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Article

Soil Types and Degradation Pathways in Saudi Arabia: A Geospatial Approach for Sustainable Land Management

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Abstract

Land degradation (LD) is a dominant threat of the decade, which is deteriorating arable lands globally. Therefore, this intensification of LD has stimulated global governing bodies and researchers to take the initiative against this dilemma through sustainable and eco-friendly approaches. Geographical mapping is critical for analyzing land formation, its types, and uses; data-based maps provide a detailed overview of land use. In this study, we have created simplified SRTM-based maps for Saudi Arabia related to soil types, soil thickness, and soil uses either as vegetation or for agricultural aspects using GIS tools. Results of these GIS analyses showed that the maximum area of the country is sandy, followed by loam and sandy loam. Meanwhile, the maximum soil thickness is either under 0-4 meters or 43-50 meters. This geological display of the country could be instrumental in assessing the soil types and what sort of inputs or steps can be taken to make each type of soil fertile. Moreover, we also mentioned the land degradation pathways impacting the country's arable lands and explained the pathways that can help assess such land losses. Besides land loss pathways, we explained the most suitable mitigation strategies, including mulching, cover cropping, agroforestry, riparian buffer strips, agroforestry, terracing, and nutrient use efficiency. In this article, we also focused on the aims of the Saudi Green Initiative and the steps that are being taken by international governing bodies like UNDP, UNEP, FAO, and the World Bank to mitigate land degradation in the region. However, further studies are required to assess the intensity of these solutions at each soil type and thickness.

Keywords: Saudi Arabia; geomorphology; GIS; land degradation; degraded land restoration

1. Introduction

Saudi Arabia is the most developing region of the Arabian Peninsula and is the second-largest producer and exporter of oil (AlGhamdi, 2020). Besides the industrial revolution, this region is also struggling with the crisis of arable land, soil fertility, and availability of water resources both for agriculture and public use (Alotaibi et al., 2023). Global warming, variable rainfall patterns, and frequent prevalence of drought stress are further damaging the agricultural sector of the country, where small-scale farmers or family farmers facing challenging situations of water scarcity and the rise of insect pest attacks on their crops (Miyan, 2015; Giordano et al., 2019). Therefore, the negligence of governing bodies towards these issues may cause a significant impact on national agricultural productivity along with food and nutritional insecurity. According to FAO guidelines, 0.21 ha per person is suitable for domestic farming; however, in Saudi Arabia, this land limit is even lower than 0.010 ha per person (Ibrahim et al., 2012). Therefore, the agriculture sector is only contributing up to 2.71% of the gross domestic product (GDP) of Saudi Arabia (Ghabban, 2024).

Besides natural factors, certain anthropogenic activities are deteriorating soil health, for instance, deforestation, agro-chemicals, inappropriate tillage practices, overgrazing, and poor quality of irrigation water (Shahane and Shivay, 2021; Bulut and Gökalp, 2022; Kibret et al., 2023). Additionally,

soil degradation also occurs through the oil extraction processes where toxic chemicals and heavy metals are incorporated into the soil, which results in poor soil quality, low nutrient content, and ultimately resulted in lower crop growth (Manzoor et al., 2020; Shahane and Shivay, 2021). Moreover, the region's soil is lower in organic matter, around 0.2% and anthropogenic and natural activities roughly influence it (Ghandour and Aljahdali, 2021). Aridisols, arenosols, and aerisols soil orders of Saudi Arabia are also the primary components of soil loss and its degradation, as these orders carry poor nutrient values and organic matter (Al-Ghamdi et al., 2021). Under arid and semi-arid regions, soil sublayers usually hold a significant accumulation of gypsum, salt, and sodium, which causes soil salinity and hinders nutrient movement (Osman and Osman, 2018; Naorem et al., 2023). Furthermore, the soil of arid regions is coarse in texture and has a low porosity rate, which decreases soil water use efficiency, water holding capacity, and water retention property (Dlapa et al., 2020; Wang et al., 2022).

Remote sensing and GIS are the trending and viable tools that can be used to assess geological and morphological changes in the soil and environment (Jasmin & Mallikarjuna, 2011; Kumar et al., 2016). Therefore, land degradation and its sources can be easily monitored through GIS and remote sensing after extracting and modeling of relevant data (Reddy et al., 2018; AbdelRahman, 2023). Various studies have been conducted to examine soil health through these GIS tools; for instance (Akhavan et al., 2023) examined the soil vegetation cover of Iran and ran the produced findings on the Normalized Difference Vegetation Index (NDVI) to predict land degradation. Similarly, (Reddy et al., 2018) GIS and NDVI modeling were also used to investigate global soil biological changes and land degradation patterns. Moreover, they followed NDVI and net primary production (NPP) mechanisms to observe rain use efficiency and specify which specific areas are most vulnerable to land degradation. Therefore, this study was planned to examine the characteristics of Saudi Arabian soil using systematic methodology, the latest geospatial data, and advanced GIS tools. We also explored potential threats to the country's arable lands and how these affected lands can be recovered through sustainable approaches.

2. Geography of Saudi Arabia

Saudi Arabia is the largest country in the Arabian Peninsula, located in West Asia, and occupies a substantial portion of the northern and central regions. It shares borders with the Red Sea and the Persian Gulf. Saudi Arabia is the largest country in the Gulf, with a total territory of around 2.3 million km² and a population of more than 28 million (Tlili, 2015). Most of the country's land is arid, with vast stretches of desert, such as the world's largest continuous sand desert, Rub al Khali (Jafari et al., 2018). Saudi Arabia has a diverse topography, mainly comprising large desert regions like the Arabian Desert, with semi-deserts, shrublands, and steppes scattered throughout. Its significant geological heterogeneity is further highlighted by the topography, which consists of numerous mountain ranges and vast volcanic lava fields. The Asir Mountains in the southwest and the Hijaz range near the western coast are notable mountainous areas (Saleh & Elzahrany, 2009). Saudi Arabia is comprised of around 2,150,000 square kilometers, or 830,000 square miles (Alamri, 2018), and its weather is primarily arid, with days reaching very high temperatures and nights drastically dropping. Three climatic zones are found: a steppe environment in the western highlands, a semi-arid climate in the southwest, and widespread desert conditions. Winters are usually warm, but summers may be pretty hot, especially in the interior desert regions where temperatures frequently rise above 50°C (122°F) (Abdou, 2014). Because of their elevation, the western highlands experience a temperate temperature, contrasting with the region's more arid environment. Because of the influence of surrounding large bodies of water, temperatures are moderated in coastal areas. The distinct environmental and biological profile of Saudi Arabia is a result of the combined effects of several geological and climatic elements (Houghton, 1986; Houghton, 2001; Solomon, 2007). Cyclonic weather systems move eastward from the Mediterranean Sea throughout the winter and usually pass north of the Arabian Peninsula, occasionally causing landfall in eastern and central Arabia and the Persian Gulf. Specific wind systems follow the Red Sea by the south, delivering winter precipitation as far south as Mecca and sometimes even Yemen (Abdou, 2014). Usually, torrential precipitation

falls in March and April. Monsoonal winds provide the Asir highlands with sufficient summer precipitation to sustain a steppe-like ecosystem. The cold, wintry months of December to February may bring snow and frost to the southern highlands. December to February are the coolest months, with average temperatures of 23°C in Jeddah, 14°C in Riyadh, and 17°C in Al-Dammām. Summers are hot, lasting from June to August, with daily highs in most countries reaching 38°C. Summertime temperatures in the desert can reach up to 55°C (Change, 2013; Almazroui, 2020a). Generally, humidity is low except along the coast. Overall, precipitation is low throughout the country, although there are certain variations also. In the Asir highlands, summer monsoons cause more than 480 mm of rainfall annually, which primarily falls between May and October. Decades can pass in the Rub' al Khali without precipitation (Mashat & Basset, 2011; Abdullah et al., 2019). Except in the southwest, where semi-arid weather prevails, most of Saudi Arabia's climate is predominantly desert. Summers in the central regions are hot and dry, with highs of 27°C to 43°C inland and 27°C to 38°C at the shore. In the winter, the Red Sea shore experiences 19°C to 29°C, and the inland temperatures range from 8°C to 20°C. Most places receive less than 150 mm of rain annually, except the southwest, which receives 400 to 600 mm (Almazroui et al., 2012). Asir province and its neighboring towns, Jizan and Najran, experience intense heat during the day, a sharp drop in temperature at night, and intermittent rainfall, which is a deviation from the typical desert environment. Because they are close to vast bodies of water, coastal locations experience tempered temperatures. High relative humidity levels can reach over 85%, resulting in warm fog at night and steamy mist during the day. Temperatures rarely get beyond 38°C. Coastal areas are bearable in the summer and pleasant in the winter due to the predominance of north winds; in contrast, a southerly wind raises temperatures and humidity, resulting in storms known as Kauf in the local language. The northwesterly shamal wind brings Sandstorms and dust storms in late spring and early summer, particularly in eastern Saudi Arabia. Najd, Al Qasim Province, and the main deserts have a consistent climate with summers that average around 45°C and winters that hardly ever get below 0°C. The Indian Ocean monsoon, which lasts from October to March, adds up to 300 mm of yearly precipitation to Asir. In other places, there is little to no consistent rainfall; rain is just brief, intense downpours the whole year. Although certain areas can experience years without rain, the average annual rainfall is 100 mm. It can result in drought conditions that can negatively affect agriculture and livestock (Almazroui et al., 2012; Mahmoud et al., 2018).

Rainfall and temperature are two of the most critical climate variables in Saudi Arabia since they affect agriculture and water replenishment. Droughts in the area have been made worse by population growth, industrial development, and greater agricultural use (Ragab and Prudhomme, 2000; Şen et al., 2013). Forecasting and modeling are challenged by changes in the climate on a variety of temporal and spatial scales (Lioubimtseva, 2004). Saudi Arabia typically has hot, dry summers and moderate, rainy winters with a wide range of rainfall (Almazroui, 2011b, 2012a) Since the late 1990s, the Arabian Peninsula has experienced rising temperatures (Almazroui, 2012b). Numerous studies (Nasrallah and Balling, 1996; Elagib and Abdu, 2010; Rehman, 2010) have documented temperature increases over time. Studies on rainfall show seasonal and regional variations, and predictions indicate that by 2050, there will be more extremes in both temperature and precipitation (Kotwicki and Al Sulaimani, 2009; Almazroui et al., 2012; Almazroui et al., 2014). Rainfall patterns in the southwestern region, which is influenced by mountain ranges and monsoonal winds, show substantial annual variations and are necessary for understanding the future climate of Saudi Arabia (Almazroui, 2011a; Almazroui et al., 2012; Furl et al., 2014).

Saudi Arabia is significantly impacted by severe flash floods and droughts, with the latter having worse effects recently (Barlow et al., 2016; Almazroui and Islam, 2019). Severe flooding has increased in Saudi Arabia within the last ten years, especially in the country's north, east, and southwest. It is fair to conclude that global warming is the cause of these increasingly frequent extreme rainfall occurrences as simulated by climate models (Myhre et al., 2019; Almazroui, 2020b).

2.1. GIS Mapping of Country's Arable Lands

We collected data on different parameters of soil types and their uses, and then each dataset was treated and processed independently. There would be an implication regarding the accuracy and/or the certainty of the results due to the spatial resolution variations between some of the data. This is a data availability issue as we deal with a regional scale. Moreover, the data interpretation was based on direct visualization and some of the statistical aspects of the feature, such as area/extent and thickness. The integration between different datasets was done using the ArcGIS software. ArcGIS software has a variety of elements of map design. Different kinds of colors and effects tools (i.e., transparency, lighting, and shading) were used to obtain a readable map that can express the aim of the study. Therefore, the resulting maps offer a detailed and visually appealing representation of soil types, soil thickness, vegetation, and cultivated areas in Saudi Arabia, providing valuable land management and planning insights.

We visualized the soil type data in Saudi Arabia after extracting the data from the World Soil Database and Harmonized World Soil Database (HWSD) through the FAO's Soils Portal. Due to the complexity of the dataset, we clipped the dataset to focus on our area of interest, i.e., Saudi Arabia, by using ArcGIS. Soil mapping units were extracted and classified based on their textural composition (sand, silt, and clay) into five soil types: sand, loam, loamy sand, and sandy loam, and then the final soil type map provides a detailed view of the soil distribution across the region (Figure 1).

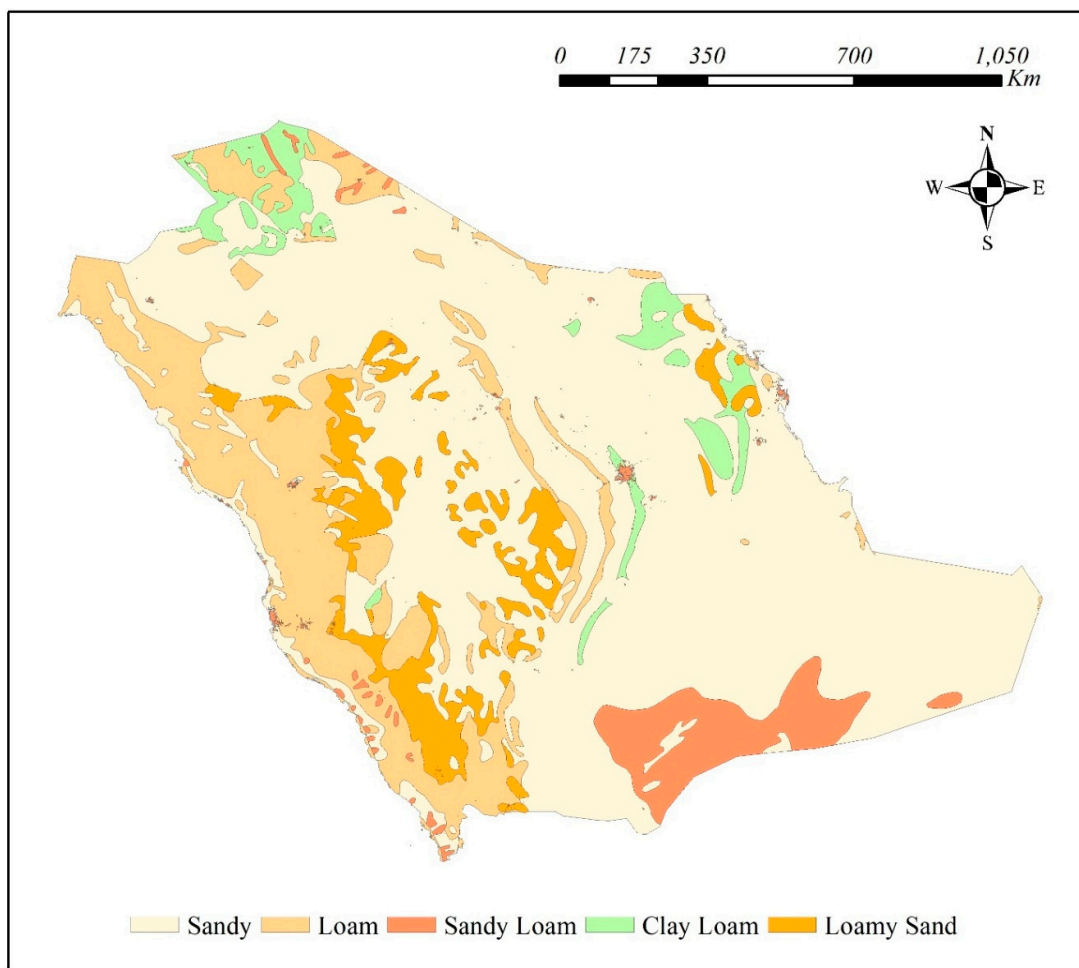


Figure 1. Soil types of Saudi Arabia.

Meanwhile, soil thickness data was sourced from NASA's Oak Ridge National Laboratory Distributed Active Archive Centre, with a resolution of 1 kilometer. The data for Saudi Arabia was clipped using the Extract by Mask tool in ArcGIS. We classified the soil thickness into six categories, ranging from 0 to 50 meters, to illustrate the variations in soil thickness (Figure 2). Moreover, the vegetation and cultivated area data were obtained from the latest Land Use/Land Cover (LULC) dataset, including vegetation, cultivated area, built-up, and bare land. We isolated the vegetation and cultivated area classes using the Con tool from the Spatial Analyst toolbox. We calculated the areas using the Calculate Geometry tool in ArcGIS and validated the data with formulas in Excel. The results were also validated with NDVI, and a color ramp was applied to differentiate between vegetation and cultivated areas to produce a clear and informative map.

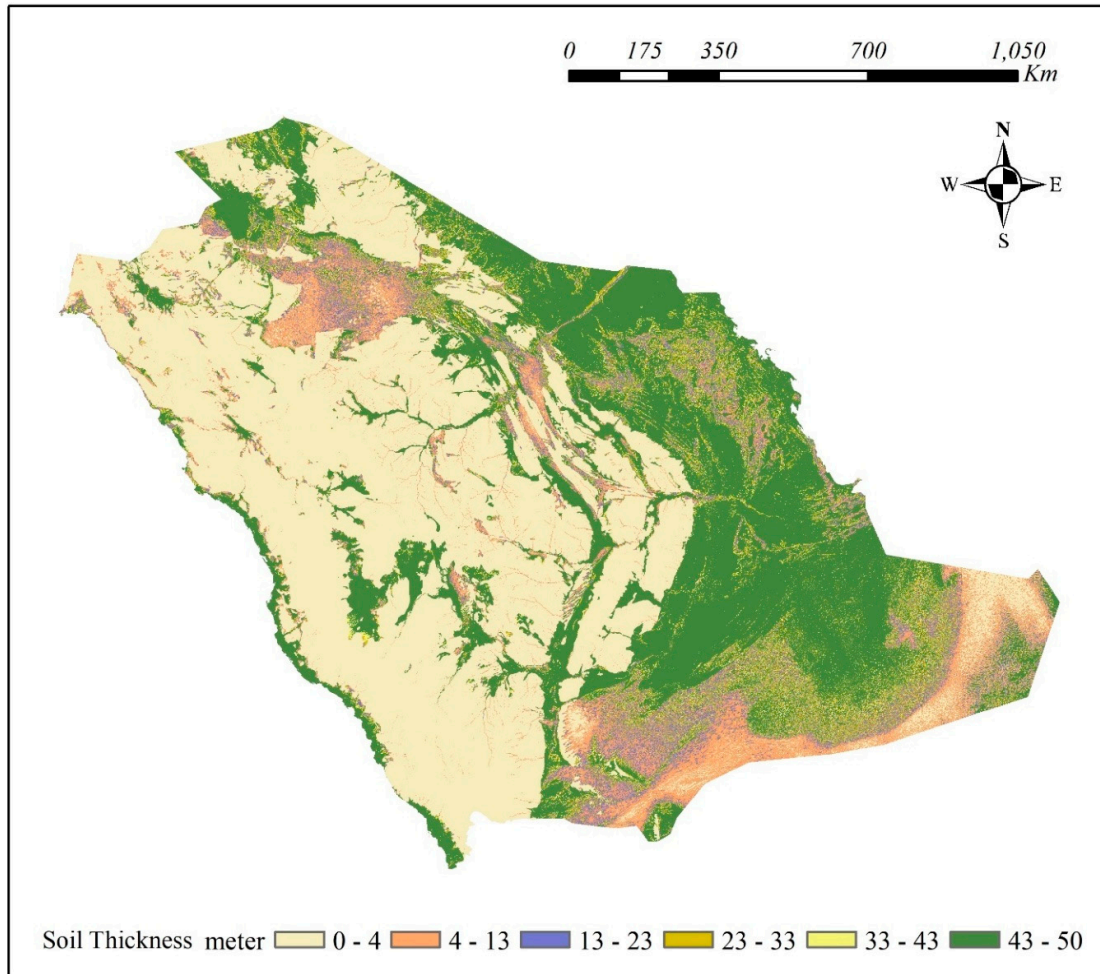


Figure 2. A general display of soil thickness in meters.

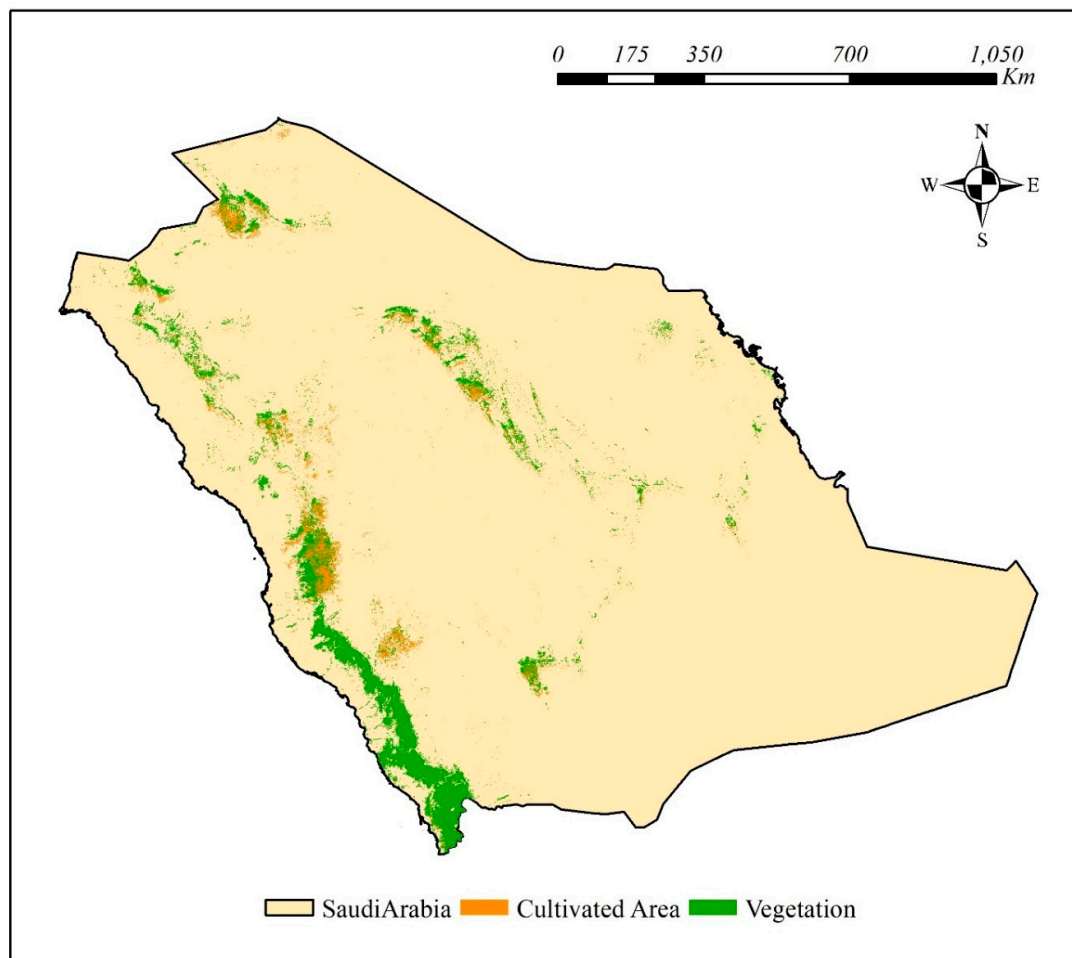


Figure 3. Map showing the cultivated and natural vegetation zone of the country.

2.2. Land of Saudi Arabia

A large portion of the Arabian Peninsula, around four-fifths, comprises the desert country of Saudi Arabia. It is made up of 98.5% semi-arid to arid land. Saudi Arabia's total area is 214,969,000 ha, out of which arable land is only 3,650,000 ha; permanent crops are 90,000 ha; permanent pastures are 120,000,000 ha; forest and woodlands are 1,800,000 ha; and others are 89,429,000 ha (Amin, 2004). Saudi Arabia has 0.11 hectares of arable land per person, among the world's lowest. Cultivable land makes up about 1.6% of the country's total area. Saudi Arabia is categorized as a "water-stressed" country, and severe water scarcity is anticipated by 2050. The country's non-replenish aquifers were rapidly depleted because of unsustainable agricultural practices. In order to address the issues of food insecurity, this circumstance necessitates a change in farming methods. Saudi Arabia must use precision agriculture to increase its agricultural output and guarantee food security (Elbashir, 2024). Saudi Arabia has a total of 13 provinces: Makkah (153,128 Km²), Al Bahah (9,921 Km²), Al-Qaseem (58,046 Km²), Ha'il (103,887 Km²), and Al-Jouf (100,212 Km²), Tabouk (146,072 Km²) and Al-Madina (151,990 Km²), Eastern region province (672,522 Km²), Northern Border province (111,797 Km²) and Riyadh (404,240 Km²), Najran (149,511 Km²) and Aseer (76,693 Km²). Saudi Arabian land is divided into cultivated areas, natural vegetation, hills/mountains, and plains. The total cultivated area of Saudi Arabia is only 26486 Km². Makkah, Al Bahah Al-Qaseem, Hail, and Al-Jouf have cultivated areas; Tabuk and Al-Madina have very few cultivated areas; the Eastern region, Northern Border, and Riyadh only have negligible cultivated areas; and Najran, Aseer, and Jizan totally have no cultivation. The area covered with natural vegetation is 54938 Km². Al-Jouf, Tabuk, Al-Madina,

Makkah, Al Bahah, Aseer, and Jazan have more natural vegetation than other provinces; Ar-Riyadh, Al-Qaseem, and Hail have very little vegetation; the Eastern region and Northern Border are sparsely covered with vegetation, and Najran has no vegetation. On the other hand, hilly areas of Saudi Arabia spread over an area of 387215.88 Km², and plain land has an area of 1548863.52 Km². Total Area of Saudi Arabian land is 1936079.4 Km² which is divided into five soil types: Clay Loam has an area of 72496.4 Km² (3.74%); Loam spread over an area of 351552 Km² (18.16%); Loamy Sand 138988 Km² (7.18%); Sand 1270860 Km² (65.64%); Sandy Loam 102183 Km² (5.28%). The most prevalent and major soil type in Saudi Arabia is sandy soil; it has spread in the areas of Tabuk, Makkah, Najran, Eastern region province, Riyadh, Qaseem, Hail, Northern Border, and Jawf. Sandy loam soil is mainly present in Najran but also in some areas of the Northern Border, Jizan, and Riyadh. Loamy Sand soil is present mostly in areas of Riyadh, Qaseem, Al-Madina, and Makkah, but in the case of Najran and Eastern region province, it is present only in some regions. Loam soil is found in the Northern Border, Jawf, Tabuk, Al-Madina, Makkah, Aseer, Riyadh, Qaseem, and Jawf. Clay loam soil is not that prevalent in Saudi Arabia; it is present in Jawf, the Northern Border, the Eastern region province, Riyadh, and a little bit in Makkah. The evidence suggests that most of Saudi Arabia's land is sandy, which presents difficulties for conventional agriculture. Nonetheless, substantial areas with clay loam and loam soil types are more suited for farming. Clay, silt, and sand are evenly distributed in the clay loam soils—their capacity to hold on to moisture and nutrients benefits agriculture. Loam is considered perfect for farming because it contains an even distribution of clay, silt, and sand. This soil holds moisture well, is easy to deal with, and is fertile. Loamy sand soils consist mostly of sand, with trace amounts of silt and clay. Although these soils drain easily, more organic matter could be needed to improve fertility. Sandy soils are less suitable for farming without substantial amendments to improve water retention and nutrient levels because they have big particles and drain quickly. Sandy loam soils comprise sand, silt, and a small amount of clay. It is appropriate for some kinds of agriculture because it offers better drainage and is more straightforward to work with than pure sand.

Table 1. Strategies to assess land degradation pathways as per the guidelines of (Kapalanga, 2008).

S. No.	Assessment level	Methods	Assessed parameter	Units/value
1	Full Cover Analysis	experts opinion (e.g. indicators, questionnaires, etc.)	Land/soil degradation: (severity, degree, extent) Soil (erosion, fertility, productivity, etc.)	Classes (1,2,3,4,5 - light - very severe / excellent - very poor, etc.),
2	Partial cover	Remote sensing and giS (e.g. mapping)	Vegetation change Biodiversity loss	t ha ⁻¹ y ⁻¹
3	Drylands, rangelands, grasslands, forests, deserts, etc.,	Expert opinion (e.g. indicators, questionnaires, interviews, focus groups, etc.) Remote Sensing and giS (e.g. NDVI, MODIS, etc.) Modelling (e.g. CORINE, PESERA erosion models, etc.)	Land/soil degradation: - severity, degree, extent, impact, causes, & risks - Soils (erosion, fertility, productivity, etc.). Vegetation change Land cover Land uses Slopes. Climate (rainfall,	%, Classes (1,2,3,4,5 for light - very severe / excellent - very poor, etc.),

		(mainly for croplands) Field monitoring and measurements (measurements to verify models) -pilot areas	temperature) for modelling. Biodiversity loss.	
4	Soils, rivers	Land users opinion (e.g. indicators, etc.) Remote Sensing and giS (e.g. NDVI, MODIS, MSDI ect.) modelling (e.g CORINE, PESERA models, etc.) Field monitoring and measurements (measurements to verify models) - pilot areas grid System monitoring (eu)	Vegetation change Land cover Biodiversity loss Land uses. Rangeland health/conditions, Climate (rainfall, temperature), etc.	t ha ⁻¹ yr ⁻¹ . Frequency of Indicators.

3. Sources of Land Loss

Because of both natural and human activities, desertification reduces the economical viable productivity of arable land to a barely sustainable level. As a result, it is critical to investigate the causes of arable land desertification and develop strategies to mitigate those effects. Sand accumulation is burying crops and damaging arable land. Middle Eastern countries also have the issue of salinization of agricultural land; it also affects arable land and causes degradation, although statistical data is not readily available for this. (Alqurashi and Kumar, 2019). Al-Ahsa oasis's arable land area was estimated to be around 16000 hectares; however, over the last 15 years, resalinization of soil due to over-irrigation and inadequate drainage has caused this area to decrease to about 8,000 hectares. (Alqarni et al., 2018). Desertification causes economic loss of productivity of arable land to a bare sustainable level due to natural and man's activities. Therefore, it is important to study factors causing the desertification of arable land and to find solutions to diminish the intensities of these factors. The following are some of the primary causes of desertification, either directly or indirectly:

3.1. Aridity

A significant cause of land degradation is aridity, especially in drylands with persistent water deficits where precipitation is less than 65% by evaporative demand (Berdugo et al., 2020). Aridity, defined as a ratio of precipitation to potential evapotranspiration on a multiannual scale of less than 0.65 mm/mm, causes poor water availability, which in turn causes land degradation (Právělie et al., 2019). It is a degradative state, which includes near-surface climatic conditions, a significant process of degradation that leads to desertification (FAO, 1999; Montanarella et al., 2015) and profound changes in the structure and function of ecosystems around the world (Berdugo et al., 2020). The patterns of global aridity are essential to comprehending its effects. Around 66.7 million km², or 45% of the Earth's surface area, are covered by drylands; Africa and Asia are the two most vulnerable regions, with roughly 23 million km² impacted each (Právělie et al., 2016). Africa is the second most affected continent after Australia, with over 90% of its territory affected. Africa is notably a hotspot, with 75% of its land being drylands. Approximately 40% of the world's drylands are found in Australia, China, the United States, Russia, Kazakhstan, Algeria, and Argentina. Further noteworthy

nations that collectively give 30% are Saudi Arabia, Sudan, India, Canada, Libya, Iran, Mongolia, Mexico, Chad, Mali, Brazil, Niger, South Africa, and Mauritania (Prävälíe et al., 2016). There are 126 countries afflicted by aridity, 41 of which have more than 90% of their territory affected. However, drylands can have beneficial effects on the climate, including lowering solar radiation and storing large amounts of carbon (470 Pg of organic carbon and 578 Pg of inorganic carbon) (Plaza et al., 2018). Furthermore, through the dispersal of dust from deserts such as the Sahara, drylands supply vital nutrients to various ecosystems (Mahowald et al., 2018; Jewell et al., 2021). However, aridity also carries with it a host of environmental problems. It impacts 7.8 million km of arable land, which is necessary for the security of food worldwide (Prävälíe, 2021). Seventy percent of agricultural drylands are affected by desertification, which can cost up to 10% of agricultural GDP annually (Pandit et al., 2018). Severe desertification affects ten to twenty percent of drylands, which directly and indirectly impacts 250 million people (Reynolds et al., 2007). Desertification is made worse by the loss of vegetation brought on by human activities and climate change, and it affects regions such as southern Argentina, the southwestern United States, the Sahel, eastern Africa, and portions of Asia (Abd-Elmabod et al., 2019; Abel et al., 2021). Dryland dust storms can harm human health as they destroy crops and deteriorate the quality of soil and water (Greaver et al., 2012; Middleton & Sternberg, 2013). In significant worldwide aquifers like California, the Middle East, China, and India, groundwater depletion is a serious problem (Montanarella et al., 2015; Martínez-Valderrama et al., 2020). Due to aridity, nutrient imbalances endanger ecosystem stability in drylands (Moreno-Jiménez et al., 2019).

Socioeconomic problems like food insecurity, poverty, migration, and wars are also made worse by aridity. (Hsiang et al., 2013). Over 2 billion people now reside in drylands, and by 2050, it is predicted that this number will have increased by 40-50%, making the present challenges worse. (Stavi et al., 2022). According to predictions, drylands may develop to encompass 56% of Earth's surface by 2100 in a pessimistic scenario and 50% in an optimistic one. (Huang et al., 2020). According to (Lal, 2019) This increased aridity due to development will accelerate desertification and decrease carbon sequestration, a process that is already taking place in many dryland regions.

3.2. Wind Erosion

Wind transports coarse and fine soil particles across landscapes, dispersing them into the atmosphere and redistributing them across the Earth's surface, known as wind erosion. This process consists of three primary stages: (1) soil particle detachment, also known as deflation, where particles are lifted off the ground; (2) surface creep, suspension, and saltation during transportation; and (3) particle deposition, where particles settle. (Goossens and Riksen, 2004). The environmental impact of these particles, both locally and distantly, depends on their size, composition, and flight duration. (Goossens and Riksen, 2004). Over time, more than one-third of the Earth's land area has been affected by wind erosion, predominantly in dry regions with strong winds or on bare soils with minimal plant biomass. (Skidmore, 2017). Human activities such as overharvesting vegetation, monoculture practices, deforestation, overgrazing, agricultural abandonment, and prolonged fallow periods exacerbate soil loss rates. (Chen et al., 2014; Duniway et al., 2019). Certain variables influencing wind erosion include wind speed, soil moisture, surface roughness, soil texture and aggregation, organic matter content, farming practices, vegetation cover, and field area. (Skidmore, 2017). Evaluating wind erosion rates necessitates understanding the interaction of these variables. (Doetterl et al., 2016). Soil aggregation and stability are critical indicators of a soil's vulnerability to wind erosion. (Tatarko, 2001).

Wind-driven soil erosion and subsequent dust emissions significantly impact Earth systems and human environments. Soil-derived dust particles, originating from various sources, are significant components of global aerosols (Katra & Lancaster, 2008; Katra et al., 2017). Globally, up to 3000 million tons of dust, including particulate matter (PM) with diameters less than 10 micrometers (PM₁₀), are emitted into the atmosphere annually. PM₁₀ is particularly significant as it contains clays and organic carbon, aiding soil water and nutrient adsorption (Aimar et al., 2012; Yitshak-Sade et al.,

2015; Katra et al., 2016). Additionally, PM₁₀ is critical in aerosol radiative forcing (Kok et al., 2017) and poses health hazards as a significant air pollutant (Kok, 2011; Krasnov et al., 2016). The primary determinant of soil erodibility is its structural stability, reflecting its susceptibility to erosion under specific conditions and forces (Ben-Hur & Agassi, 1997). Dust particles generally experience cohesive inter-particle forces, forming aggregates in undisturbed soils due to strong cohesive forces, typically stronger than aerodynamic and gravitational forces, thus preventing direct wind lifting of dust (Kok, 2011). Dust is closely associated with saltation, initiated when wind stress is sufficient to transport sand-sized particles (~63–500 µm) into the fluid stream. The impact of saltation facilitates the entrainment of cohesive dust particles from soil aggregates at lower wind velocities (Swet & Katra, 2016). External factors, including land use and climate changes, influence soil aggregation and erodibility. Soils with larger aggregates are generally more erosion-resistant (Ben-Hur et al., 2009). Research on wind erosion often focuses on the erodible fraction, considering aggregates less than 840 µm in diameter (Zobeck et al., 2003; Webb & Strong, 2011; Aimar et al., 2012; Avezilla et al., 2015). Agricultural practices modify soil characteristics, affecting its resistance to erosion. Wind erosion and dust emissions can lead to significant nutrient loss and soil degradation of fertile lands (Ginoux et al., 2012).

3.3. Water Erosion

Water-induced soil erosion is regarded as a crucial type of land degradation, with a much higher global prevalence than wind erosion (Vanmaercke et al., 2021). Aggressive water action causes soil to be displaced from its formation site in this process in sheet, rill, and gully erosion (Poesen, 2018; Batista et al., 2019; de Nijs and Cammeraat, 2020). Some of the adverse effects of water erosion are reduced water-holding capacity, decreased infiltration rates, loss of nutrients and organic matter, degradation of soil structure, and decreased soil depth and fertility (Ravi et al., 2010; Borrelli et al., 2017; Sartori et al., 2019). Soil health is significantly impacted by severe erosion, defined as rates beyond the acceptable threshold of 10 t/ha/yr (Sartori et al., 2019). According to analysis of global spatial data indicates that severe soil erosion (>10 t/ha/yr) affects roughly 10 million km², or ~7% of the world's land area. Asia is the most affected continent, especially China, which accounts for nearly 1.5 million km² of severely eroded land. Significant hotspots that account for over 47% of the world's severely degraded areas are also found in Brazil, Russia, the United States, and India. The most severely impacted are tropical nations, where severe erosion has devastated more than 20–30% of their national territory; in extreme situations, such as Bangladesh, it has reached or exceeded 60% (Borrelli et al., 2017). The coarser database employed in the analysis may have led to an overestimation of the spatial scope of this degradation process, although overall estimates are relatively consistent with other sources (Middleton and Thomas, 1992; Middleton and Sternberg, 2013). A 25% overestimation in previous estimates has been confirmed by recent high-resolution data, which points to a global severe water erosion area of roughly 7.5 million km² (Borrelli et al., 2017).

Water erosion is a primary environmental concern worldwide, even though it is difficult to precisely define the extent of soil erosion due to different data resolutions and models (Haregeweyn et al., 2015; Cerdà et al., 2017; Novara et al., 2018; TENG et al., 2019; Maltsev and Yermolaev, 2020; Wuepper et al., 2020). According to several studies (Oldeman et al., 1990; Middleton and Thomas, 1992; Ravi et al., 2010; Stavi and Lal, 2015; Poesen, 2018), water erosion has been considered a prevalent form of land degradation for decades. Anthropogenic (deforestation, tillage, overgrazing, and agricultural intensification), geomorphological (steep slopes, for example), and climatic (rainfall erosivity) factors are the leading causes of soil erosion (Pimentel and Burgess, 2013; Panagos et al., 2016; Cerdà et al., 2017; Rodrigo-Comino, 2018). According to recent studies, between 2001 and 2012, there was a 2.5% global increase in erosion rates due to changes in land use, particularly the growth of farmland (Borrelli et al., 2017). By changing temperature, precipitation, and vegetation cover, climate change also affects water erosion patterns. Vegetation cover reduces runoff and intercepts rainfall, thus controlling erosion (Li and Fang, 2016; Ma et al., 2021). According to projections, water erosion will become more severe worldwide due to climate change, especially in tropical and

subtropical areas (Borrelli et al., 2017). About 30% of the world's arable land (~4.3 million km²) is affected by erosion, which seriously impacts agriculture because it causes significant soil loss and related financial losses (Montanarella et al., 2015; Právělie, 2021). Due to declining agricultural yields, rising food prices, and a disruption of socioeconomic stability, the world's food security is at risk. Furthermore, erosion modifies the storage and flux of vital elements such as carbon, nitrogen, and phosphorus, which affects biogeochemical cycles (Chappell et al., 2016; Berhe et al., 2018; Martínez-Mena et al., 2020). Future trends point to probable net losses of soil carbon due to erosion and synergistic pressures like climate warming, while the net effect of erosion on the carbon cycle is still up for debate (Crowther et al., 2016; He et al., 2016; Lugato et al., 2018).

3.4. Salinization

Soil salinization is a common form of land degradation which is considered a significant environmental disruption impacting ecological and agroecological productivity due to phytotoxicity from high concentrations of dissolved salts (Ca²⁺, Mg²⁺, K⁺, Na⁺, Cl⁻, and others) in the soil (Herbert et al., 2015; Minhas et al., 2020). In addition to its direct effects on plant development, this phenomenon also indirectly affects soil structure degradation, organic matter reduction, biodiversity loss (except halophytes), and water uptake and infiltration problems (Ben-Hur et al., 2009; Corwin, 2021). The degree of these effects varies according to the salt tolerance of the plants and can be attributed to primary salinization processes (natural accumulation) as well as secondary salinization processes (anthropogenic activities) (Corwin, 2021). Approximately 2.6 million km², or ~2% of the Earth's terrestrial surface, are affected by soil salinization worldwide, with Asia being the most affected region with ~1.3 million km² (or 50% of all salinized lands). Australia is the most afflicted continent in percentage terms, with 6% of its entire area affected. It also has the most extensive salinized land area (~0.5 million km²), accounting for 19% of the world's salinized soils (Cherlet et al., 2018). Notable hotspots that contribute to 55% of global salinization include Kazakhstan (~319,000 km², 12%), China (~307,000 km², 12%), and Iran (~300,000 km², 12%). According to research, Iran has the most national salinization, with 19% of its land affected (Middleton and Thomas, 1992; Cherlet et al., 2018). Most salinization occurs in arid and semi-arid areas because not much freshwater is available to remove accumulated salts. Salts from deeper soil layers have been mobilized to the surface due to high rates of evapotranspiration caused by intensified irrigation in these locations (Rozema and Flowers, 2008; Minhas et al., 2020). Recent studies show severe salinization occurs in Australia, China, Kazakhstan, and Iran. At the same time, unanticipated rises in salinity rates have been observed in Brazil, Peru, Sudan, Colombia, and Namibia due to growing salinity rates after 1980 (Hassani et al., 2020).

Salinization is primarily caused by anthropogenic activity, such as irrigation, altered land use, and the eradication of native flora. For example, increasing groundwater intake by trees in Argentine tree plantations, which have replaced native grasslands, has increased salinization (Nosetto et al., 2013). Salinization has increased in Central Asia due to the Aral Sea's drying due to heavy irrigation (Yu et al., 2019). Under forest or shrub cover, water recharge and discharge are balanced in dryland areas, maintaining the distribution of salts in the soil mantle. When natural vegetation is removed, significant soil moisture loss during rainfed agriculture causes elevated salt levels in soils. If mitigating measures are not taken, salinization might affect more than 20% of the world's irrigated lands by 2050 (Singh, 2021). Iran's significant salinization is caused by inadequate drainage and widespread groundwater extraction from salty aquifers (Emadodin et al., 2019). Global agriculture suffers greatly from soil salinization, which affects over 0.3 million km² (~2%) of arable land and costs about \$27 billion a year in lost agricultural yields (Qadir et al., 2014). Salinization causes 18-43% of agricultural losses in dry and semi-arid areas (Singh, 2021). Climate change is accelerated by this process, which also adds to the decreasing soil organic carbon storage. According to estimates, 6.8 Pg C may be lost by 2100 due to increased soil salinization (Setia et al., 2013). Conclusively, soil salinization, a result of both natural and man-made factors, represents a serious global environmental issue that substantially impacts agriculture, biodiversity, and climate stability. Developing effective

management and mitigation strategies is crucial to dealing with this growing issue and its associated environmental and economic consequences.

3.5. Soil Carbon Loss

A crucial sign of land degradation is the loss of soil organic carbon (SOC) (O'Rourke et al., 2015; Právělie, 2021). Soil organic matter (SOM) is mainly formed of decomposed plant and animal components, accounting for 55-60% of SOM by mass. SOC is a significant component of SOM. Structure, water retention, nutrient cycling and storage, biodiversity, and biological activity are just a few of the properties of soil that are influenced by SOM (Obalum et al., 2017; Kögel-Knabner and Amelung, 2021). Decreased soil fertility and productivity, diminished nutrient retention, diminished water holding capacity and infiltration, destabilized soil structure, and lower biodiversity are all consequences of a reduction in soil organic carbon (SOC) (Alcántara et al., 2017). The loss of SOC intensifies climate change since soil is a significant worldwide carbon source. According to estimates, soils contain about 1500 Pg C in the upper meter, which is three times as much carbon in terrestrial plants as in the atmosphere (Lal, 2018, 2019). The top 30 cm of the soil contains about 50% of this carbon (Montanarella et al., 2015; Plaza et al., 2018). According to recent data, between 2001 and 2015, SOC decreased in nearly 2.7 million km² of land worldwide (or roughly 2% of the world's surface area). Brazil (~412,000 km²), China (~300,000 km²), Russia (~289,000 km²), the United States (~210,000 km²), Canada (~115,000 km²), and Indonesia (~83,000 km²) are the countries that are most affected (Právělie, 2021). Since 2001, these countries have been responsible for more than half of the global SOC loss. However, the most considerable percentage-based SOC losses are found in Europe, especially in the central and northwest areas, where several nations record losses, including more than 15-20% of their total land area (Právělie, 2021). Land use change, especially converting natural ecosystems to croplands, is the leading cause of SOC loss. This technique raises carbon outputs through plowing while reducing carbon inputs from plant litter. Agricultural topsoils have lost up to 176 Pg C due to these changes and unsustainable land management practices during the last 200 years (van der Esch et al., 2017). According to West et al. (2010), deforestation and increased agricultural practices are causing the most significant SOC losses in tropical regions, including Brazil and Indonesia. Furthermore, in countries like the US, China, Canada, and Russia, logging in boreal forests and urbanization in temperate zones are essential causes of SOC loss (Seto et al., 2012; Hansen et al., 2013; Curtis et al., 2018). Erosion causes significant losses in SOC; since 1850, water erosion has removed 74 Pg C, mostly from grassland and agricultural systems (Naipal et al., 2018). Wind erosion also significantly causes SOC loss (Chappell et al., 2019). By upsetting the equilibrium between carbon imports from plant photosynthesis and carbon outputs from microbial breakdown, climate change poses an even more significant threat to the SOC pool (Davidson, 2016). According to projections, by 2050, worldwide soil organic carbon (SOC) declines in upper soil horizons could be caused by climate warming. This reduction mainly affects permafrost soils and could accelerate climate change through positive soil carbon-climate feedbacks (Crowther et al., 2016).

3.6. Land Pollution

Land pollution is another form of land degradation that affects land quality worldwide. It results from various anthropogenic activities (mine, industrial, and agricultural) that release toxic compounds into the environment. The overabundance of various substances, including fertilizers (nitrogen, phosphorus) (Bruulsema, 2018), pesticides (fungicides, insecticides, herbicides) (Tang et al., 2021), heavy metals (cadmium, mercury) (Liu et al., 2021), persistent organic pollutants (polychlorinated biphenyls, DDT) (Van den Berg, 2009) radionuclides (90Sr, 137Cs) (Lelieveld et al., 2012), electronic waste (Akram et al., 2019) petroleum products (Daâssi and Qabil Almaghribi, 2022), and plastic and microplastics (Rochman and Hoellein, 2020), cause land pollution. Additionally, these chemicals pollute freshwater systems (lakes, rivers) worldwide (Schwarzenbach et al., 2010), and makes the systems more vulnerable to secondary pollution, like cyanobacteria in phosphorus-enriched waters, a toxic microorganism (Sukenic et al., 2015). Vegetation, including forest

ecosystems, suffers from regional or local pollution as a result of atmospheric nitrogen deposition (Du et al., 2019) or radionuclide contamination (e.g., radiocesium) from nuclear tests or accidents like Chernobyl and Fukushima (Koarashi et al., 2016; Thiry et al., 2020). Additionally, pollutants affect coastal ecosystems; the Eastern Atlantic and Western Pacific regions have the highest amounts of pollutants (Lu et al., 2018). Surface waterways are subsequently jeopardized by groundwater pollution resulting from mining and other inland water resource operations (Lall et al., 2020). Ecosystem damage, eutrophication, biodiversity decline, changes to the biogeochemical cycle, and general degradation of ecosystem services are just a few of the many adverse effects of land pollution (Orgiazzi et al., 2016; Garnier et al., 2021). Numerous local researches have confirmed these effects, but there are few worldwide evaluations of the ecological ramifications and cartographic depictions of land contamination. Interestingly, no global map of soil pollution routes exists (FAO and GSBI, 2020), even though such a resource is essential for bettering soil protection globally and comprehending pollution in connection to other problems with soil degradation. A recent study that determined and mapped the worldwide risk of pesticide pollution shows that about 31% of agricultural land is at high risk (Tang et al., 2021).

3.7. Land Subsidence

Land subsidence is characterized by soil compaction due to vertical downward displacement of the ground surface (Kok and Costa, 2021). The causes of this phenomenon are both artificial and natural. Natural reasons include geological movements, karst activities, permafrost thawing, and the effects of climate change, such as drought-induced groundwater depletion and hydrodynamic processes (Smith and Majumdar, 2020; Kok and Costa, 2021). However, anthropogenic effects are more frequent and prevalent all over (Bagheri-Gavkosh et al., 2021). Urbanization, coal mining, anthropogenic drainage, groundwater, gas, and oil extraction are a few of these (Erban et al., 2014; Liu et al., 2020; Kok and Costa, 2021). The primary cause of land subsidence globally is overexploitation of groundwater, primarily for agricultural irrigation (Jeanne et al., 2019) and urban water usage (Bierkens and Wada, 2019). The fast increase in the world's population and the spread of irrigated agriculture have worsened this problem in recent decades (Bierkens and Wada, 2019). Because of their dense populations and high natural subsidence rates, deltaic regions are especially susceptible to land subsidence (Hallegatte et al., 2013). More than 500 million people live in deltas, many of whom reside in megacities (Giosan et al., 2014). According to Syvitski et al. (2009) and Tessler et al. (2015), human activities worsen subsidence by drastically lowering sediment loads from rivers through the construction of dams and irrigation channels or by hastening soil compaction by underground mining of groundwater, gas, or oil (Syvitski et al., 2009; Tessler et al., 2015). The deltas of the Nile (98% reduction), Indus (94%), Rhone (85%), Mississippi (69%), and Danube (60%) are a few examples of notable sediment trapping (Giosan et al., 2014). Impacts of subsurface mining include the Po delta in Italy (3-5 m subsidence in the 20th century due to methane extraction), the Yellow delta in China (up to 25 cm/year subsidence from groundwater extraction), and the Chao Phraya delta in Thailand (5-15 cm/year subsidence due to intense groundwater use) (Syvitski et al., 2009; Giosan et al., 2014). Climate change is anticipated to worsen land subsidence by increasing the demand for water for household, agricultural, and industrial uses during prolonged droughts, accelerating groundwater depletion (Minderhoud et al., 2020). Land degradation and exposure to coastal flooding are likely to grow in deltaic locations due to subsidence mixed with other vulnerability variables, such as low altimetry and rapid sea-level rise rates (Minderhoud et al., 2020). Large populations in these locations are at risk from the possibility of rapid coastal flooding brought on by subsidence and sea level rise; as of 2017, 339 million people were expected to live in worldwide river deltas alone (Edmonds et al., 2020).

3.8. Sand Encroachment

In the arid regions of the Kingdom of Saudi Arabia, loose sand particles' susceptibility to wind erosion is a significant concern, resulting in the formation of windblown sand and sandstorms. This vulnerability is primarily attributed to the inherent lack of strong cohesion among these sand particles. This causes land degradation and desertification, which exacerbate the effects of sand encroachment (Miao et al., 2022). During sand encroachment events, sand particles are lifted from the surface, following parabolic trajectories as the wind gradually accelerates them before striking the ground. These saltating particles cause further detachment of particles, leading to the destruction of vegetation cover and the abrasion of crusted surfaces, resembling a sandblasting process. This process ultimately releases fugitive dust particles (with a diameter of less than 70 μm) into the atmosphere (Shao, 2008). The consequences of sand encroachment in these regions are far-reaching and severe, leading to many environmental challenges. These encompass biodiversity loss, the release of stored carbon from the soil into the atmosphere, air pollution with dire health implications, degradation of water quality, food insecurity affecting livelihoods, and population migration (Shepherd et al., 2016; Goudie, 2018; Huang and Hartemink, 2020). Additionally, wind erosion adversely impacts agriculture and the economy by depleting soil nutrients, generating fine particles, and burying infrastructure (Modaihsh et al., 2014). Desertification poses a substantial challenge globally, affecting approximately 41% of the Earth's land area and impacting over 38% of the global population (Huang et al., 2020). Dust generated during desertification can carry soil pollutants and fine particles that pose respiratory health risks (Ostro et al., 2021) (Chen et al., 2016; Li et al., 2021). Consequently, addressing land desertification and reducing sandstorm occurrences remains a significant global challenge. Current strategies to combat sand encroachment and land desertification include the construction of windbreaks and fences, the application of chemical soil stabilizers, and planting vegetation. Nevertheless, these conventional methods have limitations and adverse environmental effects. While planting vegetation can ameliorate erosion resistance, its efficacy is truncated in desert regions due to the scarcity of water resources (Miao et al., 2015) In response to drought challenges, Saudi Arabia has initiated a comprehensive strategy to combat land degradation and sand encroachment by harnessing the potential of treated wastewater (Husain and Khalil, 2013).

3.9. Natural Oil Extraction

Soil is the ecosystem that sustains all living things. Due to increased human activities and population growth, different persistent pollutants and xenobiotics are causing soil pollution; natural oil extraction is also one of those activities. Oil spills seriously threaten every component of the ecosystem of Saudi Arabia (Sarkar et al., 2005). Soil pollution results from the regular spilling of crude oil and its refined products during extraction, transportation, storage, and distribution (Macaulay and Rees, 2014). Because of their propensity to accumulate in living things and their ability to enter the food chain, soils contaminated with petroleum-related persistent organic pollutants (POPs), such as polycyclic aromatic hydrocarbons (PAHs), pose a significant risk to human health also (Honda and Suzuki, 2020). Because the disposal of PAHs modifies soil properties, microbial biodiversity, enzymatic activity, and physicochemical characteristics, oil contamination leads to pollution and land deterioration (Bastami et al., 2013). When land degrades, the microbial community is impacted by petroleum contamination, soil fertility, and structure change (Czarny et al., 2020). Particulate matter pollutants (POPs), such as PAHs, can cause environmental risks and threaten all aquatic and terrestrial life. Soil contaminated by petroleum has been found to have a high degree of salinization (Buzmakov and Khotyanovskaya, 2020). Hazardous compounds like benzene, toluene, ethylbenzene, xylene, and naphthalene, which can be detrimental to all aspects of the ecosystem, particularly the land, are found in petroleum hydrocarbons (PHs) (Sarkar et al., 2005; Kuppusamy et al., 2020). The primary issue arising from the exploitation of oil resources is the degradation of upland and floodplain soils due to benzo(α)pyrene contamination and salinization. Accidental spills of produced oil and technological emissions of hydrocarbons into the atmosphere are responsible for petroleum pollutants (Buzmakov and Khotyanovskaya, 2020). PAHs are persistent in soils; as their

molecular weight and the number of benzene structures increase, they become more harmful since their solubility and biodegradability decrease (Meador, 2008). Because of PAHs' high toxicity, mutagenicity, carcinogenicity, and teratogenicity to humans, the US Environmental Protection Agency (USEPA) has designated them as priority pollutants (Rengarajan et al., 2015; Polidoro et al., 2017). Given the toxicity, carcinogenicity, and mutagenicity of petroleum hydrocarbons, cleaning up and restoring PAH-polluted places poses a significant environmental and technological challenge for sustainable development. Although there are a number of remediation techniques for PAH-contaminated soils, intriguing microorganisms, fungi, and their enzymes receive much attention (Daâssi and Qabil Almaghribi, 2022). Various techniques are employed to remediate soil contaminated by petroleum, including biostimulation (Wu et al., 2016), bioaugmentation (Patel and Patel, 2020), rhizoremediation (Rostami et al., 2021), plasma oxidation (Liu et al., 2022), microbial electrochemical system (Hao et al., 2020), thermal desorption (Wei et al., 2022), vapor extraction (Cao et al., 2021), and biochar adsorption (Bianco et al., 2021).

4. Strategies to Conserve Arable Lands and Pathways to Improve Their Fertility

4.1. Conservation Tillage and Terracing

Conservation tillage reduces soil erosion as it leaves approximately 30% of the crop residue at soil surface (Seitz et al., 2019). Water consumption efficiency and soil water storage are increased by conservation tillage techniques such as mulch tillage, ridge tillage, zero tillage (no-till), decreased tillage, and contour tillage (Bekele, 2020; Unger, 2023). Therefore, this method can be used for effective water conservation additionally, it maintains plant remains on the soil surface and a higher water content on topsoil (Unger, 2023). This leads to increased water content in the soil due reduced evaporation as a result of coverage. Furthermore, this mechanism has significant benefits under arid or semi-arid conditions where plant water availability is very limited. The soil in Saudi Arabia is very coarse due to which the water runs off quickly leading to lesser water conservation. This runoff also carries away most of the soil sediments and residual agrochemicals. Under such circumstances, application of conservation tillage not only decreases the water runoff but also protects the water quality and soil health (Cárceles Rodríguez et al., 2022). According to previous research, it has been concluded soils under the conservation tillage showed high efficiency in water usage and conservation along with the retention of macronutrient compared to the soil which were exposed to severe tillage and digging (Wolka et al., 2018; Sarvade et al., 2019; Rahman et al., 2020). Therefore, this technique is very instrumental for the water deficient areas specifically arid or semi-arid regions. Therefore, conservation tillage is sustainable solution for the improvement of water and nutrient use efficiency as this method not only improve roots growth but also enhances crop growth and yield indexes.

Meanwhile, terracing is also another technique of soil conservation which is used to prevent soil erosion by minimizing the rainfall runoff on a sloping land (Wolka et al., 2018). Terracing has been one of the most crucial methods for reducing soil erosion, saving water, and raising agricultural yield for thousands of years (Chen et al., 2017; Deng et al., 2021). Additionally, it is one of the first methods of soil and water conservation, is popular in hilly and mountainous areas under significant population pressure (Wei et al., 2016). It is an ancient technique that can be used for improved water conservation and increased agricultural production. It is usually done along the curve lines on the slopes in order to make different level areas, these slopes reduces the runoff along with sufficient increase in water infiltration (Morbidelli et al., 2018). Terracing intercepts the rainwater which leads to increased retention of soil moisture (Wei et al., 2019). In this way, terracing improves the water conservation, which is very essential for agricultural growth in harsh and dry regions as it reduces the volume and speed of runoff which ultimately leads to reduced soil erosion (Wolka et al., 2018). The soil erosion in semi-arid areas like Saudi Arabia is very high which results in reduced agricultural yield and loss of fertile land. Therefore, terracing can prove to be very effective in such areas by reducing soil erosion which ultimately helps to prevent nutrient loss. Dry and hilly areas of Saudi

Arabia are the suitable candidate to experience terracing which will help into produce cultivable land, enhance water retention, and lessen the soil erosion.

4.2. Agroforestry and Riparian Buffer Strips

A sustainable land management approach that works well in Saudi Arabia's climate is agroforestry as this technique offers several advantages including fuelwood, fodder, revenue, and environmental protection, entails combining trees with pastures or crops in the same field (Dagar, 2016). An age-old method of land management called agroforestry can greatly increase the productivity of the soil in arid areas (Krishnamurthy et al., 2019). In agroforestry systems, legume trees fix nitrogen, improving soil fertility and contributing nutrients through root decomposition and litterfall (Sileshi et al., 2020; Fahad et al., 2022). Agroforestry systems benefit from the windbreak function of trees, which lowers wind speed and water evaporation and increases crop yield (Mume and Workalemahu, 2021). Rehabilitating degraded land, raising land production, and protecting natural resources are the three major goals of agroforestry in dry zones. In agroforestry, woody species' deep root systems retrieve water from lower soil levels and redistribute it to higher ones, supporting plant growth in arid conditions (Bayala and Prieto, 2020). Agroforestry can ameliorate land degradation, reduce carbon emissions, combat pollution, and increase land vegetation cover. Additionally, higher practices of agroforestry would exceed the current global target of 17% by increasing the percentage of protected areas to almost 30% of the country's total land area, or approximately 600,000 square kilometres (Brès et al., 2023b). Therefore, Agroforestry can support rural development in addition to providing fuel, firewood, fodder, and timber to rural communities and helping them diversify their sources of income. This practice can also improve soil microclimates by lowering wind speed and soil evapotranspiration, which modifies temperature and moisture content (Jacobs et al., 2022). Furthermore, agroforestry systems are very successful at storing carbon in soil organic matter, harvested products, and tree biomass in addition to effectively sequestering greenhouse gases.

Another useful technique that can improve water conservation in Saudi Arabia is the establishment of riparian forest buffers. According to (Asbjornsen et al., 2014), these vegetated regions by water bodies improve farm revenue potential, improve the environment, and create habitats for wildlife. Riparian buffers are essential for managing surface runoff, urban runoff, and deep-water flow in arid and semi-arid climates meanwhile these buffers also assist reduce pollution, nutrients, and sediments (Bogis, 2021; Yan et al., 2023). The use of vegetative buffer strips is being pushed extensively as a successful method of shielding rivers and streams from the damaging effects of nearby land uses, such as forestry and agriculture (Norman, 2017). By limiting livestock access to streams, lowering nitrogen inputs from animal excrement, and minimising streambank erosion, riparian buffers enhance the quality of water (Essien, 2012). Additionally, they shield rivers and streams from the detrimental effects of nearby land uses by acting as physical barriers to sediment, fertilizers, and pesticides (Kroll and Oakland, 2019). Riparian floodplains and associated buffer zones have a crucial ecological significance in arid and semi-arid regions. Surface runoff, wastewater and urban pollutants, deepwater flow, and infiltration processes are among the surface and subterranean water flows that they affect or lessen. Numerous environmental services, including pollution, sedimentation, and nutrient control, are accomplished by these processes. High rates of infiltration occur in riparian corridors prior to development, which postpones the 'period of concentration,' or the amount of time it takes for water to move from the furthest point in a watershed to the lowest spot at the outflow (Watson et al., 2018). By preserving high infiltration rates and postponing the duration of concentration—the amount of time it takes for water to move from a watershed's most remote point to its outlet—riparian buffers help reduce the risk of flooding in metropolitan areas like Jeddah (Blair et al., 2006). Riparian buffers are beneficial to the ecological health of water bodies because they facilitate chemical changes including denitrification and plant uptake of nutrients (Haycock and Pinay, 1993; Cooper and Gilliam, 1987).

4.3. *Mulching and Cover Cropping*

The world's major water user is Agriculture sector as it consumes around 70% of the whole consumption (Wakeel et al., 2016). The scarcity of water might be due to varying rainfall patterns or climate change that cause reduction in agriculture production in arid or semi-arid regions. The availability of water for agricultural producers is gradually reducing as a result of urban populations' increasing water needs (McGrane, 2016). Mulching is a widespread procedure that involves spreading materials such as sand, cement, crop leftovers, plastic material, and livestock manure on the soil surface before, during, or shortly after sowing (El-Beltagi et al., 2022). Materials used for organic mulching include animal manures, processed leftovers, wood industrial wastes, and agricultural wastes whilst inorganic mulching carries materials include polyethylene plastic sheets and synthetic polymers (El-Beltagi et al., 2022). A number of novels environmentally friendly plastic films that are photodegradable and biodegradable, as well as surface coating and biodegradable polymer films for flexibility and simplicity of use, were also introduced. Mulching enhances soil productivity, moisture availability, and other characteristics much better than other approaches. The soil's organic content increases swiftly when organic mulch breaks down, enhancing the soil's capacity to retain water. Because mulches decrease evaporation, more moisture is accessible near the plant roots, extending the time for plants to absorb water as a result, mulched areas require less water (El-Beltagi et al., 2022). Frequently mulching is believed to be beneficial to stressed environments (heat, drought, and salinity) as it changes the rate of evaporation and transpiration (El-Beltagi et al., 2022). Mulches appear to be effective at changing water or heat balances on the soil's surface or improving the growing environment for plants. By delaying evaporation, mulches preserve soil moisture, although their capacity to affect soil temperature varies according to the composition and optical characteristics of the mulch (El-Beltagi et al., 2022). In general, organic mulches reduce maximum soil temperatures but boost minimum soil temperatures, whereas polyethylene mulches enhance maximum or minimum soil temperatures compared with un-mulched soil (El-Beltagi et al., 2022). Mulch effectiveness is dependent on both the site's climate and soil characteristics, moreover, using crop residue as mulching material can massively encourage crop growth, water conservation and soil health (Ren et al., 2023). Since mineral mulch often withstands water vapor better than organic mulch, it is anticipated that it will save soil water more effectively. Additionally, the preservation of soil moisture was enhanced when tillage and mulching were applied combined. Because the mulch shades the soil surface from the sun, it slows down the evaporation of soil water.

Moreover, the cover crop changed the temperature of the soil and had an impact on soil evaporation (Yang et al., 2021). It has been reported that under some conditions cover cropping had better results compared to mulching it remarkably improved soil water holding capacity by improving soil porosity, nutrient content, water infiltration and minimized land erosion. In contrast to no mulching treatment, the wheat straw mulch (5000 kg ha⁻¹) raised the soil water content by 2.5 and 3.0% at 0–15 cm and 15–30 cm soil layers, respectively under arid region, additionally these treatments also decreased the daytime temperature by 1.9 and 1.5°C (El-Hendawy et al., 2022). However, it is crucial to use the right mulching materials for increasing crop yield and water use efficiency specifically under arid conditions. Global crop residue production is projected to be between 3.5 and 4.0 billion tons annually, with cereals, sugar, legumes, tubers, and oil crops accounting for 75, 10, 8, 5, and 3% of this total respectively which can be used as mulching material (Kumar et al., 2023). Similarly, Saudi Arabia produces about 400,000 tons of date palm leftovers annually based on the 20 million date palm trees that grow there and the 20 kg of dry leaves that each tree produces annually (Makkawi et al., 2022). Therefore, there is an enough supply of palm wastes in Saudi Arabia that can be used for mulching.

4.4. Nutrient Management

Now a days soil degradation is the major concern in agriculture sector worldwide as a result 60 % of eco system services declined where 33% loss linked with land degradation (Bai et al., 2013). Extensive agricultural practices and climate cause forest degradation which is ultimately reduction in biodiversity. The degradation of soil/forest is caused by some biological, chemical, physical and environmental processes which subsequently degrade soil quality and fertility. Biological degradation lead towards the depletion of soil organic matter which cause declined in biodiversity and enhanced greenhouse gas emission (Navarro-Pedreño et al., 2021). In arid and hyper arid regions physical degradation can cause the reduction in water holding capacity and dropping the nutrient retention worldwide (Naorem et al., 2023). Therefore, a set of suitable soil indicators is chosen to address this problem, which is a challenge to perform under field conditions. In sustainable agriculture, organic matter contributes not only for soil fertility but also stimulates and moderates soil formation, biological, physiochemical properties and hydrothermal features (Kocsis et al., 2022; Lodygin et al., 2023). Humic substances are the primary source soil organic matter and these substances enhanced the plant growth, soil water holding capacity and cation exchange capacity by modifying soils chemical, physical and biological properties to improve tilth and aeration (Gurmu, 2019; Ampong et al., 2022). All the essential nutrients which are required for plant growth and sustainable crop production is present in the soil with balanced amount and their input and output determine its fertility and nutrient use efficiency in different crop production system (Zhang et al., 2011). If the soil showed the decreasing trends of organic matter, then several important soil properties in which water infiltration rate, water holding capacity, macro porosity, soil aggregate stability and structure abundance of microbial biomass nutrient balance also depleting (Liu et al., 2019; Bashir et al., 2021). In nutrient management practices, organic compost and chemical fertilizer either alone or combination has become an effective approach. Composting is widely used practice of Saudi Arabia where about 40% of food waste, 13% cardboard, 5% paper, 6% yard waste, and 3% wood waste make up Saudi Arabia's organic waste stream, which accounts for over 67% of the country's municipal solid waste stream used (Anjum et al., 2016). This amounts to over 5 million tons of organic waste annually, all of which can be directed toward composting programs that will be beneficial and have a net positive impact (Farhidi et al., 2022). Organic waste composting is a complicated process with many biochemical and microbiological aspects. Any changes to these parameters will likely have an impact on other parameters as well because microbial activity is dependent on oxygen levels, feedstock material particle sizes, temperature, moisture content, acidity/alkalinity, pH, and nutrient levels and balance (as indicated by carbon/nitrogen) (Palansooriya et al., 2019). Moreover, digested crop residue contains approximately 30% N, 30% P and 200% K which indicates that composts is the best alternative option of synthetic fertilizer to maintain soil fertility and sustainable crop production.

4.5. Land Use Planning

The term "land use" describes how people utilize and manage land and its resources in order to survive (Briassoulis, 2020). Basically, it includes use of agricultural, residential, commercial or any other anthropogenic uses It's not the same as land cover, which is the term for the physical and biological elements that make up the land's surface, whether they are created naturally or by humans (Abd El-Kawy et al., 2011). Saudi Arabia soil either deep and shallow young soils over rocks as studies on the characteristics and composition of the soils in Saudi agricultural land have revealed that these areas primarily feature sand, loamy sand, and sandy loam soil texture (Almalki et al., 2022).

However, acquiring accurate and precise data regarding the characterization of landforms in a timely and economical manner is crucial for comprehending land use and cover is essential for the formulation of successful policy (Nedd et al., 2021). Because of their low levels of precipitation, gulf countries are known as desert zones as water resource management, flash floods, and aridity are major problems in these areas (Saber and Habib, 2016). Water resource management is challenging because of the intricate changes in hydrologic conditions that exacerbate these issues.. Pollution from

urbanization and agriculture has a cumulative effect on the amount of water impacted, ultimately affecting water quality worldwide (de Mello et al., 2020). Water quality is declining due to pollutants like pesticides and fertilizers entering the water system, as well as waste from industry, sewage, and agriculture (Singh et al., 2020). UN statistics state that all of the gulf countries aside from Oman have "acute scarcity" of water, which denotes an annual sustainable water supply of less than 500 m³ per capita (Amery, 2015). Furthermore, Saudi Arabia with its thirteen provinces has the most land area and people meanwhile, country possesses the most dams 563 with a capacity of 2.6 BCM (Salem et al., 2022). Because of the restricted amount of surface water resulting from poor rainfall and significant evaporation, Saudi Arabia is primarily dependent on its groundwater supplies and desalination (Baig et al., 2020).

5. Steps of Governing Bodies to Improve Land Conservation

To combat land desertification and improve soil fertility in Saudi Arabia, several initiative have been taken. Global governing bodies like United Nations Development Programme (UNDP), United Nations Environment Program (UNEP), Food and Agriculture Organization (FAO) and United Nations Convention to Combat Desertification (UNCCD) are working closely with the Institutes of Saudia Arabia to minimize land loss. For instance, UNDP launched projects entitled "Capacity development for sustainable development and management of water resources in the kingdom of Saudi Arabia" (UNDP, 2024) and "Development of policies and capacities for sustainability environment and natural resources" (UNDP, 2016) to conserve national natural reserve through sustainable solutions. Additionally, World Bank is working remarkably for the improvement of soil health as over the past decade, the Bank provided strategic support to the ministry on various issues, including assessing the cost of rangeland degradation and desertification, as well as valuating Saudia Arabia's mountain forests and mangrove. The findings are highly relevant for Saudi Arabia's ambitious Vision 2030 and support the proposed large-scale reforestation and landscape restoration initiatives. Additionally, Middle East green Initiative (MGI) is another significant step to restore degraded lands, mainly in dryland countries, with a budget of at least US\$2.5 billion over 10 years (Bank, 2024). Moreover, the MGI is complemented by an ambitious national program, the Saudi Green Initiative (SGI), which unites environmental protection, energy transition and sustainability programs with the overarching aims of offsetting and reducing GHG emissions by increasing forest areas and support land restoration.

The Saudi Arabian government's project, known as the Saudi Green project (SGI), was introduced in 2021 with the goal of promoting climate action and outlining a plan for environmental protection both inside and beyond the Kingdom. The project, which has high goals for the next several decades, is to conserve the environment, increase the use of clean energy, and mitigate the effects of fossil fuels in order to enhance living standards and save future generations.

By growing reliance on sustainable energy, mitigating the impact of fossil fuels, and conserving the environment, the program seeks to improve the quality of life and save future generations. Its ambitious ambitions cover the upcoming decades. In Saudi Arabia's highlands, there are over 2.1 million hectares of woodland woods, most of which are remote, rugged, and unapproachable (Abuzinada, 2020). Additionally, 70% of these superficies whose natural rangeland area is estimated to be 1,460,000 Km² is degraded or being affected by desertification because of overgrazing (Abuzinada, 2020). The loss of shrubs and trees, inappropriate farming practices causing surface soil instability, and ensuing erosion. Moreover, wildfires burn an average of 11,348 hectares year⁻¹ in total which means state of rangelands has deteriorated so much in recent years (Abuzinada, 2020). In addition to these, a number of other issues, like urbanization, pollution, woodcutting, and overexploitation of freshwater resources, also play a role in the destruction of habitats.

Additionally, a key component of the SGI is planting 10 billion trees within the Kingdom over the next few decades (SGI, 2021). This would equate to restoring about 40 million hectares of degraded land and represent over 4% of the Kingdom's contribution to meeting the global target of 1 trillion trees to be planted and 1% of the initiative's goals to limit the degradation of lands and

marine habitats (SGI, 2021). Additionally, replanting can lessen sandstorms, fight desertification, enhance air quality, and lower temperatures in nearby locations.

6. Conclusions

This study provides a detailed overview about the geography of Saudi Arabia where we examined the land types, thickness and use of the lands through advanced GIS tools. Moreover, potential sources of land degradation such as aridity, erosion, salinization, carbon loss, land pollution and natural oil extraction are also spotted in this study. We also prioritized the best recommended solutions to mitigate land degradation for instance the application of mulching, cover cropping, conservation tillage, nutrient management, land use management and agroforestry. Besides these recommendations, role SGI, UNDP, UNEP, FAO and world bank also summarized for the mitigation of land degradation in the study. However, further detailed studies are required to assess the role of each recommended practices under open field conditions for better understanding.

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