A new index to assess soil sustainability based on temporal changes of soil measurements using geomatics – an example from El-Sharkia, Egypt

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ABSTRACT
A Soil Sustainability Index (SSI) is developed based on integration of Soil Degradation Rate (SDR), Soil Fertility Index (SFI), Soil Quality Index (SQI) and Soil Resilience Rate (SRR). SDI, SRR, SQI, and SFI resemble in being measurable from soil attributes that reveal the soil-environment functionality. This approach index was calculated based on four vertices, which are represented by the SDR and SRR exploring the inherent soil properties, SOI; capacity of the soil to function, and SFI; the presence of adequately available plant nutrients. The four studied indices were categorized as low, moderate and high classes with percentages of total area for the study area for SFI being: 4.01, 54.46, 31.21%; and for SQR: 19.26, 30.27, 40.15%; while for SDR: 34.00, 29.19, 26.48%; and SRR: 17.80, 56.99 and 14.89%. The SSI was calculated to assess the current state of the soil under the influence of different agricultural management practices. It depends on the area of the square where SQI, SFI, SDR and SRR are the four vertices of the square. The proposed SSI equation obtaining results of: 7.65, 41.88, and 40.15% of total area as low, moderate and high classes, respectively. This work obtained new formula and definition for soil sustainability.

1. Introduction

Increasing population has led to an increase in the intensive use of agricultural land to cover the gap between demands and limited resources. The soil ecosystem is the backbone for agricultural development which depends heavily on goods and services (Tahoun and El-Naka, 2002; 2007). This pressure on soils by different land degradation processes threatens sustainable farm production progress (AbdelRahman & Tahoun, 2018; Tahoun et al., 1999). This highlights the urgent need for monitoring soil status trends and assessing the impacts of interventions. This could be done by determining reliable parameters of Soil Sustainability (SS) based on integration of Soil Degradation Rate (SDR), Soil Fertility Index (SFI), Soil Quality Index (SQI), and Soil Resilience Rate (SRR). Monitoring soil functional properties is an important input for proper sustainable management to maintain any agroecosystem. (AbdelRahman & Tahoun, 2018). In this context, the case of the El-Sharkia Governorate offers an illustrative example. The soils of the governorate occupy an area in the irregular fringe zone between the flood plain of the Nile River and the elevated plateau of the Eastern Desert. Consequently, soils of different textural classes, ranging from clay to sand, are encountered.

The El-Sharkia Governorate is considered one of the important agricultural governorates in Egypt. Its agricultural area is about 400,000 hectares (or approximately 10% of the total area of agricultural land in Egypt). Unfortunately, a large part of the agricultural area in the El-Sharkia Governorate has been affected by salts (Metwally et al., 2016; Shaddad & Hendawi, 2018). During the field activities in this study, the farmers in the northern region unanimously agreed that some lands of the Al-Hussainiya plain are unsuitable for agriculture because of the high level of soil salinity. This prompted the farmers to convert most of their lands to fish farms, and they confirmed that these practices led to the leaching of salts from the soil in periods ranging from five to ten years. During the field survey, an observation was made that the level of some lands in the Al-Hussainiya plain formed from sandy islands such as the island of Saud. The Al-Hussainiya plain is arranged in the form of an arc of high lands and consists of sand, gravel, sandy clay or impure alluvial. In addition part of Wadi Tumaylat is located in Al-Husainiyah, a sandy depression representing one of the branches.

South of the lands of Al-Husainyiah is an ancient alluvial soil of various textures on the sides of the ancient tributaries of the Nile. Its fertile, arable soil was formed from both sand and silt deposits. This
mixed formation is a result of the influence of sandy lands and the deposition of Nile waters in the lands of the plains, which are the areas sandwiched between swamps in the north and alluvial river lands in the south. The north of Al-Husayniyah has lands where limestone, marine and river sediments overlap, which leads to the presence of dense soil with very fine grains, which is unsuitable for agriculture due to its high salinity. Parts of these soils have been reclaimed with rice grown in San Al-Hajar in the north. From the above, we note a great diversity in the nature of the surface and soil due to the wide area of the Al-Hussainiya plain. The unified complaint during the field study was that most of the lands of the study area had relatively high salt concentrations.

Systematic evaluation through long-term experimentation is needed for establishing quantitative criteria of (i) soil quality in relation to specific functions; (ii) soil degradation in relation to critical limits of key soil properties and processes; and (iii) soil resilience in relation to the ease of restoration through judicious management and discriminate use of essential inputs. Quantitative assessment of soil degradation can be obtained by evaluating its impact on productivity for different land uses and management systems (Lal, 1997). Therefore, multidisciplinary research is needed to determine the effects of soil degradation on reduced productivity, reduced biomass, and environmental quality degradation in terrestrial ecosystems. Data from the years 1975, 2011, 2018 and 2021 in principal ecoregions were specifically collected to identify indicators of soil quality and soil resilience and establish critical limits of important properties for soil degradation and soil fertility. This was done in order to develop and standardise techniques for measuring soil sustainability in agricultural uses.

Managing soil in a sustainable manner will be the challenge, through proper nutrient management and appropriate soil conservation practices. This is to avoid further soil degradation and depletion of its capabilities due to wrong agricultural management, and failure to maintain soil fertility and quality. Soil Sustainability Index (SSI) is a process whose procedures express the basic concept of steps for managing soil properties that result in building and maintaining healthy soil, with the aim of increasing production and maintaining its sustainability, which emphasises soil value as one of the most important resources. In this context, selection of Soil Degradation Rate (SDR), Soil Fertility Index (SFI), Soil Quality Index (SQI), and Soil Resilience Rate (SRR) are important measurements required to identify the agricultural system. According to Oldeman et al. (1991) and Eswaran et al. (2001), the land degradation issue has a direct link with sustainability (Metwally et al., 2016; Shaddad & Hendawi, 2018; Lal, 1997; Oldeman et al., 1991; Eswaran et al., 2001; Yang et al., 2020), and therefore the proper management of land requires systematic technologies to integrate ecological and socioeconomic principles in agricultural use to achieve intergenerational equity.

According to Eswaran et al. (2001), SDR is determined by factors that are influenced by causes of land degradation. These are any processes and/or factors which force and/or influence the effectiveness of land degradation (Gobin et al., 2020; Malhi et al., 2020; Maqsoom et al., 2020; Othman et al., 2021; Sakai et al., 2020). Therefore, land quality must be matched with appropriate land use to reduce such discrepancies, prevent land degradation and assure sustainability (Aslam et al., 2020; Gopalakrishnan & Kumar, 2020; Gxokwe et al., 2020; Samarín et al., 2020; Senanayake et al., 2020; Tessema et al., 2020). Implementation of agricultural activities with effective decisions requires knowledge of SFI (Nkettia, Panwar et al. (2011) proved by using Pearson’s correlation matrix that there is a strongly significant positive correlation of soil fertility index with soil properties used as soil evaluation factor. Therefore, achieving and maintaining appropriate levels of soil fertility, especially plant nutrient availability, is of paramount importance if agricultural land is to remain capable of sustaining crop production at an acceptable level (Rashed, 2015). By monitoring changes in soil quality, optimal management of soil functions could be designed by understanding soil quality which help in determining a sustainable set of practices (AbdelRahman & Tahoun, 2018; Dumanski, et al., 1991a; Kwabena, 2011; Panwar et al., 2011; Rashed, 2015; Webb et al., 2017).

Ludwig et al. (2018) stated that soil resilience is an effective measure of soil management sustainability. Soils are resilient to environmental changes and shocks – that is, they will recover from or adjust to change if sufficient ‘pedological’ time is allowed. The soil management practices that have been applied by humans in a short time frame (AbdelRahman et al., 2021; Amato et al., 2015; Antoneli et al., 2020; Halbac-Cotoara-Zamfir et al., 2020; Ludwig et al., 2018) are unsustainable; a declining soil health threatens human livelihood. The resilience of the soil in terms of human expectations and time frames will depend on its ability to recover to an equilibrium state once improved practices have been extensively applied (Esmali Ouri et al., 2020; Gisladóttir & Stocking, 2005; Huang & Kong, 2016; Jurišić et al., 2020; Ken et al., 2020; Wijitkosum, 2020).

The sustainability index is the result of long-term factors assessing soil quality based on short-term factors under the influence of soil fertility affected by different fertiliser management practices (Kang et al., 2005). Soil
sustainability is an agricultural practice that aims to maintain soil health to ensure that it can support the successive and continuous growth of crops. Soil is an essential component of the least surface area of the Earth. The importance of this element lies in the provision of all basic services to sustain life. However, soil degradation has occurred in various forms and degrees, despite the resilience of soils, which requires devising a methodology for measuring soil sustainability that includes social and economic concepts affecting soil fertility and quality. Since soil management already reflects the social status and economic capacity of the farmer, the soil fertility index and the soil quality index are the most appropriate two factors to express in this way. In the present paper, we reiterate the importance of the interaction between soil indicators SDR, SFI, SQI and SRR. Meanwhile, we focus on the interdisciplinary nature of soil to reduce and understand soil sustainability. Based on the foregoing, we can define Soil Sustainability (SS) as an account of the resilience of the soil to resist various degradation processes and the extent of its response to fertility processes, and thus a reflection of soil quality to provide the ecosystem and social services through its capabilities to perform its functions and respond to external influences. Based on the above, we can define Soil Sustainability (SS) as an account of the resilience of soils to resist various degradation processes and their response to fertility processes, and thus as a reflection of soil quality to provide ecosystem and social services through their capabilities to perform their functions and respond to external influences. Thus, the term soil sustainability includes a wide range of features that take into account the functional capacity of the soil with the characteristics of its response to various factors, whether in-site or off-site influences. Thus, SS provides integrated information on the sum of different soil properties, with respect to the level of socio-economic system that influences soil services. Correlation of SS index values with SFI, SQI and SRR; makes it a composite indicator of soil based on the response characteristics and external factors (climate, land use) and makes it a realistic example for expressing the level of risks to which the soil is exposed, and thus determines the priorities of soil zone management.

To complete this effort, data for the years 1975 and 2011 collected from Ali, (2012) and this research work of 2018 and 2021 were used to compare soil properties and to illustrate changes. And simultaneously monitors the change of soil properties due to human influence for the years 1975, 2011, 2018 and 2021. This carried out taking into account that problems with soil fertility can typically be quickly addressed with inputs, whereas improving soil quality is generally a long-term process. The study area was carefully selected in the east of the Nile Delta in Egypt, to represent different soil textures where its soil is characterized as heavy clay texture in the north and clay texture in the center and west of the region, while it is sandy texture in the southeastern region. The fluctuations in soil properties are primarily due to agricultural processes in the study area. Northern portions of the study area have been exploited with practices of fish farms, whereas subsurface agricultural drainage was established. This improved the water table level and the degree of soil salinity. The increase in soil fertility and quality, in addition to the increase in its resilience, led to an increase in the value of the sustainability index. While the high rate of soil degradation led to weak values of the sustainability index.

This study aimed to monitor the change of soil properties due to human influence, and simultaneously develop a Soil Sustainability Index (SSI) based on integration of Soil Degradation Rate (SDR), Soil Fertility Index (SFI), Soil Quality Index (SQI), and Soil Resilience Rate (SRR). The study approach will help in investigation of soil problems in order to find appropriate solutions, which may increase land use efficiency, increasing the awareness of the beneficiaries and participants of the proposed equation and the continuity of their implementation. Ultimately, the equation developed will be used to obtain digital maps using geographic information systems (GIS) that will enable participating authorities and beneficiaries to make decisions, which in turn will lead to achieving sustainable development for the area. Therefore, the objectives of this study focused on developing a soil sustainability index for the dry region, and monitoring changes in soil properties as a result of agricultural management.

2. Materials and methods

The selected area (Figure 1) falls in a fragile portion of the eastern Nile Delta occupying approximately 4576 km². The area consists of Neonile deposits that were placed in the late Pleistocene (Said, 1993). It is located on the margins of the eastern delta. The northern and western parts of the study area cover part of the Nile Delta, while the southeastern part covers part of the northern area of the Eastern Desert of Egypt. In the middle between them is an area of overlap between the two types of land.

A selected set of soil analyses from 40 soil profiles was used to present the actual situation of the area under investigation. Thirteen soil profiles were used to compare soil properties during the years of 1975, 2011, 2018 and 2021. The selection of these 13 profiles is based on the condition that all samples were collected from the same site for all study periods. These 13 soil profiles are located in the same place during the years 1975, 2011, 2018 and 2021.
2.0.1. Soil Degradation Rate (SDR)

Ali (2012) indicated that the area has undergone slight to moderate rates of degradation processes, i.e. water logging, soil compaction, salinisation and alkalisation. According to Lal (1997), susceptibility to degenerative processes can be grouped into five classes (Table 1). Soils, depending on their inherent characteristics and climatic conditions, range from highly resistant or stable to extremely sensitive and fragile. Fragility, extreme sensitivity to degenerative processes, may refer to the whole soil, a degenerative process or a property (e.g. soil structure). Nutrient depletion is another principal process of soil degradation (Stoorvogel et al., 1993). Annual soil fertility depletion rates were estimated at 22 kg of N, 3 kg of P and 15 kg of K ha$^{-1}$.

Table 1. Rating scheme for soil degradation rating and soil degradation classes.

| Limitation | Relative weighting factor | Class | Susceptibility to degradation | Description                                                                 |
|------------|---------------------------|-------|-------------------------------|-----------------------------------------------------------------------------|
| None       | 1                         | 0     | resistant                     | extremely resistant to stress and very stable                               |
| Slight     | 2                         | 1     | slight                        | resistant to stress and stable                                              |
| Moderate   | 3                         | 2     | moderate                      | susceptible to stress and moderately stable                                 |
| Severe     | 4                         | 3     | severe                        | highly susceptible to stress and unstable                                   |
| Extreme    | 5                         | 4     | extreme                       | extremely susceptible and fragile                                            |

Figure 1. A: Landforms modified after Ali et al. (2007) and Ali (2012) and soil profile locations for the years 2011 after Ali (2012) and location map of soil profiles collected during this study in 2018 and 2021.
B: The DEM used for Landforms processing in GeoTIFF format, ALOS PALSAR Pixel spacing is 12.5 m for high-resolution (RT1).
C: Geology map of the study area according to Conoco (1987).
D: Land use/Land cover of the area, produced from sentinel data 2021.
If there is no limitation, the weight is 1, and when the limitation is extreme, the weight is five. This means that the least SDR is for good soils and the highest SDR is for poor soils.

Soil degradation is the loss of actual or potential productivity or utility as a result of natural or anthropogenic factors Lal (1994). Essentially, it is the decline in soil quality or reduction in its productivity and environmental regulatory capacity. Soil degradative processes, mechanisms that set in motion degradative trends, include physical, chemical and biological processes. Important among the physical processes is decline in soil structure, leading to crusting, compaction and unsustainable use of natural resources. Significant chemical processes include leaching, salinisation, reduction in CEC and loss of fertility. Biological processes include reduction in total and biomass carbon and decline in soil biodiversity. Soil structure is an important property that affects all three degradative processes. Factors affecting soil degradation are biophysical environments, which determine the kind of degradative processes, such as salinisation. Causes of soil degradation are the agents that determine the rate of soil degradation. These are biophysical forces (land use and soil management) that influence the effectiveness of processes and factors of soil degradation.

The provisional methodology of FAO, UNEP and UNESCO (1979) was applied on a regional level. The application of the parametric approach on different units was used to estimate the risk of soil degradation and the present day soil degradation. The general form of the parametric formula is:

\[ D = f(C, S, T, V, L, M) \] (1)

where \( D \) = soil degradation, \( C \) = climatic factor, \( S \) = soil factor, \( T \) = topographic factor, \( V \) = natural vegetation factor, \( L \) = land use factor, \( M \) = management factor.

The values of the variables are chosen in such a way that solving of the equation provides the numerical indication of the degradation rate. However, since the formula approximately describes the degradation processes and the values assigned to each factor can only be approximated for the present state of knowledge, the final results should not be regarded as absolute values for the soil loss or soil degradation. These values provide an approximate indication of the likely magnitude of degradation FAO, UNEP and UNESCO (1979).

Two types of assessment can be followed: A-Present degradation: degradation actually occurring expressed in an annual rate and not as the accumulated damage from the past to the present. B- Degradation risk: the risk that degradation will occur under certain defined conditions. In order to evaluate the risk of soil degradation, the relatively variable factors are standardised, and the general formula can be written as:

\[ D = f(C, S, T, K) \] (2)

In which: \( K \) = the constant, representing the standard conditions of \( V \), \( L \) and \( M \). under standard conditions, \( V \) is the vegetation factor, \( L \) is land use factor and \( M \) is management factor.

For the assessment of the present state of soil degradation, the vegetation land use factors are substituted instead of the value of standard conditions. For each of the soil degradation processes, a similar formula is used. The climatic aggressivity factor can be obtained from the average data of the national meteorological stations. The final result of the calculations falls into one of the soil degradation classes (Table 2).

The soil analyses shown in Table 3 were selected based on the concept of the minimum data set of soil analyses stated by (AbdelRahman & Tahoun, 2018) for the determination of soil status. The score/class of the suggested approach was built depending on the standard rating of each parameter used in this study. This will facilitate the use of any soil property as an easily used indicator in the calculation of SSI.

The general relationship of soil bulk density (BD) to root growth based on soil texture after (Arshad et al., 1997) considered either ideal bulk densities for plant growth (sandy < 1.60 g/cm³, silty 1.40 g/cm³ clayey 1.10 g/cm³) or BDs that restrict root growth (g/cm³) (sandy < 1.80 g/cm³, silty 1.65 g/cm³ clayey 1.47 g/cm³).

### 2.0.2. Soil Fertility Index (SFI)

The scored value of the indicator index \( S_i \) of soil is to sustain nutrients required by plants in adequate quantities and correct proportions (Jin et al., 2011). The soil fertility index (SFI) is a regularly used indicator for assessing soil fertility. Calculating an SFI, on the other hand, necessitates the measurement of several soil parameters in a laboratory, which adds to the expense and complexity of traditional approaches (Equation 3). Equation 4 may provide chances to test soil parameters and the SFI in a cost-effective and timely manner.

According to the implementation of Andrews et al. (2004) by Nketia (i), the SFI equation is as follows:

\[ SFI = \sum_{i=1}^{n} \frac{S_i}{n} \] (3)

where \( S_i \) = the scored value of the indicator index, and \( n \) = number of indicators following the procedures of Aslam et al. (2020) and Tessema et al. (2020).

The suggested equation for this approach is as follows according to (Nketia,):

\[ SFI = \sum_{i=1}^{n} \frac{S_i}{n} \times 10 \] (4)

All of the previous equations are multiplied by 10 to provide index values in the range of 1 to 10 rather than 0 to 1.
2.0.3. Soil Quality Index (SQI)

Soil quality index (SQI) is a tool to evaluate crop productivity. Soil quality indices improve when considering topsoil and subsoil properties (Vasu et al., 2016). The soil quality index (SQI) integrates the measured soil physical and chemical properties into a single parameter that can be used as a representative value of the overall assessment of spatial variability in soil fertility of the study area.

Table 2. Soil degradation classes of salinisation, chemical, physical and biological degradation (FAO, UNEP and UNESCO, 1979).

| Excess of salts (S) | Salinisation (Si) increase in conductivity 0–60 cm layer mmhos/cm/year | Alkalisation (Sa) increase in ESP 0–60 cm layer percent/year |
|---------------------|------------------------------------------------------------------------|-------------------------------------------------------------|
| none to slight       | <1                                                                     | <1                                                          |
| moderate             | 1–3                                                                    | 1–3                                                         |
| high                 | 3–5                                                                    | 3–5                                                         |
| very high            | >5                                                                    | >5                                                          |
| Chemical degradation (C) | Decrease of pH 0–30 cm layer pH units/year                              | Decrease of base saturation 30 cm layer percent/year         |
| none to slight       | <0.05                                                                  | <2.5                                                        |
| moderate             | 0.05–0.2                                                               | 2.5–5                                                       |
| high                 | 0.2–0.5                                                                | 10-May                                                      |
| very high            | >0.5                                                                  | >10                                                         |
| Physical degradation (D) | Increase in apparent density 0–60 cm g/cm3/year                      | Decrease in total porosity 0–60 cm percent/year              |
| none to slight       | <0.1                                                                  | <1                                                          |
| moderate             | 0.1–0.2                                                                | 3-Jan                                                       |
| high                 | 0.2–0.3                                                                | 5-Mar                                                       |
| very high            | >0.3                                                                  | >5                                                          |
| biological degradation (B) | Decrease in organic matter 0–30 cm layer percent/year             | Decrease in permeability 0–60 cm cm/h/year                 |
| none to slight       | <1                                                                    | <0.5                                                        |
| moderate             | 1–10                                                                  | 0.5–5                                                       |
| high                 | 1–20                                                                  | 20-May                                                      |
| very high            | >20                                                                   | >20                                                         |

Where \( S_i \) = the scored value of the indicator index, and \( n \) = number of indicators following the procedures of Aslam, Maqsoom, Kazmi, Sodangi et al., 2020; Tessema et al. (2020). Furthermore, the index value was used as a representative value of the overall assessment of spatial variability in soil fertility of the study area.

The authors used this method to assign threshold values to soil properties based on a literature research and expert opinion (Tables 2 and 3). SQI was calculated by combining the threshold levels and corresponding soil index score values in the Arc GIS model builder. After that, the separate index values were added together to get a total SQI.

The maximum value of the total SQI is 26 if all 19 soil properties are measured. The total SQI is then expressed as a percentage of the maximum possible value of the total SQI for the soil properties that are measured: \( SQI, \% = \frac{\text{total SQI}}{\text{maximum possible total SQI}} \times 100 \). Thus, missing properties do not contribute to the index. However, we recommend that SQIs based on only a few of the 19 measured soil properties not be included in any data analysis, since these values could provide a distorted assessment of soil quality because they are based on too few measured properties.

In this method, soil parameters were given threshold values based primarily on the literature review and expert opinion of the authors (Tables 2 and 3). The threshold levels and associated soil index score values were combined in Arc GIS model builder to get SQI. The individual index values were then summed to obtain a total SQI.

Soil bulk density may indicate soil compaction but is dependent on many soil factors including particle size distribution, soil organic matter content, and coarse fragment content. Generally, bulk density increases with increasing sand and rock content and decreases with increasing organic matter content. A mineral soil with ‘ideal’ physical properties has 50% solids and 50% pore space occupying a given volume of space. At optimal water content, half the pore space is filled with water. Such a soil will have a bulk density of 1.33 g/cm³. In general, roots grow well in soils with bulk densities of up to 1.4 g/cm³, and root penetration begins to decline significantly at bulk densities above 1.7 g/cm³ (Gopalakrishnan & Kumar, 2020; Senanayake et al., 2020). 1.5 g/cm³ was selected as the threshold.
Table 3. Threshold values of soil properties used to develop scores and classes for integrating SFI, SDR and SRR into SFI.

| Score/Classa | Non-Slight | Low | Moderately | High | Very High |
|--------------|------------|-----|------------|------|-----------|
| EC (dS/m)    | 0 < 2 Non-saline | 2 < 4 Very slightly saline | 4 < 8 Slightly saline | 8 < 16 Moderately saline | ≥ 16 Strongly saline |
| ESP          | <6 Non-sodic | 6–10 Sodic | 10–15 Moderately Sodic | 15–25 Strongly Sodic | ≥ 25 Very strongly Sodic |
| pH           | <4.5 Very low | 4.5–6.0 Low | 6.0–7.0 Moderate | 7.0–8.3 High | >8.3 Very High |
| Texture      | Sands | Fine Sandy Loams | Loams and Silt Loams | Clay Loams | Clays |
| CEC (meq/100 g) | 1–5 | 5–10 | 10–15 | 15–30 | >30 |
| CaCO₃ (%)    | 0 Non-calcareous | 0–2 Slightly calcareous | 2–10 Moderately calcareous | 10–25 Strongly calcareous | >25 Extremely calcareous |
| OC (%)       | 0–.25 | 0.25–0.5 | 0.5–0.75 | 0.75–1.02 | >1.02 |
| Water table (cm) | 0–50 | 50–75 | 75–90 | 90–120 | >120 |

*The parameters used for the calculation of SFI are EC, ESP, pH, Texture, CEC, CaCO3 and OC in addition to the parameters in Table 3. The parameters used for the calculation of SQI are EC, ESP, pH, Texture, CEC, CaCO3, OC, and Water table in addition to the parameters in Table 3. The parameters used for the calculation of SDR and SRR are EC, ESP, pH, Texture, CEC, CaCO3, OC, and Water table.*
Table 4. Soil quality index values and associated soil property threshold values and interpretations (adapted from Amacher et al. (2007)).

| Parameter                  | Level   | Interpretation                              | Index |
|----------------------------|---------|---------------------------------------------|-------|
| Bulk density (g/cm³)       | >1.5    | Possible adverse effects                    | 0     |
|                           | ≤1.5    | Adverse effects unlikely                    | 1     |
| Coarse fragments (percent) | >50     | Possible adverse effects                    | 0     |
|                           | ≤50     | Adverse effects unlikely                    | 1     |
| Soil pH                    | <3.0    | Severely acid – almost no plants can grow in this environment | −1    |
|                           | 3.01 to 4.0 | Strongly acid – only the most acid tolerant plants can grow in this pH range and then only if organic matter levels are high enough to mitigate high levels of extractable Al and other metals | 0     |
|                           | 4.01 to 5.5 | Moderately acidic – growth of acid intolerant plants is affected depending on levels of extractable Al, Mn, and other metals | 1     |
|                           | 5.51 to 6.8 | Slightly acidic – optimum for many plant species, particularly more acid tolerant species | 2     |
|                           | 6.81 to 7.2 | Near neutral – optimum for many plant species except those that prefer acid soils | 2     |
|                           | 7.21 to 7.5 | Slightly alkaline – optimum for many plant species except those that prefer acid soils, possible deficiencies of available P and some metals (for example, Zn) | 1     |
|                           | 7.51 to 8.5 | Moderately alkaline – preferred by plants adapted to this pH range, possible P and metal deficiencies | 1     |
|                           | >8.5    | Strongly alkaline – preferred by plants adapted to this pH range, possible B and other oxanon toxicities | 0     |
| Total organic carbon in mineral soils (percent) | >5 | High – excellent build-up of organic C with all associated benefits | 2 |
|                           | 1 to 5 | Moderate – adequate levels | 1 |
|                           | <1     | Low – could indicate possible loss of organic C from erosion or other processes, particularly in temperate or colder areas | 0 |
| Exchangeable Na percentage (exchangeable Na/ECCE x 100) | >15 | High – sodic soil with associated problems | 0 |
|                           | ≤15    | Adverse effects unlikely                    | 1     |
| Total nitrogen in mineral soils (percent) | >0.5 | High – excellent reserve of nitrogen | 2 |
|                           | 0.1 to 0.3 | Moderate – adequate levels | 1 |
|                           | <0.1   | Low – could indicate loss of organic N | 0 |
| K (mg/kg)                 | >500    | High – excellent reserve | 2 |
|                           | 100 to 300 | Moderate – adequate levels for most plants | 1 |
|                           | <100   | Low – possible deficiencies | 0 |
| Mg (mg/kg)                | >50    | High – excellent reserve | 2 |
|                           | 50 to 500 | Moderate – adequate levels for most plants | 1 |
|                           | <50    | Low – possible deficiencies | 0 |
| Ca (mg/kg)                | >1000  | High – excellent reserve, probably calcareous soil | 2 |
|                           | 101 to 1000 | Moderate – adequate levels for most plants | 1 |
|                           | 10 to 100 | Low – possible deficiencies | 0 |
|                           | <10    | Very low – severe Ca depletion, adverse effects more likely | −1 |
| Al (mg/kg)                | >100   | High – adverse effects more likely | 0 |
|                           | 11 to 100 | Moderate – only Al sensitive plants likely to be affected | 1 |
|                           | 1 to 10 | Low – adverse effects unlikely | 2 |
|                           | <1     | Very low – probably an alkaline soil | 2 |
| Mn (mg/kg)                | >100   | High – possible adverse effects to Mn sensitive plants | 0 |
|                           | 11 to 100 | Moderate – adverse effects or deficiencies less likely | 1 |
|                           | 1 to 10 | Low – adverse effects unlikely, possible deficiencies | 1 |
|                           | <1     | Very low – deficiencies more likely | 1 |
| Fe (mg/kg)                | >10    | High – effects unknown | 1 |
|                           | 0.1 to 10 | Moderate – effects unknown | 1 |
|                           | <0.1   | Low – possible deficiencies, possibly calcareous soil | 0 |
| Zn (mg/kg)                | >10    | High – possible toxicity to Zn sensitive plants, may indicate mining areas or industrial sources of Zn | 0 |
|                           | 1 to 10 | Moderate – effects unknown, but adverse effects unlikely | 1 |
|                           | <1     | Low – possible deficiencies in calcareous or sandy soils | 0 |
| 0.03 M NF4 + 0.025 M HCl (Bray 1) P (mg/kg) | >30 | High – excellent reserve of available P for plants in acid soils, possible adverse effects to water quality from erosion of high P soils | 1 |
|                           | 15 to 30 | Moderate – adequate levels for plant growth | 1 |
|                           | <15    | Low – P deficiencies likely | 0 |
| pH 8.5, 0.5 M NaHCO3 (Olsen) P (mg/kg) | >30 | High – excellent reserve of available P in slightly acidic to alkaline soils, possible adverse effects to water quality from erosion of high P soils | 1 |
|                           | 10 to 30 | Moderate – adequate levels for plant growth | 1 |
|                           | <10    | Low – P deficiencies likely | 0 |

The 19 soil parameters for SOIL are combinations of parameters from Tables 3 and 4 (EC, ESP, pH, Texture, CEC, CaCO3, OC, Water table, Bulk density, Coarse fragments, Total nitrogen, K, Mg, Ca, Al, Mn, Fe, Zn, and P).

value for bulk density, above which there is an increasing probability of adverse effects from soil compaction or high rock content. Soils with a coarse fragment content of > 50% have a greater probability of adverse effects from infiltration rates that are too high, water storage capacity that is too low, more difficult root penetration, and greater difficulty in seed germination and seedling growth. High coarse fragment contents have been shown to limit forest soil productivity (Rodrigue & Burger, 2004). Soil organic matter is a key component of soils because of its influence on soil physical and chemical properties and soil biota (Fisher, 1995). Soil organic matter is composed of many elements, but C and
N are two of the most important. The organic C and N contents of soils are the result of all the inputs and outputs and soil forming processes, but generally, higher levels of organic C and N are found in colder and wetter soils (wetlands) where organic matter tends to accumulate. Lesser amounts are found in more sandy soils because of warmer temperatures. Various disturbances and land management practices can result in decreased soil organic matter levels (Jenco et al., 2020; Wang et al., 2020). Soils with total organic carbon (TOC) and total N contents of less than 1% and 0.1%, respectively, are at a greater risk of decline if soil erosion and/or other disturbances that accelerate organic matter loss continue to result in a net loss of soil organic matter, particularly in areas where nearby undisturbed, native soils are found to have higher levels of TOC and total N (USDA-NRCS-SQI 2003).

The suggested equation for this approach is as follows:

$$\text{SFI} = \sum_{i=1}^{n} \frac{W_i \times \text{S}}{\sum W_i} \times 10 \quad (6)$$

All of the previous equations are multiplied by 10 to provide index values in the range of 1 to 10 rather than 0 to 1.

### 2.0.4. Soil Resilience Rate (SRR)

Soil quality vs. soil resilience is defined as (Lal, 1997). Soil quality becomes a function of soil resistance during or immediately following a disturbance, whereas after a disturbance, soil quality becomes a function of soil resilience (Seybold et al., 1999).

$$S_r = -dS_q/dt \quad (7)$$

where $S_r$ = soil resilience, $S_q$ = soil quality, $t$ = time and $d$ = rate of soil degradation (rate of change of soil quality).

Soil properties and management affect soil renewal rate. (Lal, 1994) proposed the following model. The soil resilience formula after (Lal, 1997) is as follows:

$$S_r = S_a + \int_0^t (S_n - S_d + I_m)dt \quad (8)$$

where $S_r$ = soil renewal rate, $S_a$ = antecedent condition, $S_n$ = rate of soil renewal, $S_d$ = rate of soil degradation, $I_m$ = management input and $t$ = time.

The soil resilience formula after (Lal, 1997) was adopted as follows:

$$S_r = (S_a + \int_0^t (S_n - S_d + I_m)dt) 	imes 10 \quad (9)$$

All of the previous equations are multiplied by 10 to provide index values in the range of 1 to 10 rather than 0 to 1.

### 2.0.5. Soil Sustainability Index (SSI)

Each of SDR, SFI, SQI, and SRR depends on the computation of laboratory measurements for soil analysis in this study. Meanwhile, these soil analyses are the common and inter-related factors, which are used separately to measure and identify the actual state of the soil. These values could change over time through proper agricultural management as a means of soil conservation for sustainability. It is suggested that the equation derived in this study should be used to estimate the soil sustainability of agriculture as shown in Figure 2.

The proposed equation for soil sustainability according to Andrews et al. (Andrews et al., 2004) in this case is as follows:

$$\text{SSI} = f_s \left( \frac{SDR + SRR + SQI + SFI}{n} \right) \times M \quad (10)$$

Where SSI is Soil Sustainability Index, $f_s$ is function of time (scored as number of years); $f_s$ is the number of parameters used in calculation of SDR, SRR, SQI and SFI. $M$ is the human and management factor ($M$ is scored as 100 for very suitable management, 80 for suitable management, 60 for proper management, 40 for mismanagement), and $n$ is number of soil parameters used for the calculation of SDR, SRR, SFI and SQI.

The 13 joint soil profiles, located in the same places between all the study years 2011, 2018 and 2021 were used to determine the changes in soil properties to determine the spatial and temporal changes.

![Figure 2. Methodology flowchart for producing soil sustainability.](image-url)
While the rest of the 37 soil profiles were used to determine and measure the accuracy of the results. Forty soil profiles were excavated and the analyses used for the calculations of SDR, SFI, SQI, and SRR. Then the results were implemented in GIS model-builder to produce SSI. All indicator values of SDR, SFI, SQI, and SRR were converted to 0, 0–1 or 1, indicating low, moderate or high spatial variability respectively. These ranges of scored values were compared with the standard ranges of soil status. In Table 3 the standard values of EC classes (0–4, 4–8, 8–16 and more than 16 dS/m), and in Table 2 the soil degradation classes of salinisation were 0–1, 1–3, 3–5 and >5. This means that if the EC value was 4.1, salinity is moderate (class 1–3) as shown in Table 2 or class 4–8 as shown in Table 3.

The model-builder was used to build the spatial distribution of SDR, SFI, SQI, and SRR, and the evaluation was based on the weighting rates for each. The proposed methodology in this study indicates that the ability of soil to sustain is based on two factors, time and management. Time factor was calculated based on the rate of change of each parameter per the period of study, while management factors were collected by survey approaches from the field. Sustainable land management combines technologies and activities to maintain and/or enhance production, reduce the level of production risk, protect the potential of natural resources, prevent soil and water degradation, be economically viable, and be socially acceptable (Smyth et al., 1993).

In Table 5, selected soil properties were calculated for weighted average of each soil profile data for the years 2011 and 2021.

### 3. Results and discussion

#### 3.1. Soil parameters status

A selected set of soil analyses (EC, ESP, CaCO3, BD, water table level, OM, CEC and pH) from 40 soil profiles was used to identify the actual situation of the area under investigation. Thirteen data profiles were used to compare soil properties during the years 1975, 2011 and 2021. The selection of these 13 profiles is based on falling into the same locations, which means all profiles located in the same area are used for quantitative assessment of rate changes of soil properties. Figures 3, 4, 5, 6, 7 and 8 illustrate the changes of selected soil properties.

Organic matter content (OM), cation exchange capacity (CEC) and soil pH experienced slight changes in the area. Most of these changes are negligible with slight effects. Low values of OM and CEC were found in the areas with coarse soil texture of the Aeolian plain of sandy remnants (OS1 and OS2).

(Ali, 2012) stated that the area has undergone slight to moderate degradation processes, i.e. water logging, soil compaction, salinisation and alkalislation. Consistently, the results of this study reveal the same rates of soil deterioration as (Ali, 2012) found. The rate of all these degradation process increased from none to slight to low rates during the period of 2011 to 2021.

The following figures illustrate the changes of selected soil properties. Salinity (EC) increased during the period studied (0.01, 0.13 and 0.15 dS/m for the years 1975, 2011 and 2021, respectively), as the weighted average for the whole area. There was a decrease by 0.14 dS/m in landforms OB1, OB2, DB1, DB2, T1, T2 and TB (Figure 3). Moreover, ESP increased from 0.01% to 0.07% during 1975 to 2011, to 0.09 in the year 2021. The results indicate a decrease in ESP values to 0.03 in the landforms DB1, DB2, T1, T2 and TB (Figure 4). The results of the changes between 1975 and 2011 are the same as results demonstrated by (Ali, 2012). Data indicate that the rate of ESP is slight to moderate.

The annual salinity (EC) increased from 0.01 to 0.13 dS/m during 1975 to 2011 to 0.15 dS/m during 2021 as a weighted average for the whole area. There was a decrease by 0.14 dS/m in landforms OB1, OB2, DB1, DB2, T1, T2 and TB (Figure 3). Moreover, ESP increased from 0.01% to 0.07% during 1975 to 2011, to 0.09 in the year 2021.

### Table 5. Weighted average of soil properties for selected soil profiles.

| Map Unit | Bulk density (BD) (g/cm³) | pH | OM (%) | EC (dS/m) | CaCO3 (%) | CEC (cmol+/kg Soil) | ESP (Exchangeable sodium percentage) | Water Table (cm) |
|----------|--------------------------|----|---------|----------|-----------|---------------------|------------------------------------|-----------------|
| CF1      | 1.35                     | 1.46 | 8.1     | 8.23    | 1.4       | 1.6                 | 13.11                             | 15.1            |
| CF2      | 1.35                     | 1.44 | 8.2     | 8.21    | 1.6       | 1.71                | 21.2                              | 21.2            |
| OS1      | 1.12                     | 1.31 | 7.7     | 7.8     | 0.2       | 0.45                | 7.4                                | 5.9             |
| OS2      | 1.13                     | 1.24 | 8.0     | 7.9     | 0.4       | 0.51                | 13.6                              | 12.6            |
| OM1      | 1.33                     | 1.36 | 7.8     | 7.9     | 0.9       | 1.1                 | 8.3                                | 5.9             |
| OM2      | 1.35                     | 1.46 | 7.8     | 8.1     | 1.21      | 1.3                | 9.4                                | 10.1            |
| OB1      | 1.36                     | 1.33 | 8.1     | 7.9     | 1.61      | 1.33               | 1.9                                | 2.1             |
| OB2      | 1.36                     | 1.34 | 8.2     | 8.1     | 1.23      | 1.34               | 7.8                                | 5.7             |
| DB1      | 1.43                     | 1.24 | 8.1     | 8.0     | 0.95      | 1.1                | 3.19                               | 2.3             |
| T1       | 1.16                     | 1.21 | 7.9     | 8.0     | 1.42      | 1.34               | 1.6                                | 0.98            |
| T2       | 1.30                     | 1.36 | 7.8     | 7.9     | 1.2       | 1.24               | 5.6                                | 3.9             |
| TB       | 1.30                     | 1.21 | 7.4     | 7.3     | 1.4       | 0.9                | 2.8                                | 1.6             |
Figure 3. Spatial changes of soil salinity (EC) during 2011 and 2021 using IDW geostatistics techniques and the changes associated with landforms between 1975, 2011 and 2021.

Figure 4. Spatial changes of exchangeable percentage (ESP) during 2011 and 2021 using IDW geostatistics techniques and the changes associated with landforms between 1975, 2011 and 2021.

Figure 5. Spatial changes of calcium carbonate content during 2011 and 2021 using IDW geostatistical techniques and the changes associated with landforms between 2011 and 2021.

Figure 6. Spatial changes of bulk density during 2011 and 2021 using IDW geostatistical techniques and the changes associated with landforms between 1975, 2011 and 2021.
A decrease in ESP to 0.03 was observed in the landforms DB1, DB2, T1, T2 and TB (Figure 4). The results of the changes between 1975 and 2011 are the same as results demonstrated by (Ali, 2012).

It is clear from Figure 5 that there are no changes in lime content in the area except in landform units CF1, CF2, and OS1, which have a slight increase of lime content because of its addition by farmers to reclaim alkaline-salt affected soils. This indicates that decrease of soil salinity in unit OS1 may be due to human activities in the area to reclaim soil for agricultural purposes.

The increase of soil compaction (bulk density, Figure 6) is due to modern heavy agricultural machinery. This combined with over irrigation and human intervention in natural drainage may be the main cause of high water
table level (Figure 7). The areas which show slight improvement, as in units T1, T2, and T8, may be due to the combination of proper agricultural practices, artificial drainage and coarse textured soils.

3.2. Actual status of soils in the year 2021

Different soil properties were estimated to illustrate directly the productivity level of soils. Estimated SDR, SRR, SFI, and SQI demonstrated that soils of the northern part of the study area are naturally degraded, especially the low areas of Manzala Lake. Over irrigation, decreased effective depth, and high soluble salts levels are the main reasons of decreasing productivity factors in this portion of the governorate. However, it is noted from the agricultural practices due to the fertilisers led to high available content of micro nutrients in the units of CF1 and CF2 which led to increased values of SFI. Aeolian deposits (OS1 & OS2) show low values of selected estimated indicators due to the low quality of the original soil properties like coarse soil texture. Soil salinity and effective depth showed small changes in increasing the estimated SDR, SRR, SFI, and SQI due to cultivation practices.
that were started in the year 2003 (Ali, 2012). SDR, SRR and SQI showed low levels in landform units OM1 & OM2 of the overflow mantle. This could be due to effective soil depth, compaction, alkalinity and soluble salts concentrations. The agricultural practices and addition of fertilisers led to SFI increases. The landforms OB1 and OB2 showed the same results for the same reasons as the previous units when considering the important drainage condition factors in these units. To the contrary, the high efficiency of drainage networks led to increases of SRR and SQI in the units of decantation basins (DB1 and DB2). The overall result of the degree of improvement of the soil properties due to human intervention in the area was around 36.7%, while about 43.3% of the area deteriorated due to mismanagement, and almost 20% of the area is naturally degraded due to the natural deterioration factors in the area as shown in Figure 10.

The north area is a flat plain with abundant water resources resulting from rains whose waters descend from the southern highlands. In the past, the farmers practiced the process of land washing to reclaim salt affected soils to increase agriculture production (Dumanski, et al., 1991a; Fisher, 1995). Also, one of the excellent salt washing practices in the region is the use of land for fish farming for periods of no less than five years. The large amount of water used helps to wash salts from the soil profiles in the area, and the organic additives used in fish feeding improve the chemical, physical and biological properties of soil in the area (Henderson, 1995; Schlesinger, 1997). It has a comparative advantage in the production of untreated crops to be suitable for exportation. The administration of the agricultural area provides seeds, fertilisers and extension courses for farmers, which helps to increase productivity (Schlesinger, 1997; Seybold et al., 1999; Smyth et al., 1993).

Figure 10. Soil Degradation Rate (SDR), Soil Resilience Rate (SRR), Soil Fertility Index (SFI) and Soil Quality Index (SqI) in the study area in 2021.
From Figure 9 it is obvious that the northern region has a noticeable change in the properties of the soil due to the change of land uses in the region between rice cultivation and the conversion of saline lands to fish farms and their reuse in agricultural activity during the past decade. These results are similar to those obtained by (S.A.H., 2009). It could be concluded that these practices are the main reasons behind the changes of the physio-chemical properties in this area.

The soil texture ranged between silt, clay loam, clay, sandy loam, and loamy sand, according to the findings. The measured soil salinity concentration varied by location, ranging from very low to very high. High to extremely high salinity, with a wide range of soil salinity (14.9 to 21.2 dS/m), defined the northern area of units CF1 and CF2. T1, on the other hand, was found to have low to absent salinity, with electrical conductivity of saturated soil-paste extract (ECe) values less than 0.95 dS/m in the southern section of the research region. The rest of the research region had a salinity of 4-8 dS/m, which was moderately high.

Except in some regions with rising groundwater, where the water table level ranged between 60 and 90 cm, soil depth was not deemed a limiting issue throughout the research area, with soil profile depths ranging from 100 to 150 cm (deep to extremely deep). The measured soil organic matter content ranged from 0.45 to 1.71%, while the bulk soil density in the research region ranged from 1.10 to 1.46 mg/cm3, with bulk soil density being associated with soil texture. Except for CF1, which was found to be calcaric with CaCO3 levels ranging from 12.5% to 13.1%, the soil in the research region was non-calcareous, with CaCO3 levels ranging from 1% to 9%.

### 3.3. Soil indices: (SDR), (SRR), (SFI) and (Sqi)

Soil resistance results indicate that the average soil resistivity is as low as 17.8%, moderate of 56.99%, and high of 14.89% of the total area to recover its health. This difference between values is in response to the continuous process that contextualises the short time that humans have extensively used the land, changed and directly depended on the soil. This explains the different degrees in the rate of land degradation as shown in Table 6 and Figure 10.

From Table 6, SQR indices demonstrate the ability of soil to operate at a large scale, while SFI results show that the soil in the study area provides adequate plant nutrients. This demonstrates that soil fertility problems can be quickly addressed through inputs, while improving soil quality is generally a long-term process, which reflects mismanagement through agriculture practices in the area.

Dry Sabkhas = 0.77%, Turtle backs = 0.14%, Fishponds = 7.95%, Swamps = 1.47%

These measurements were used to assess the sustainability of the soil based on all previous factors as a function of time from 1975, 2011 to 2021 with results represented in Tables 6 and 7.

The measurements used to assess the sustainability of the soil based on all previous factors as a function of time are represented in Table 3.

Based on this research, the proposed equation for soil sustainability is as follows:

\[ SSI = f \left( \frac{SDR + SRR + SQI + SFI}{n} \right) \times M \]

Soil sustainability index results demonstrate the importance of the use of suitable agriculture practices to overcome natural hazards and inherent soil degradation.

### Table 6. Total areas in percentages of SRR, Sqi, SFI, SDR, and SSI by class in the study area.

| Classes | SRR (%) | Sqi (%) | SFI (%) | SDR (%) | SSI (%) |
|---------|---------|---------|---------|---------|---------|
| Low     | 17.80   | 19.26   | 4.01    | 34.00   | 7.65    |
| Moderate| 56.99   | 30.27   | 34.46   | 29.19   | 41.88   |
| High    | 14.89   | 40.15   | 31.21   | 26.48   | 40.15   |

### Table 7. Soil Sustainability Index (SSI) based on integration of Soil Degradation Rate (SDR), Soil Fertility Index (SFI), Soil Quality Index (Sqi), and Soil Resilience Rate (SRR).

| Landforms                  | Soil             | SQI | SFI | SDR | SRR | SSI |
|---------------------------|------------------|-----|-----|-----|-----|-----|
| Decantation basin Low elevated | Typic Torrifuvents | High | Moderate | Low | Moderate | High |
| Sandy remnants Low elevated               | Typic Torrifuvents | Moderate | Moderate | Moderate | Moderate | Moderate |
| Sandy remnants High elevated                 | Typic Torrifuvents | Low     | Moderate | Moderate | Moderate | Moderate |
| Decantation basin Low elevated               | Modern Argids     | Moderate | High | Low | Low | Low |
| Decantation basin High elevated               | Modern Argids     | High    | High | High | Moderate | High |
| Decantation basin High elevated               | Modern Argids     | High    | High | High | High | High |
| Decantation basin High elevated               | Modern Argids     | High    | High | High | High | High |
| Decantation basin High elevated               | Modern Argids     | High    | High | High | High | High |
| Turtle backs                  | Modern Argids     | High    | High | High | High | High |
| Clay flats Relative low            | Modern Argids     | High    | High | High | High | High |
| River terraces Relatively low                | Modern Argids     | High    | High | High | High | High |
| Sandy remnants High elevated               | Modern Argids     | High    | High | High | High | High |
| Decantation basin High elevated               | Modern Argids     | High    | High | High | High | High |
| Decantation basin High elevated               | Modern Argids     | High    | High | High | High | High |
| Decantation basin High elevated               | Modern Argids     | High    | High | High | High | High |
processes. The SSI result considering human management factors revealed that 36.7% was high sustainable agricultural area, while about 43.3% was moderate sustainable agricultural area and almost 20% of the area was low sustainable agricultural area as shown in Figure 11.

The result was validated using model builder, and the overall accuracy was 97.3% for the spatial distribution. Soil analysis results in the selected years are much better for accuracy assessment of any other reference data. Thus, the accuracy was assessed referring to the
congruous soil (i.e. EC data 1975, 2011 and 2021). It was done by taking 10 and 20 samples from the classes using ArcGIS 10.4. The suggested formula by (Congalton & Green, 2019) was used to compute the Kappa coefficient, and producer accuracy and overall accuracy were also computed.

The statistical correlation (Figure 12) revealed that the SSI has a significant correlation with SRR, SDR, SFI, and SQI \((R^2 = 0.93, 0.88, 0.93, \text{and } 0.88, \text{respectively})\). Overall, the used soil properties for caulations of all indices had correlation of 90%. Therefore, this obtained regression equation was used for measure the accuracy of the approched SSI. These salinity classes were defined using the international salinity thresholds. While the reclasses method was used to classify the different SSI levels, according to the different standard classes of remain indices. These SSI classes were defined using the international thresholds of all inputs.

4. Conclusions

Individual soil indicators were modelled in an integrative measure of Soil Sustainability Index (SSI) which was developed using an adapted conceptual framework by integration of SDR, SFI, SQI after and SRR after. Soil Degradation Rate (SDR) and Soil Resilience Rate (SRR) are important factors exploring the inherent soil properties, while Soil Quality Index (SQI) and Soil Fertility Index (SFI) are the most important indices to demonstrate the off-site and on-site soil processes which affect directly soil characteristics. Therefore, the integration of all of these parameters increases the accuracy of sustained measures. This level of studying soil properties could serve as a guide for efficient proper management to maintain soil productivity. In this study, soil analyses were used as common factors in calculating indices. Taking into consideration that the key factor influencing the values of all these equations is management over time, soil sustainability index was calculated by combining all these indices. This emphasises the importance of the suggested approach which could be used as a standard approach to estimate the quality of the applied agricultural management practices. In this case, the estimated SDR, SRR, SFI, and SQI demonstrated that soils of the northern part of the study area are naturally degraded, especially the southern areas of Manzala Lake. Over irrigation, decreased effective depth and high soluble salt levels are the main reasons of decreasing productivity factors in this portion of the governorate. The overall result of the degree of improvement of the soil properties due to human intervention in the area was around 36.7%, while about 43.3% of the area deteriorated due to mismanagement, and almost 20% of the area is naturally degraded due to natural deterioration factors. In the study area, there is a clear need to trace the continuity of the current pattern of agricultural management and its impact on sustainability. Because of this pattern, there is a need to intervene in agricultural rotations, irrigation systems and agricultural management to improve the management and land use systems in the area. It is expected that demand for agricultural crops will increase with the growth of the population. Increasing the quantity and quality of food produced in response to the increasing demand will require an increase in agricultural intensity. Proper agricultural practices, combined with correct use and effort, are often one of the best ways to increase the productivity of smallholders. The proposal presented in the study for the sustainability measurement of the land will help to increase production and improve quality.

Author Contributions

Writing original draft, M.A.E.A and H.M.A.; Methodology, M.A. E.A, H.M.A and M.S.E.; Planned and designed, H.M.A. and H. M.A.; Formal analysis, M.A.E.A, H.M.A. and M.S.E; Writing review & editing, M.A.E.A.; H.M.A. M.S.E and B.A.E.; and Supervision, M.A.E.A. and B.A.E. All authors have read and agreed to the published version of the manuscript and all authors confirm that all the text of this paper is new and has not been published previously.

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