	132,000	U.S. Soil Taxonomy	1:50,000	2003	National Consulting Bureau (NCB)
The middle coastal strip*	500,000	Russian	1:50,000	1980	Solkhozprom Export
Northeast region*	600,000	Russian	1:50,000	1980	Solkhozprom Export
Northeast region*	53,830	U.S. Soil Taxonomy	1:250,000	1997	Omar Al-Mukhtar University
Northeast region*	902,167	U.S. Soil Taxonomy	1:50,000	2005	Omar Al-Mukhtar University
Northwest region (Jafara plain)*	400,000	U.S. Soil Taxonomy	1:50,000	1994	Moroccan company (Telecart)
Northwest region (Al-Ajeelat)*	60,000	U.S. Soil Taxonomy	1:50,000	1991	The Man-Made River company
Northwest region (Beer Alhawd)*	60,000	U.S. Soil Taxonomy	1:50,000	1998	National Consulting Bureau (NCB).
Northwest region**	N/A	U.S. Soil Taxonomy	1:250,000 to 1:500,000	1972	French company (Geffly)
Southwest region (Almjdwl -Alsaria, Alqatarun-Rhbt Almunqar, and Tajrihi)***	17,000	U.S. Soil Taxonomy	1:10,000 1:5,000	1998	Regwa Company

Note: Type of soil survey - * Semi-detailed; ** Rapid reconnaissance/Reconnaissance; *** Detailed low and high intensity.

The creation of soil databases is the first step in developing sustainable land use and soil management decisions. Information about soils in Libya are not easily accessible, nor are they organized for efficient access. Table 5 provides a list of the typical soil properties from the soil databases of Libya with the units and most common measuring methods that have been used in Libyan soil survey reports.

Table 5. Typical soil properties from the soil databases of Libya.

Soil Properties	Typical Units	Common Method of Measurement
Mechanical analysis	% sand, % silt, and % clay	Hydrometer method [18].
Bulk density	g/cm^3	Core method [19].
Electrical conductivity (EC)	dS/m at 25 °C.	1:1 extract by EC bridge (EC-meter) [20].
Soil pH	-	1:1 extract by pH meter [21].
Soluble cations (Ca^{2+}, and Mg^{2+}, Na^+, and K^+)	meq/L	Soluble Ca^{2+} and Mg^{2+} obtained by extracting the soil with water and measuring their concentrations in the extract by titration with EDTA. Soluble Na^+ and K^+ measured in the extract by flame atomic absorption spectrophotometry [22].

Soluble anions: (CO_3^{-2}, HCO_3^{-}, SO_4^{-2}, and Cl^{-})	meq/L	Soluble CO_3^{-2} and HCO_3^{-} obtained by extracting the soil with water and determining their concentrations in the extract by titration with 0.5 N HCl. Soluble SO_4^{-2} in the extract measured by precipitation as $BaSO_4$ and back titration of excess Ba^{2+} with EDTA. Soluble Cl^{-} in the extract measured by titration with 0.05 N $AgNO_3$ [22].
Exchangeable cations (Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+})	meq/100 g soil	Soil exchangeable Na^{+} and K^{+} extracted with 1.0 N ammonium-acetate at pH 7 and measured in the extract by flame atomic absorption spectrophotometry. Soil exchangeable Ca^{2+} and Ma^{2+} estimated by subtracting exchangeable Na^{+} and K^{+} from the total CEC [23].
Exchangeable sodium percentage (ESP)	%	$ESP\ \% = \frac{Na^{+}(Exchangeable)}{CEC} * 100$
Gypsum ($CaSO_4.2H_2O$)	%	Precipitation with acetone followed by measurement with EC- meter [23].
Calcium carbonate $CaCO_3$	%	Addition of excess 0.5 N HCl followed by normalization with 0.25 N NaOH [23].
Cation exchange capacity (CEC)	meq/100g soil	Cation exchange sites saturated with Na^{+} using multiple treatments with 1.0 N sodium-acetate at pH 8.2. Exchanged Na^{+} then extracted with 1.0 N ammonium-acetate at pH 7 and measured by flame atomic absorption spectrophotometry [24].
Organic carbon	%	Oxidation of organic matter (Walkley–Black method) [24].
Organic matter	%	Estimated by multiplying the % organic carbon by 1.72 [25].

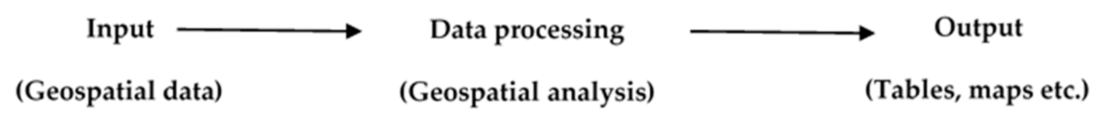
2.2. Integration and Organization of Soil Databases for Accounting and Reporting of ES Valuation

Libyan soil databases can be integrated with ES accounting frameworks, as demonstrated in Table 6, which describes a framework (adapted from [26]) and provides specific examples: 1) population demands for potassium (K) estimated using K replacement costs, and 2) soil inorganic carbon (SIC) storage for regulating ES (shown in a later section). Because most available soil databases are already in a geospatial format, this framework can be applied using geospatial tools for data processing and ES analysis (Table 6).

Table 6. Using soil databases within an existing ecosystem service (ES) accounting framework (adapted from [26]) with geospatial analysis.

Biophysical Accounts (Science-Based)	Administrative Accounts (Boundary-Based)	Monetary Accounts	Benefit	Total Value
Soil Extent:	Administrative Extent:	Ecosystem Service(s):	Sector:	Types of Value:
		General		
- Soil order - Soil profile - Soil depth	- Country - Territories - Capital cities	- Provisioning - Regulating - Cultural	- Agriculture - Industry - Tourism etc.	Market-based value

	- Major cities - Farms etc.	- Supporting		- Non-market value - Instrumental value - Intrinsic value, etc.
Example (Population demand): K replacement cost				
Not applicable	- Country - Territories - Capital cities - Major cities	- Provisioning (e.g., food) - Commodity	Agriculture: - Fertilizer equivalent (e.g., potassium chloride, KCl)	Market-based value: - Replacement cost (price of KCl, based on a moving 5-year average price of U.S. $500 per metric ton of potassium chloride, KCl [27])
Example (Soil regulating services): Soil inorganic carbon (SIC) storage				
- Soil type	- Country	- Regulating	Environment	Value based on avoided social costs of carbon emissions: $80 per ton of SIC [28]



3. Results

3.1. Integration of Soil-Based Ecosystem Services for Libya with Market and Non-Market Institutions

The ES values of soils, or "true values," are not recognized in the current Libyan land market, resulting in market failure and the inefficient use of land. The use of soil-based ESs for Libya with market and non-market institutions may benefit the welfare of the country, and lead to more efficient use of limited soil resources as well as more innovative applications (Figure 3) [29].

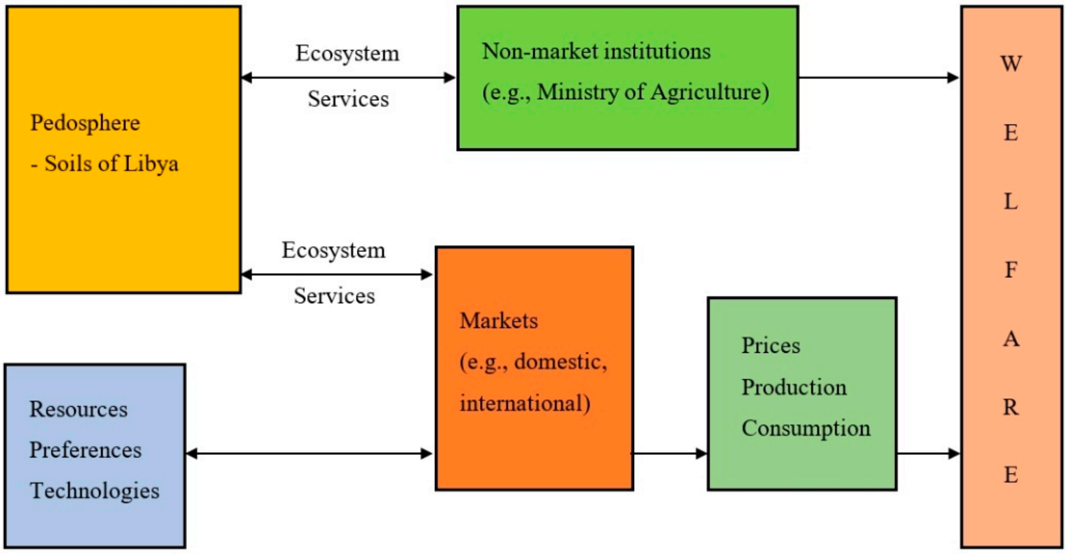


Figure 3. A conceptual diagram for Libya of how market and non-market institutions can potentially transform soil resources into goods and services that meet the population demand (adapted from [29]).

3.2. Provisioning Services

Provisioning services are products obtained directly from ecosystems (e.g., food, fiber, timber) (Table 7). Population growth (especially in urban areas) has been a key factor driving increases in agricultural production, which in turn has been increasing pressures on natural resources, especially water. The total population of Libya increased from 2 million in 1970 to 5.6 million in 2003 [13,30], but the annual population growth rate decreased to under 1% over the period 2005–2015. In 2006, the total population was approximately 5.75 million (0.8 million non-Libyans) [13]. Most people live in the northwestern and northeastern coastal areas (Figure 1). The General Information Authority Census of Libya has predicted that the population will be more than 10 million by the year 2025. Consequently, future demand for food and other essential requirements will continue to increase.

Table 7. Provisioning soil-based ecosystem services by territories.

Provisioning Services	Libyan Territories			
	Tripoli	**Al-Khalij**	**Benghazi**	**Fezzan**
Food				
- Vegetables	+	+/-	+	+/-
- Fruits	+	+/-	+	+/-
- Cereals	+/-	+	+/-	+
- Fodder	+/-	+	+/-	+
Fuel				
- Wood, charcoal, dung	+	+/-	+	+/-
Fiber				
- Wood	+	+/-	+	+/-
Raw materials				
- Clay, sand, gravel	+	+	+	+
Gene pool	+	+	+	+
Ornamental	+	-	+	-
Fresh water/water retention	+/-	+	+/-	+

Note: + indicates that ecosystem service is present; - indicates that ecosystem service is absent; +/- indicates that ecosystem service is somewhat present.

3.2.1. Healthy Eating Plate and Food Security

Food provision is urgently needed in Libya, especially in the major cities. Food availability also depends on sustainable water provisioning by watersheds, aquifers, and reservoirs [31]. Water in Libya is scarce (below 500 m^3/year per capita) [32]. Experts from the Harvard School of Public Health and Harvard Medical School created the Healthy Eating Plate that refers consumers to healthy choices in the major food groups. This plate provides detailed guidance for people to make better eating choices (Figure 4). This Healthy Eating Plate can be modified based on typical Libyan produce (Figure 4).

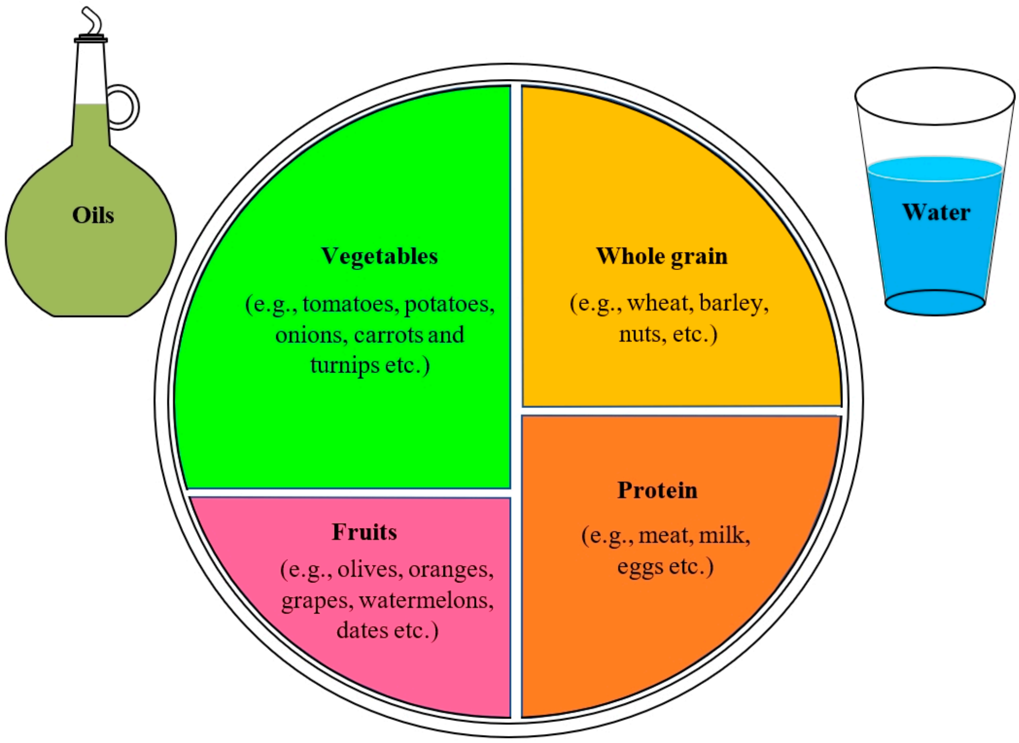


Figure 4. Healthy Eating Plate based on typical Libyan produce (based on [33]).

The major production crops in Libya are shown in Figure 5 [30]. Agricultural activities in Libya depend greatly on groundwater to satisfy their irrigation needs [32], which limits cultivated areas for grains (wheat, barley), vegetables (tomatoes, potatoes, onions, carrots, turnips), fruits (olives, dates, plums, sloes, watermelon, grapes, and oranges), and fodder crops. Most Libyan farms are relatively small (5–20 hectares).

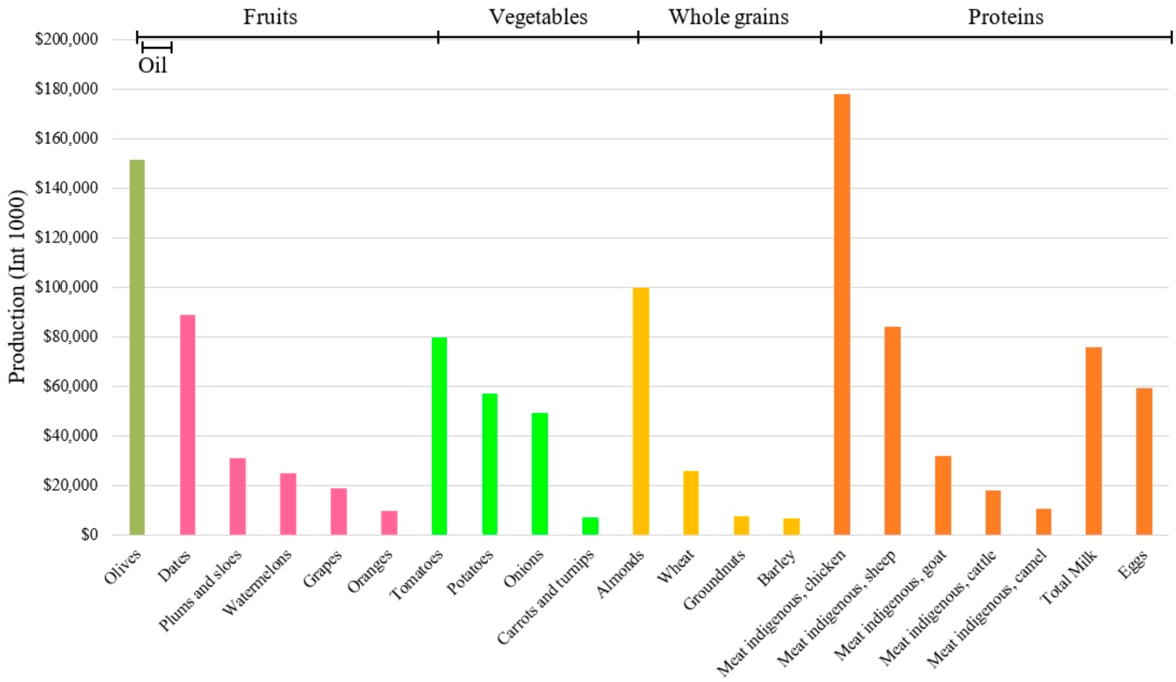


Figure 5. Values of crops produced in Libya in 2016 [34] in relation to the Healthy Eating Plate [33].

Currently, Libya relies on imported food. In 2015, cereal crops were almost 10% below average production levels (254,000 tons). Consequently, Libya imported up to 90% of its cereal consumption needs in 2015. Imports in 2015 were estimated to be 3.7 million tons, an increase of about 7% compared to the previous year as reported by the FAO [32]. Fisheries and livestock (sheep, goats, camels, cows, and poultry) are also important for agricultural production. Determining how to use land efficiently in Libya is an ongoing need. Previous attempts to improve soil management in Libya used a productivity rating index [16], which was then integrated within GIS [35]. This soil productivity rating index takes into account the following soil properties: soil texture, compaction, depth, water table level, internal soil drainage, salinity, exchangeable sodium percentage, soil reaction, calcium carbonate percentage, erosion, and slope. Future improvements to this index should include integrating the soil productivity rating with dynamic climatic factors to better forecast future climate change scenarios.

3.3. Regulating Services

Regulating services are described as the benefits obtained from the regulation of ecosystem processes, such as climate regulation, carbon sequestration, water purification, etc. Regulating services include mitigation of erosion and flood control, maintenance of water quality, biological control of pests and diseases, waste recycling and detoxification, carbon sequestration, and regulation of greenhouse gas emissions [36]. All of these regulating services are found in all four territories.

3.3.1. Climate Regulation

Climate regulation is one of the most important ESs at the global and regional levels, and directly links to major socio-economic and agricultural development in North Africa. Libya has an arid to semi-arid climate (i.e., xeric or Mediterranean climate) with rainfall in the winter and almost no precipitation in the summer. The average annual rainfall in Libya varies with geographic position and topography [37]. For example, the southern part of Libya has a torric moisture regime [16]. The annual average temperature is 20.7 °C, and the soil temperature regime in the study area is thermic [16].

Climate projections for North Africa predict a decrease in precipitation between 10% and 20% by 2050, and an increase in temperature between 2 and 3 °C [38]. A study [39] projected an increase of "hot days" across the African continent by modeling the number of days per year from 1961 to 2100 (Table 8). The model projects there will be more hot days in the future, which will negatively impact agricultural production in the region. Insufficient precipitation to leach salt accumulation in the soil profile, due to higher temperatures and evaporation, will lead to an increase in the land areas affected by salinity.

Table 8. Regional projections of hot days per year in Libya (adapted from [39]).

Part of Libya	Average Number of *Hot Days per Year 1961–1990	Projected Increase in Average Number of Hot Days per Year in 2011–2040	Projected Increase in Average Number of Hot Days per Year in 2041–2070	Projected Increase in Average Number of Hot Days per Year in 2071–2100
Coastal areas	91–172	11–30	31–50	51–80
Inland areas	173–241	11–30	11–30	31–50

* Hot days = Days where the apparent temperature (AT) max ≥ 27 °C.

3.3.2. Carbon Sequestration

Carbon sequestration involves the transfer of atmospheric CO_2 to long-term, stable storage pools [40]. Soils in Libya have developed under arid conditions with limited soil organic carbon (SOC) and abundant soil inorganic carbon (SIC). A study [41] of soil carbon sequestration in the Near East North Africa (NENA) region found that 69% of the soils in the region had SOC stocks below 30 tons ha^{-1}. Soil types that were dominated by calcareous rocks (Solonchaks, Rendzinas, Yermosols) had the highest SIC content, while Lithosols and Xerosols had the lowest SIC content [41]. In general, Libyan soils store significant amounts of SIC (Table 9, Figure 6). Dry climatic conditions in Libya result in high accumulations of calcium carbonate in soils, with the presence of gypsum in some areas, as well as salt accumulation, which leads to naturally saline soils [42].

Table 9. Soil inorganic carbon (SIC) storage in Libyan soils and the SIC value based on the avoided social cost of CO_2 emissions following [28].

Soil Type	Area (km^2)	Average $CaCO_3$ (%)	Soil inorganic storage (SIC) (metric tons)	Total value of SIC (U.S. $) based on $80/ton of SIC	Value per Area ($/$m^2$)
Calcaric Fluvisols	23,535	22	5.65 E + 08	4.52 E + 10	1.92
Calcic Xerosols	55,566	15	9.10 E + 08	7.28 E + 10	1.31
Calcic Yermosols	548,148	45	3.19 E + 10	2.55 E + 12	4.66
Dunes or Shifting Sand	348,269	23	3.10 E + 09	2.48 E + 11	0.71
Eutric Gleysols	10,863	8	9.49 E + 07	7.59 E + 09	0.70
Gypsic Xerosols	22,855	32	9.22 E + 08	7.37 E + 10	3.23
Gypsic Yermosols	6246	35	2.20 E + 08	1.76 E + 10	2.82
Haplic Xerosols	6648	48	4.82 E + 08	3.86 E + 10	5.81
Haplic Yermosols	397	44	2.26 E + 07	1.81 E + 09	4.55
Lithosols	64,014	14	1.02 E + 09	8.19 E + 10	1.28
Lithosols—Calcaric Fluvisols—Calcic Xerosols	23,269	14	4.82 E + 08	3.85 E + 10	1.66
Lithosols—Calcic Xerosols	865	32	4.56 E + 07	3.65 E + 09	4.21
Lithosols—Eutric Fluvisols	1882	60	1.86 E + 08	1.49 E + 10	7.90

Lithosols—Eutric Gleysols	6581	8	5.75 E + 07	4.60 E + 09	0.70
Lithosols—Vertic Cambisols—Chromic Luvisols	8613	14	1.38 E + 08	1.10 E + 10	1.28
Lithosols—Xerosols	552	48	4.36 E + 07	3.49 E + 09	6.32
Lithosols—Yermosols	9797	29	3.20 E + 08	2.56 E + 10	2.61
Orthic Solonchaks	8842	44	6.41 E + 08	5.12 E + 10	5.80
Rock	40,330	8	3.52 E + 08	2.82 E + 10	0.70
Salt	709	11	7.60 E + 06	6.08 E + 08	0.86
Yermosols	571,559	25	1.68 E + 10	1.34 E + 12	2.35
Total value	**1.75954 E + 12**	**28**	**5.83 E + 10**	**4.6657 E + 12**	**2.65**

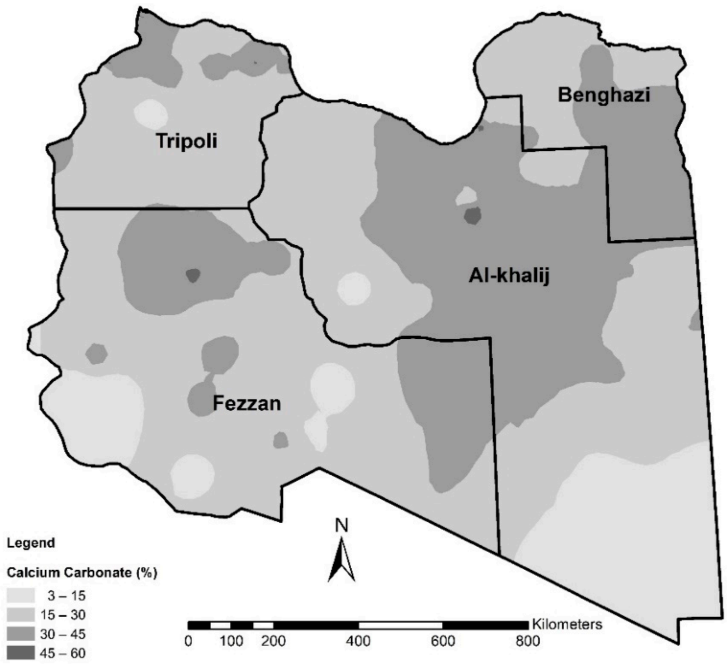


Figure 6. Calcium carbonate distribution in Libyan soils.

3.3.3. Water Purification

The water used in Libya comes from several sources: groundwater; surface water; desalinated seawater; and recycling of wastewater [43]. Groundwater can be found both in shallow aquifers and in deep aquifers ("fossil" water) [30]. Libya relies almost exclusively on non-renewable, "fossil" groundwater resources [44], which come from several water basins (Al-Jabal Al-Akhdar, Al-Kufrah/as-Sarir, Jafara Plain region, Jabal Nafusah/al-Hamada, and Marzek basin) covering a wide range [30,45].

3.3.4. Waste Regulation

Population growth, urbanization, and industrialization in Libya have increased the country's solid waste problem, with the average rate of generation of 0.95 kg/capita/day. Typical municipal solid waste consists of organic materials (54%), paper (12%), and plastic (7.8%) [46–48]. Considerable amounts of solid waste could be recycled and reutilized if separated, but these efforts are poorly organized.

3.4. Cultural Services

The Millennium Ecosystem Assessment (MEA) [48] is based on the concept of linking cultural services to address issues, such as "cultural identity and diversity, spiritual and religious values, knowledge systems, educational values, aesthetic values, social relations, space sense, cultural heritage and recreation, and ecotourism opportunities." Cultural services are nonmaterial benefits to humanity from ESs (e.g., recreation, esthetics, education, and cultural heritage) [48]. In general, cultural services provided by soil ecosystems are the least studied because of conceptual and methodological difficulties. All of the cultural soil-based ecosystem services identified in this section can be found in all four Libyan territories.

3.4.1. Recreation

Soil ecosystems, alone or as part of the landscape, provide numerous opportunities for recreation, cultural heritage, folklore, and education [48]. Libyan culture is highly influenced by life on the Mediterranean. Approximately 80% of the Libyan population lives near the capital city of Tripoli, which is rich in history and architecture and has long been considered the "Jewel of the Mediterranean." Tourism in Libya is associated primarily with desert safaris and beach resorts. The Libyan coastline stretches about 1950 km along the Mediterranean Sea and has some of Africa's most spectacular beaches, famous for their pristine white sands. In the northern regions, there are many historical and archaeological sites that attract visitors, including the Ruins of Sabratha; Leptis Magna "Labdah"; Ptolemais; and Cyrene. These sites provide evidence of more than 2000 years of continuous human habitation along the North African coast.

Libya has a vast desert region that spreads across the southern part of the country, where the climate is extreme with hot summers and cool winters. In this desert, there are several oases, such as Al Jaghbub, Awjilah, and Al-Kufrah in the southern part of Al-khalij territory; and Ubari, Ghat, and Gabroun in the southwestern part of the territory of Fezzan. These oases have traditionally provided shade, water, camels, and dates for caravans in the past, and now have become tourist destinations for people from various countries. For example, Gaberoun is an oasis with a large lake surrounded by golden sand dunes in the desert region of the Libyan "Idehan Ubari" (Figure 7).

Figure 7. Gaberoun Oasis, a large lake in the Idehan Ubari desert region of the Fezzan region in southwestern Libya, with a rudimentary tourist camp, complete with a handful of sleeping huts and a small market [49].

3.4.2. Cultural Heritage and Esthetics

Soils are components of natural, forested, and agricultural lands, and therefore can be considered a part of the natural heritage. For example, making various objects from clay is part of the cultural heritage in Libya and this art is present in mountain cities, such as Gharyan. People typically use a mixture of clay types with a high percentage of kaolinite (found in Cambisols) to create different clay products. The chemical composition of clay makes it possible to mold various pottery products used for home decor, crockery, and many other purposes (Figure 8). People also mix clay with dry straw/hay between two pieces of wood to build houses, especially in the northwestern coastal strip area in the cities, such as Sorman, Zawiya, Souq Al Jumma, and Tajoura. In this process, referred to locally as "Darb Albab", the clay, straw, and/or hay is mixed by a group of people with their feet for several hours before being left to dry to a hardened state. Construction with this material has existed for hundreds of years and resists rain and wind while providing good heat insulation.

Libyan esthetics and culture can be seen in desert oases, by camping in the desert (safari) to enjoy the sand vistas, and/or in cities where museums provide insight and examples of Libyan artistic expression, culture, and history. For example, Libya's National Museum in Tripoli houses a unique collection of Libya's archaeological and historical heritage.

Figure 8. Clay vessels in Gharyan.

3.4.3. Education

Frameworks and concepts associated with soil ecosystem services can be incorporated into existing Libyan soil science education at various levels by developing innovative educational materials that emphasize the human benefits (including monetary) derived from soil ecosystem services. In Libya, soil science education is taught to students at different levels starting from elementary school. At the elementary and the middle school levels, students learn about the benefits provided by soils as the essential environment for plant growth. At the high school level, students learn more specific subjects in soil science, such as soil texture and structure, etc. Beginning at the university level, students learn about soil physics, soil chemistry, soil microbiology, and soil genesis and classification. There are many institutions in Libya that teach various soil science programs, for example: University of Tripoli, Omar Al-Mukhtar University, Sebha University, Al Zawia University, Sirte University, University of Elmergib, University of Al Jabal Al Gharbi, Higher Institute of agricultural techniques (Al-Gheiran, Tripoli).

3.5. Supporting Services

Supporting services are defined as the support of ecosystem function and all other ESs that maintain the conditions for life on earth, such as "soil weathering/soil formation, nutrient cycling, and provisioning of habitat". All of these supporting soil-based ecosystem services are found in all four territories.

3.5.1. Weathering/Soil Formation

Soil formation factors and soil weathering rates in Libya are characterized primarily by its hot, dry climate (e.g., shortage and irregularity of rainfall, hot temperatures, wide range of daily and seasonal temperatures, high wind speeds). Climatic conditions are crucial factors affecting both the form and the physical and chemical weathering rate of the soil parent material. Generally, aridity is the main characteristic of Libyan soils [42]. Aeolian deposits are one of the important processes in the formation of Libyan soils with a sandy texture, which are the most dominant soils in the region. Chemical weathering is confined to those areas having more abundant precipitation. Physical weathering processes are dominant primarily in desert areas or areas receiving limited amounts of rainfall. Most Libyan soils are undeveloped, which is typical of arid regions [37].

3.5.2. Nutrient Cycling: Population Demand for Major and Trace Elements Related to Soil Supply

Current and future challenges in food security, combined with the desire for better land and soil management, dictate the need to examine links between elemental supplies from Libyan soils and the nutritional demands of people. For example, Table 10 shows the yearly replacement costs of potassium (K) for recommended dietary allowances and adequate intakes of the major elements based on the population report [13] for each of the Libyan territories and the capital and major cities [50]. These K replacement costs vary by territory and city with the overall total of over $9,000,000/ year ($1.63 per person per year). Similar calculations can be used for other elements to provide science-based information for administrative-based decision making.

Table 10. The yearly replacement costs of K (based on a moving 5-year average price of U.S. $500 per metric ton of potassium chloride, KCl [27]) using the kg/y values reported in Table 11a the each of the Libyan territories and the capital and major cities.

Territory (Capital) and Major Cities	Population	Area (km^2)	Population Density (people/km^2)	Yearly Replacement Costs ($/y)
Tripoli (Tripoli)	**3,460,358**	**238,749**	**14.5**	**5,659,000**
Tarabulus	1,063,571	1613	628.2	1,740,000
Sawjjin	543,129	56,578	9.6	888,000
Al Jfara	451,175	2412	187.1	738,000
Al Murgub	427,886	8832	48.4	700,000
Al Jabal al Gharbi	302,705	91,040	3.3	495,000
Az Zawiyah	290,637	3454	84.1	475,000
An Nuqat al Khams	287,359	6079	47.3	470,000
Nalut	93,896	68,661	1.4	154,000
Al-Khalij (Sirte)	**421,070**	**840,661**	**0.5**	**689,000**
Al Wahat	179,155	210,291	0.9	293,000
Surt	141,495	49,697	2.8	231,000
Al Jufrah	52,092	122,626	0.4	85,000
Al-Kufrah	48,328	458,047	0.1	79,000
Benghazi (Benghazi)	**1,386,266**	**144,959**	**9.6**	**2,267,000**
Benghazi	674,951	10,558	63.9	1,104,000

Al Jabal al Akhdar	206,180	8450	24.4	337,000
Al Marj	184,531	15,454	11.9	302,000
Darnah	162,857	20,772	7.8	266,000
Al Butnan	157,747	89,725	1.8	258,000
Fezzan (Sabha)	**389,998**	**535,171**	**0.7**	**638,000**
Sabha	133,206	16,327	8.2	218,000
Murzuq	78,772	306,517	0.3	129,000
Wadi Al Shatii	78,563	101,461	0.8	128,000
Wadi Al Hayaa	76,258	33,903	2.2	125,000
Ghat	23,199	76,963	0.3	38,000
Overall total	**5,657,692**	**1,759,540**	**3.2**	**9,253,000**

Note: Yearly replacement costs based on the average price of KCl: ($/y) for K = (Yearly K, kg/y) * (74.55 g KCl/39.1 g K^+) * (1 metric ton/1000 kg) * ($500/1 metric ton KCl).

Many major and trace elements are required by humans in various amounts (mg/day), which can be supplied by soil or other means. There is a need to create an inventory of the Libyan soil nutrient supply and human demands in terms of the ecosystem service supply chain. Tables 11(a) and 11(b) show the yearly recommended dietary allowances and adequate intakes based on the National Institute of Health [50] for major and trace elements by the total population report [13] for each of the Libyan territories and the capital and major cities. Such calculations are necessary to monitor the current Libyan nutrient demand and future tracking of the flows of soil-based ecosystem services within and from outside of Libya. This supply and demand is part of global ecosystem services flows and it is important for global ecosystem system accounting. In the case of Libya, most likely, major elements, such as Ca, Mg, and Na, are in adequate supply in the soil or other mediums (e.g., salt water), but P and K are in short supply.

Table 11a. The yearly recommended dietary allowances and adequate intakes of the major elements based on the population report [13] for each of the Libyan territories and the capital and major cities [50].

Territory (Capital) and Major Cities	Major Elements (kg/y)				
	Ca	P	K	Na	Mg
Tripoli (Tripoli)	**1,263,000**	**884,000**	**5,936,000**	**1,895,000**	**530,000**
Tarabulus	388,000	272,000	1,825,000	582,000	163,000
Sawjjin	198,000	139,000	932,000	297,000	83,000
Al Jfara	165,000	115,000	774,000	247,000	69,000
Al Murgub	156,000	109,000	734,000	234,000	66,000
Al Jabal al Gharbi	110,000	77,000	519,000	166,000	46,000
Az Zawiyah	106,000	74,000	499,000	159,000	45,000
An Nuqat al Khams	105,000	73,000	493,000	157,000	44,000
Nalut	34,000	24,000	161,000	51,000	14,000
Al-Khalij (Sirte)	**154,000**	**108,000**	**722,000**	**231,000**	**65,000**
Al Wahat	65,000	46,000	307,000	98,000	27,000
Surt	52,000	36,000	243,000	77,000	22,000
Al Jufrah	19,000	13,000	89,000	29,000	8000
Al-Kufrah	18,000	12,000	83,000	26,000	7000
Benghazi (Benghazi)	**506,000**	**354,000**	**2,378,000**	**759,000**	**213,000**
Benghazi	246,000	172,000	1,158,000	370,000	103,000
Al Jabal al Akhdar	75,000	53,000	354,000	113,000	32,000
Al Marj	67,000	47,000	317,000	101,000	28,000
Darnah	59,000	42,000	279,000	89,000	25,000
Al Butnan	58,000	40,000	271,000	86,000	24,000

Fezzan (Sabha)	**142,000**	**100,000**	**669,000**	**214,000**	**60,000**
Sabha	49,000	34,000	229,000	73,000	20,000
Murzuq	29,000	20,000	135,000	43,000	12,000
Wadi Al Shatii	29,000	20,000	135,000	43,000	12,000
Wadi Al Hayaa	28,000	19,000	131,000	42,000	12,000
Ghat	8000	6000	40,000	13,000	4000
Overall totals	**2,065,000**	**1,446,000**	**9,706,000**	**3,098,000**	**867,000**

Note: Values for Dietary Reference Intake (DRI in mg/d; from the Food and Nutrition Board, Institute of Medicine, National Academies, 2018) for major elements are: Ca = 1000, P = 700, K = 4700, Na = 1500, and Mg = 420. The yearly recommended dietary allowances and adequate intakes (in kg/y) = DRI (mg/d) * 365 (d/y) * Population [13] / (1 × 10^6 (mg/kg)).

Table 11b. The yearly recommended dietary allowances and adequate intakes of the trace elements based on the population report [13] for each of the Libyan territories and the capital and major cities [50].

Territory (Capital)	Trace Elements (kg/y)								
and Major Cities	**Fe**	**Cl**	**Cu**	**Zu**	**Mn**	**Mo**	**I**	**Cr**	**Se**
Tripoli (Tripoli)	**22,700**	**2,904,000**	**1140**	**13,900**	**2900**	**56.8**	**189**	**44.2**	**69**
Tarabulus	7000	893,000	350	4300	890	17.5	58	13.6	21
Sawjjin	3600	456,000	180	2200	460	8.9	30	6.9	11
Al Jfara	3000	379,000	150	1800	380	7.4	25	5.8	9
Al Murgub	2800	359,000	140	1700	360	7.0	23	5.5	9
Al Jabal al Gharbi	2000	254,000	100	1200	250	5.0	17	3.9	6
Az Zawiyah	1900	244,000	100	1200	240	4.8	16	3.7	6
An Nuqat al Khams	1900	241,000	90	1200	240	4.7	16	3. 7	6
Nalut	600	79,000	30	400	80	1.5	5	1.2	2
Al-Khalij (Sirte)	**2800**	**353,000**	**140**	**1700**	**350**	**6.9**	**23**	**5.4**	**8**
Al Wahat	1200	150,000	60	700	150	2.9	10	2.3	4
Surt	900	119,000	50	600	120	2.3	8	1.8	3
Al Jufrah	300	44,000	20	200	40	0.9	3	0.7	1
Al-Kufrah	300	41,000	20	200	40	0.8	3	0.6	1
Benghazi (Benghazi)	**9100**	**1,164,000**	**460**	**5600**	**1160**	**22.8**	**76**	**17.7**	**28**
Benghazi	4400	567,000	220	2700	570	11.1	37	8.6	14
Al Jabal al Akhdar	1400	173,000	70	800	170	3.4	11	2.6	4
Al Marj	1200	155,000	60	700	150	3.0	10	2.4	4
Darnah	1100	137,000	50	700	140	2. 7	9	2.1	3
Al Butnan	1000	132,000	50	600	130	2.6	9	2.0	3
Fezzan (Sabha)	**2600**	**327,000**	**130**	**1600**	**330**	**6.4**	**21**	**5.0**	**8**
Sabha	900	112,000	40	500	110	2.2	7	1.7	3
Murzuq	500	66,000	30	300	70	1.3	4	1.0	2
Wadi Al Shatii	500	66,000	30	300	70	1.3	4	1.0	2
Wadi Al Hayaa	500	64,000	30	300	60	1.3	4	1.0	2
Ghat	200	19,000	10	100	20	0.4	1	0.3	0
Overall totals	**37,200**	**4,750,000**	**1860**	**22,700**	**4750**	**92.9**	**310**	**72.3**	**114**

Note: Values for Dietary Reference Intake (DRI in mg/d; from the Food and Nutrition Board, Institute of Medicine, National Academies, 2018) for trace elements are: Fe = 18, Cl = 2300, Cu = 0.9, Zn = 11, Mn = 2.3, Mo = 0.045, I = 0.150, Cr = 0.035, and Se = 0.055. The yearly recommended dietary allowances and adequate intakes (in kg/y) = DRI (mg/d) * 365 (d/y) * Population [13]/(1 × 10^6 (mg/kg)).

3.5.3. Provisioning of Habitat

Soil provides habitats for wildlife and insects (Figure 9). Soil fauna and flora are indispensable to plant productivity and the ecological functioning of soils. A variety of insects and other animals are found in Libyan soils, including scorpions, scarab beetles, locusts, earthworms, ants, hedgehogs, gerbils, lizards, and snakes (e.g., serpents, cobras, horned viper, sand snakes, etc.). Although most of these are small animals, the desert monitor lizard can reach up to 1.5 meters long.

Figure 9. Soil as a habitat: ant hill in Al Garabulli, Tripoli.

4. Ecosystem Disservices and Human-Induced Degradation

4.1. Challenges and Potential Solutions for Soil-Based Ecosystem Services in Libya

Generally, ecosystem disservices are defined as "functions of ecosystems that are perceived as negative to human well-being" [51]. Proper management strategies are the key to achieving the UN SDGs and land degradation neutrality [2,52]. There are widespread inherent soil-related disservices (e.g., stone gravel land, sand dunes, barren land, etc.), which are exasperated by human-induced degradation (e.g., climate change, urbanization, pollution, etc.) (Table 12, Table 13, Figure 10). Human impacts on soil resources, together with soil-related disservices, combine to reduce the value of soil ecosystem services.

Table 12. Land cover type areas (km^2) territory based on [13].

Land Cover Type	Tripoli (Tripoli)	Al-Khalij (Sirte)	Benghazi (Benghazi)	Fezzan (Sabha)	Total area (km^2, %)
Irrigated land	3077	1325	392	1301	6095 (0.35)
Rainfed land	8773	543	5557	-	14,873 (0.85)
Stone gravel land	111,516	297,030	58,083	213,994	680,623 (38.68)
Sand dunes	2056	270,039	31,591	143,852	447,538 (25.43)
Barren land	26,424	220,806	14,550	168,181	429,961 (24.44)
Valleys land	6576	5128	646	3121	15,471 (0.88)
Natural forests shrubs	537	50	2768	1	3356 (0.19)
Rangelands	76,133	40,448	29,233	4247	150,061 (8.53)
Salinized land	2567	4924	1832	356	9679 (0.55)
Urban	1090	368	307	118	1883 (0.11)
Overall total	**238,749**	**840,661**	**144,959**	**535,171**	**1,759,540 (100)**

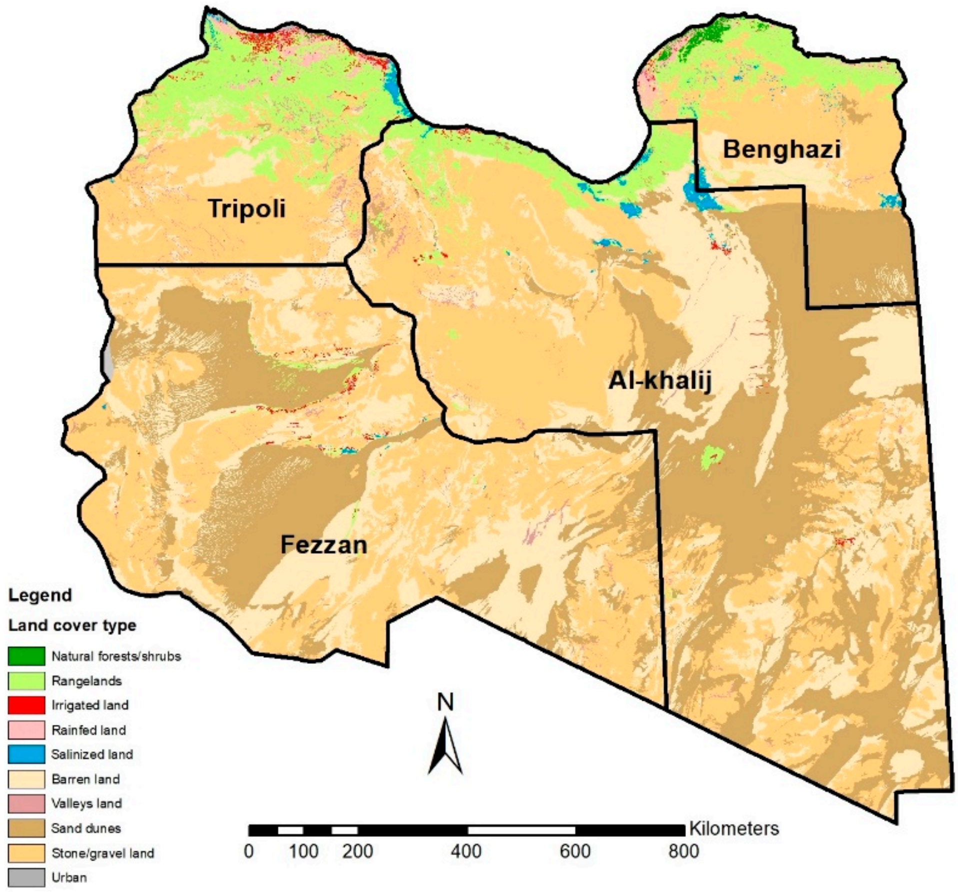


Figure 10. Map of the land cover type by Libyan territories (adapted from [13]).

Table 13. Soil-related disservices and challenges by territories.

Disservices/Challenges	Libyan Territories			
	Tripoli	Al-Khalij	Benghazi	Fezzan
Land degradation and desertification	+	+	+	+
Salinization	+	+	+	+
Pollution	+	+	+	+
Food security	+	+	+	+
Climate change				
- Temperature increase	+	+	+	+
- Extreme events	+	+	+	+
- Precipitation	+	+	+	+
- Sea rise	+	+	+	-

Note: + indicates that ecosystem disservice is present; - indicates that ecosystem disservice is absent.

4.2. Land Degradation and Desertification

Libya has a severe problem of land degradation and desertification with the highest percentages (43.7%) of degradation in the world [53,54] (Table 14). Deserts or semi-deserts cover 95% of the Libyan land surface [16]. Rapid urbanization along with the loss of fertile soil, over-exploitation of water resources, and overgrazing and the destruction of natural vegetation are the main causes of the environmental problems in the region [32].

In the southern portion of the country, people are concentrated in oases and on land irrigated to produce dates, other palms, fodder, and vegetables (Al-kufrah Oasis group) (Figure 11). Because only

Table 14. The total terrestrial ecosystem services value (ESV) for Libya before and after land degradation (adapted from [54]).

Population (2015)	Land Area (km^2)	ESV Non-degraded (US $/yr)	ESV Degraded (US $/yr)	Degradation (%)
6,317,000	1,626,966	7,470,804,809	4,209,316,004	43.7

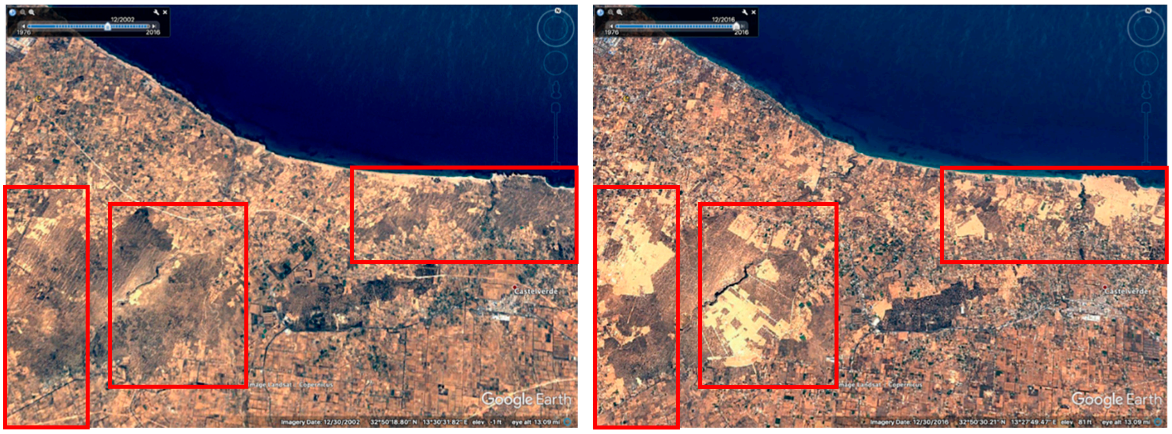
Note: ESV terrestrial: the total ecosystem services value before land degradation. ESV degraded: the total ecosystem services value after land degradation (% of potential net primary productivity, NPP) is incorporated into the estimate. Degradation (%): percent reduction in ecosystem services value between ESV terrestrial and ESV degraded.

about 2% of the Libyan land surface receives enough rainfall to be cultivated, the government established one of the largest inland agricultural areas located in the Al-kufrah Oasis group at the beginning of the 1970s (Figure 11a). The dark circles in Figure 11a indicate tracts of agriculture supported by center-pivot irrigation. This project existed because of groundwater from the Nubian Sandstone Aquifer System with the aquifer's reserves estimated at 375,000 km^3 of groundwater. This Al-kufrah Oasis group project was abandoned after 2016, and Figure 11b shows Saharan sands covering the irrigated agricultural fields.

(a) (b)

Figure 11. Irrigated agricultural fields in the Al-kufrah Oasis group: (**a**) before December 2012, (**b**) after December 2016 [55].

Forest cover in Libya amounts to approximately 400,000 ha, and other wooded land coverage is about 446,000 ha [56]. There are no forests maintained for commercial purposes in the country. The presence of natural forest is mainly in the Al-Jabal Al-Akhdar, the northeast region, Benghazi; this region is characterized by forests tree species, such as juniper (*Juniperus* spp.) and mastic (*Pistacia* spp.). In the northwestern part (Jabal Nafusah plateau), some shrublands can be found with predominant species of non-woody shrubs, such as asphodel (*Asphodeline* spp.) and wild pistachio [56]. Deforestation is also a factor inducing soil erosion (Figure 12), and increased number of animals, which rely on imported animal feed [53]. The primary cause of deforestation and natural pastures in Libya is due to the rapid urbanization process and wood extraction for charcoal.



(a) (b)

Figure 12. Deforestation in the northwestern coastal areas stretching from Tajoura to Misurata (northeast Tripoli): **a**) before December 2012, **b**) after December 2016 [57].

The high rate of urbanization has led to over 25% of the highly fertile lands being converted to urban areas [32]. The desertification processes have been triggered by climatic conditions coupled with human activities (Figure 13a). As a result, aridity is the common characteristic in most of the Libyan regions, where more than 90% of the country is extremely arid (Table 15). Soil degradation in Libya is typical for Africa, where an estimated 65% of agricultural land experienced topsoil loss and soil nutrients [58]. Erosion occurs mainly due to wind erosion, inappropriate soil use, such as intensive agricultural activities, and uncontrolled water runoff from sealed surfaces.

(a) (b)

Figure 13. (**a**) Desertification in Al Fajij, Fezzan, and (**b**) salinization in Toyoh, Fezzan (photos courtesy: Abdalla Adda).

Table 15. The aridity zones of Libya per area [59].

Aridity Zones	**Average Yearly Rainfall**	**Area (thousands of km²)**	**Total Area (%)**
Extremely arid	Less than 50	1,589.00	90.80
Arid	50–200	130.00	7.40
Semi-arid	200–400	26.00	1.50
Dry sub-humid	More than 400	5.00	0.30
Total		1750.00	100.00

Educating people who live in rural areas is one of the most important ways to protect forested land. Desertification can be controlled by limiting land misuse and exploitation of resources beyond the carrying capacity [53].

4.3. Salinity

Salinization is the primary type of soil degradation in the region [37]. The distribution of salt-affected soils in Libya varies, which can reduce the value and productivity of the affected land [42,60]. Seawater intrusion has led to a high percentage of salts in some irrigation water, which in turn has led to the deterioration of fertility and low productivity of soil. Most coastal areas are at risk due to seawater intrusion, resulting in salinity problems, and caused by subsequent irrigation through local wells. Several studies related to soil salinity assessment and mapping have been conducted in Libya using different methods [42,61–63]. Results from these studies have revealed that most coastal areas are affected by salinity. Also, the presence of closed depressions covered by evaporite deposits known as Sabkhas has also been identified (Figure 13b).

There are various techniques used to track and monitor these environmental disturbances. Remote sensing analysis has the advantage of observing and monitoring earth surface changes because of the large spatial coverage, high time resolution, and wide availability. New geospatial technology, such as Google Earth Engine, can be used to continuously monitor environmental disturbance (e.g., desertification, salinization, deforestation, agricultural production, land use changes, etc.) and may provide management strategies to mitigate the environmental consequences of these disturbances [64–66].

4.4. Pollution

Pollution of the terrestrial ecosystem is a serious environmental problem worldwide. Disposal of industrial waste in the environment is the main source of soil pollution through many different toxic elements and compounds. Soil can become contaminated with the accumulation of heavy metals near industrial zones, mining waste, disposal of high mineral waste, leaded gasoline and paints, land use for fertilizers, animal manure, sewage sludge, pesticides, and sewage disposal [67]. A recent study [68] revealed that Abu-Kammash (Libya) is contaminated with several toxic elements and petrochemical compounds, and that the soil should be not be used for agriculture until it is remediated to ensure human health. In Zliten, an area around a cement factory, the soil physicochemical characteristics (pH, water content, and organic matter) indicate a strong influence of cement dust that has settled on the soil from the factory [69].

Inappropriate disposal of petrochemical compounds into the environment poses significant risks to human health. These compounds often have high toxicities and carcinogenic properties, and can be ingested by people who consume contaminated foods [70]. The issue of soils contaminated with petroleum products is one of the most complex tasks in the field of environmental protection in terms of financial and regulatory aspects [71]. There are various remediation techniques available to decontaminate soil [72,73].

4.5. Food Security

In Libya, food demand is expected to increase significantly in the upcoming decades due to rapid population growth, expected to be nearly 1% annually. Libya imports approximately 80% of its total food [30,74]. There are many ways in which food security can be enhanced, such as improving efficiency in the agricultural sector. The most productive agricultural lands in Libya are limited to a strip along the Mediterranean Sea, where most of the rain falls. The high coastal plateau of Jebel Al-Akhdar in the Northeast and the fertile coastal plain in the Northwest are the two major areas of natural farmland, although irrigation is still vital. Agriculture contributed about 2% to the gross domestic product of Libya in 2008 and 2010 [74]. The current situation in Libya has led to a deterioration in food security due to the destruction of public infrastructure, and the lack of employment resulting from the massive exodus of foreign workers, which had been largely engaged in agricultural activities [30].

4.6. Climate Change

Climate change presents a major challenge for developing countries that lack adequate resources. Climate change will lead to severe weather events for Libya, affecting both the intensity and frequency of extreme temperature, precipitation, rainfall, and drought. The global mean temperature has increased gradually by 0.74 ± 0.18 °C during the 100 years from 1906 to 2005, and can be expected to reach an increase up to 1.5 to 2.0 °C by the year 2100 [75]. These increases are leading to global sea levels rising [76]. United States National Oceanic and Atmospheric Administration scientists project that sea levels could rise by 0.5 m by 2050 [77]. Figure 14 shows coastal areas in Libya potentially affected by this sea level rise with projections of 1, 3, and 6 m, which will result in losses of land area equaling 700, 3200, and 7200 km^2, respectively. Cities predicted to be affected by sea level rises of 1 m are those near the sea, such as Zuwara, Misurata, Ras Lanuf, Al Uqahlah, Al Brega, and Az-Zuwaytinah.

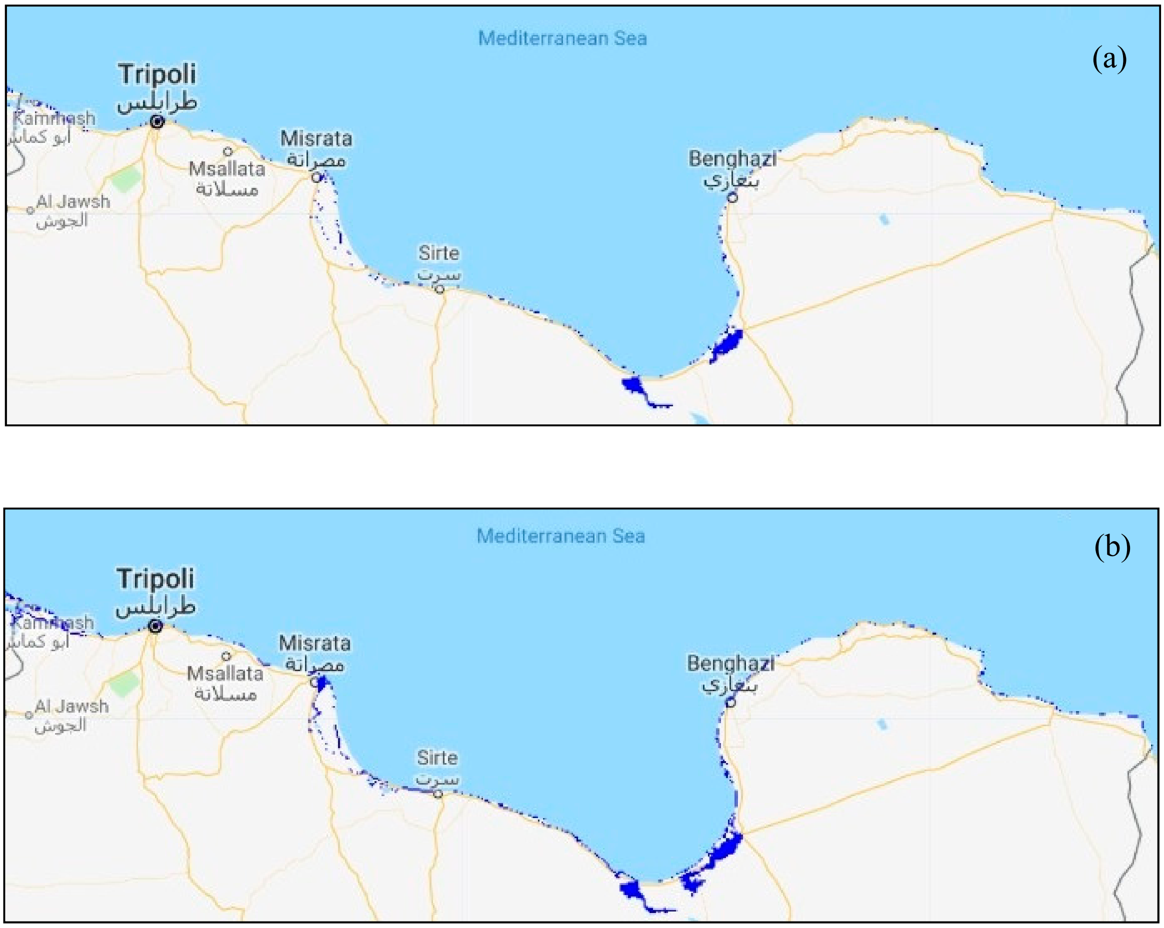


Figure 14. Projections of the future sea rise due to climate change along the Mediterranean Sea coast of Libya: (**a**) 1 m sea rise (affected area: 700 km^2), (**b**) 3 m sea rise (affected area: 3200 km^2), (**c**) 6 m sea rise (affected area: 7200 km^2).

Climatic conditions in Libya are influenced by the Mediterranean Sea and the Sahara Desert. Climate factors contribute to desertification and water scarcity, and global warming undoubtedly exacerbates these problems [53]. Decreasing water levels and water pollution in some coastal aquifers have reached alarming values in the North African countries of Egypt, Libya, Tunisia, Algeria, and Morocco and have intensified problems with seawater intrusion [78]. Extensive agricultural activities in areas near the coast, coupled with the increased use of irrigation with overdrawn supplies of fresh groundwater and increasing population, has caused extensive seawater intrusion problems. Salinity affected cropping systems and led to a significant reduction in crop yield. For example, soil salinity in the Jafara plain in Libya has reduced wheat yields from 5 tons/ha (1980s) to 0.5 tons/ha (1987) [32]. Most farms in the Jafara Plain are irrigated by individual wells using electric pumps, and these farms have been severely affected by seawater intrusion into the aquifer, particularly orange farm operations.

5. Discussion

This review article has proposed the integration of soil-based ESs for Libya with market and non-market institutions (Figure 3). Figure 15 provides several examples of soil-based ESs using goods and services that already exist in Libya. The yellow color symbolizes the pedosphere (e.g., soils of Libya) while the orange color is used for market institutions (e.g., private goods, toll goods) and the green color is used for non-market institutions (e.g., common pool resources, public goods). This ES framework provides an example that could be used to integrate soil management and conservation while encouraging economic activity.

Soil provisioning ESs are limited due to the low availability of fresh water, fertile lands, environmental conditions (e.g., desertification, salinization, deforestation), and continuous demand due to population growth. Libyan soils support agricultural production of selected fruits, vegetables, whole grains, and proteins, which could contribute to the Healthy Eating Plate. The Healthy Eating Plate can be used to organize more efficient food distribution and allocation among the population. Currently, the country relies on imported food. Seawater intrusion due to sea rise and decreases in water levels in coastal aquifers has resulted in high concentrations of salts in irrigation waters, which may then lead to low soil productivity. Future environmental changes (e.g., climate change, etc.) may disrupt the availability of these produce items related to the Eating Plate for Libya.

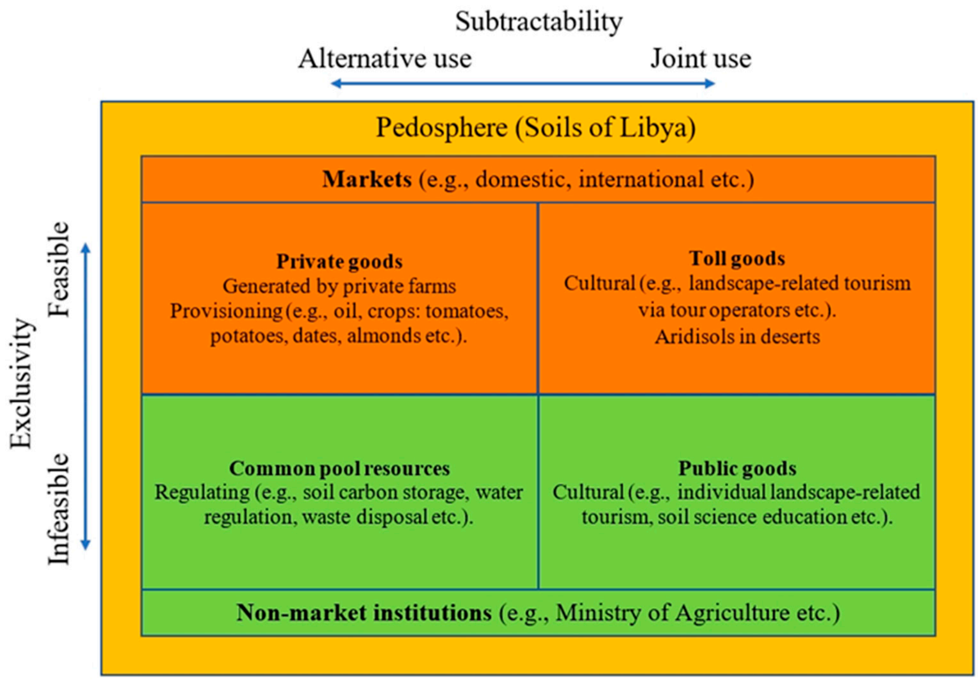


Figure 15. Examples of activities and ecosystem services derived from Libyan soil resources (modified from [79]).

Possible solutions to these challenges of improving nutritional supplies in Libya include: integrated farming systems, non-soil-based agricultural production (e.g., hydroponics), and alternative farming practices. Environmental disturbances/degradation can be visualized and documented using freely-available geospatial technology, such as Google Earth Engine, to monitor the extent of desertification, salinization, deforestation, agricultural production, land use changes, etc.

Soil regulating services are linked to SOC and SIC distribution in Libyan soils. There is a need to create maps of the quantities and distributions of SOC so that carbon sequestration can be monitored in Libyan soils. This article, for example, calculated and mapped the SIC distribution in Libya. Total SIC storage for the country is estimated at 5.83 E + 10 metric tons with a total value of 4.6657 E + 12 U.S. dollars and an average per m^2 of $2.65 (total and area based on $80 per ton of SIC).

Water regulation in soils is limited by the climate, and the water sources used predominantly for agriculture in Libya are from non-renewable resources. Libya is at the intersection between the Mediterranean and North Africa climates, and therefore it is highly susceptible to climatic changes. Coastal areas along the Mediterranean Sea are the regions most likely to be affected by climatic changes, including the expectation of temperatures that will be significantly higher in the future. The increase of hot temperatures and evaporation losses will lead to an increase in the land areas affected by salinity in the country. Practical solutions to these challenges might include: use of stress tolerant crop varieties; employment of appropriate water treatment and economical solutions for the limited water resources; adoption of sustainable agricultural practices (e.g., vegetation succession, grazing management to improve soil carbon sequestration; and provision of better solid waste management services).

Soil ecosystem services based on desert landscapes form a special part of Libya's natural and cultural heritage, and they support tourism, which contributes nearly 2% to the national gross domestic product (GDP) [80]. Various objects made from soil clay are an important part of Libyan cultural heritage. Soil provides the opportunity for soil science education, which is a cultural benefit. Climate change, desertification, and land degradation can disrupt cultural services (e.g., ecotourism and soil-based cultural object creation) provided by the soils. Possible solutions include better mapping and forecasting of these potentially disruptive events.

Soils supporting ESs are limited due to the Libyan soils, which are slightly or moderately weathered (very shallow, coarse, low in organic matter content, low water holding capacity). Thus, soil nutrients are present, but may be limited in these soils. Further research is needed to understand soil nutrient content and availability.

6. Conclusions

This review article examined the usability of Libyan soil databases for ESs in order to achieve the UN SDGs. An existing market-based framework for soil ESs was utilized at various scales with specific examples for provisioning and regulating ESs. This approach may be beneficial in selecting the most efficient solutions to numerous challenges facing Libya (e.g., population, environmental changes etc.). The link between soil resources in Libya and four main interconnected components, provisioning, regulating, cultural, and supporting ESs, were described. In addition to ESs, this study illustrates the challenges (human-induced degradation and disservices) which need to be addressed to improve the availability of services to support human needs.

Yearly recommended dietary allowances and adequate intakes for major and trace elements by total population were calculated for the country, each territory, capital, and major cities to understand the overall potential elemental demand from the soil if all food could be grown in Libyan soils. For example, for potassium (K), which is one of the most limiting nutrients worldwide the average yearly replacement costs for the Libyan population that would be required if not present in the soil is over 9 million U.S. dollars per year ($1.63 per person per year). Practical solutions to this challenge include: mapping the supply and demand for elements necessary for human well-being; implementing best soil management practices; and employing precision agriculture.

Integration of soil-based ESs for Libya with market and non-market institutions may benefit the welfare of the country and lead to more efficient use of limited soil resources, and innovative applications. From a soil expert based approach, relying on existing soil spatial databases provides unique insight into a range of types of ESs through the use of specific examples for regulating and supporting ESs.

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