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Sustainability assessment using geostatistical analysis and spatial modeling in El-Tina plain in Egypt

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Abstract

Sustainable Land Management (SLM) in agriculture is a very complex and challenging concept encompassing biophysical, socioeconomic and environmental concerns that must be viewed in an integrated manner. In order to evaluate the sustainability of agriculture sector in El-Tina plain, Egypt, Ordinary Kriging (OK), and spatial modeling were used to generate soil map and build SLM model in ArcGIS for sustainability assessment on the basis of international Framework for Evaluating Sustainable Land Management (FESLM). Five FESLM pillars: to enhance production services (productivity), to reduce the level of production risk (security), to protect the potential of natural resources and prevent degradation of soil and water quality (protection), to be economically viable (viability) and to be acceptable (acceptability) were assessed under the umbrella of biophysical and socio-economic conditions. These indicators have been included in a prototype decision support system (DSS). Feedback on the indicators was obtained from the farmers after the DSS was used to evaluate their farming system. Information extracted from 58 questionnaires carried out with local farmers aimed to characterize the land management systems, outline their constraints and potentials, 96 soil sample points and 41 observation points have been analyzed according to the FESLM methodology to develop SLM indicators that address the five pillars of the FESLM, producing maps showing soil mapping units sustainability, biophysical, social and economic conditions. As a result, this model is able to highlight these soil mapping units that are most in need of assistance to achieve sustainability. It will also be a valuable tool for evaluation and monitoring of strategies for sustainability. Major sustainability constraints could be identified as high salinity, high alkalinity and lack of infrastructure. Based on the sustainability analysis, soils of the study area belong to classes 2, 3 and 4.

1 Introduction

The term Sustainable Land Management (SLM) emerged following the global discussion on sustainable development initiated by the Brundtland Commission. Sustainable development was defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland 1987; Smyth and Dumanski, 1993). At the same time sustainability indicators have proliferated with sustainability assessments becoming increasingly common. As such, there is a wide range of approaches taken to sustainability assessment including indicators or indices, product-related assessment and integrated assessment tools (Ness et al. 2007). SLM is defined as a system that combines technologies, policies and activities which aimed at integrating socioeconomic principles with environmental concerns so as to simultaneously: maintain or enhance production/services (productivity); reduce the level of production risk (security); protect the potential of natural resources (protection); be economically viable (viability); be socially acceptable (acceptability) (Dumanski and Smyth 1994). Sustainable land management carries strong communication to environmental quality. It aims at controlling soil erosion through diversity crop rotation and conservation-oriented tillage practices. Sustainability is a concern and cannot be directly measured (Zink and Farshed 1995).

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As the sustainable management of land resources becomes more important than land supply for development, it is important to know whether current land management is leading towards or away from sustainability. Farmers, researchers and policy makers become interested in integrative measures of the current status of land quality and its change over time (Hurni 2000). There is a growing consensus that the long-term sustainability of agriculture and rural communities can be enhanced through locally-based planning and management at the farm scale, including the Farm Recommendation Unit (FRU) and Resource Management (Eswaran et al. 2000).

To enhance SLM as a decision support tool, it can be integrated with GIS to combine geographical data with multiple criteria decision models producing maps that show the ranking of options (Malczewski 2006). The use of GIS software is increasing among regional managers for storing data and producing maps. So it would be useful to develop decision support systems in GIS to decrease data transfer between software packages, reducing possible errors and loss of information.

El-Tina plain in Egypt is an important part of El-Sam canal project, unfortunately this area does not have accurate soil maps and data base to support sustainable agriculture production. In this case, the problem solving system would bring the indicator information together to rank the sustainability within the region. Thus, a decision support tool for sustainability assessment would be able to help regional managers to implement strategies to progress sustainability in a way that will have the greatest impact. But, to be an effective decision support tool, it has to integrate the best science available into the decision making process at a level that decision makers understand, preventing the loss of any important information (Giampietro et al. 2006). Therefore, the aim of this paper is to generate accurate soil maps supporting a decision support tool that integrates sustainable land management of locally selected sustainability indicators into GIS to produce a spatial decision support system (DSS) for sustainability assessment in El-Tina plain region.

2. Materials and methods

2.1 The study area

The study area is located at the north-western part of the Sinai Peninsula, Egypt, between longitudes 32º20'35"and 32º33'10" east and latitudes 30º57'25" and 31º04'28" north, approximately 174 km^2 (Figure 1). It is located under arid conditions; the annual rainfall ranges from 33.3 mm to 70.2 mm and occurs over a short period (from October to March). Air temperature ranges from 7.6 to 23.4 ˚C in winter and between 16.4 and 35.7 ˚C in summer. Mean evaporation is high and ranges from 3.7 mm/day to 7.4 mm/day (Aly 2005). El-Tina plain is almost flat and the ground elevation ranges from 0-5 m above sea level (Reda 2000). The soils of El-Tina plain were characterized by shallow to deep soil profile underlain by water table at 50-100 cm, with texture varying between sandy loam to clay. According to Nawar (2009) Calcium carbonates content ranges between 0.1 and 6.3 %. Organic matter content ranges between 0.1 and 2.1.The total soluble salts content ranges between 4.5 and 164.4 dSm^{-1}. Cation Exchange Capacity (CEC) ranges between 3.4 and 64.4 meq/100g soil. Gypsum content ranges between 0.1 and 7.9%. The total soluble salts of El-Salam canal water ranges between 0.8and 1.4 dSm^{-1}. Farag (1999) classified the soils of El-Tina plain into two orders: Entisols and Aridisols that included four subgroups: Typic Aquisalids, Typic Haplosalids, Typic Torripsamments and Gypsic Haplosalids.

2.2 Soil sampling and laboratory analysis

The methodology of data acquisition and geostatistical analysis was explained in detail in Nawar et al. (2011); for clarity important steps of these procedures are outlined below as well. Grid sampling scheme, with 800 m × 800 m spacing, was developed to explore spatial variability of the soils in the study area based on previous work (Ebrahem 2002) and satellite image ETM+ acquired in June 2006. The grid sampling scheme consisted of 96 sample points (81 soil profiles and 15 augers) and 41 observation points (Fig. 1). Sampling points were located in the field with the accuracy of 3 m using GPS guidance. Soil profiles were morphologically described according to Soil Survey Staff (1993) and FAO guidelines for soil description (2006). The collected soil samples were air-dried, crushed and passed throughout a 2 mm sieve. The fine earth (<2mm) was taken for analysis. Particle size distribution, electric conductivity (EC), $CaCO_3$, Organic Matter O.M, pH, exchangeable Na+,Cation Exchange Capacity (CEC), gypsum, and water analyses were determined according to Rowell (1995).

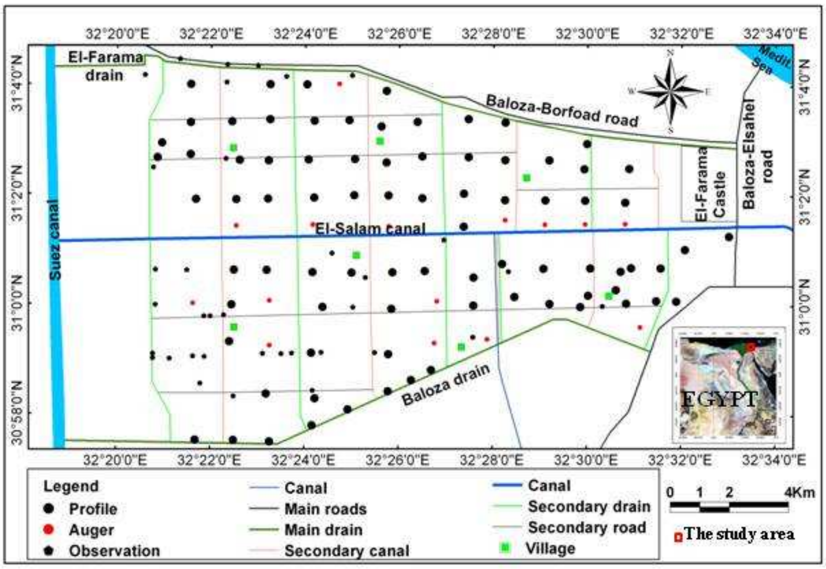


Figure1: Study area location and sampling design

2.3 Geostatistical mapping

Geostatistical techniques, including analyses of semivariograms, cross-validation, kriging and mapping of kriged estimates (Goovaerts 1997) were used to determine the variance structure of the soil properties measurements (Nawar et al. 2011). Geostatistical analysis in the study was performed using the Geostatistical Analyst extension of ArcGIS 9.3 (ESRI 2008). The semivariogram $\gamma(h)$ is described as follows:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where Z(xi) represents the measured value of the soil property at location x_i, $\gamma(h)$ is the semivariogram for a lag distance h between observations $Z(x_i)$ and $Z(x_i+h)$, and N(h) is the number of data pairs separated by a lag distance equal to h. Three models (circular, spherical and exponential; Goovaerts 1997) were fitted to the experimental semivariograms. The kriged estimate salinity values were calculated using Ordinary kriging (OK; Goovaerts 1997 and Hu et al. 2007).

Geostatistical procedures were assessed with cross-validation indicators and additional model parameters (nugget, sill and range) which helped to choose the most appropriate model to predict soil properties. The calculated statistics served as diagnostics that indicated whether the model was reasonable for soil properties maps production. To evaluate the models, three indices were used (Goovaerts 1997): Mean Prediction Errors (MPE), Mean Standardized Prediction Errors (MSPE) and Root-Mean-Square Standardized Prediction Errors (RMSSPE). General soil properties such as soil profiles depth, salipan formation, watertable depth, soil samples analyses were considered. Geostatistical analyses were used to obtain soil properties layers, which were classified to standard classes according to Soil Survey Staff (1993). Soil properties classes were overlaid using ArcGIS software to obtain boundaries between soil mapping units.

2.4 DSS-SLM Model

The framework of sustainable land management (Smyth and Dumanski, 1993), was used to recognize the criteria of sustainability. The expert system technology is a major component of the DSS-SLM model (Rais et al., 1997, modified and adapted for Egyptian conditions by El-Nahry (2001)). The information and data obtained from the studied area have been analyzed according to the international Framework for Evaluating Sustainable Land Management (FESLM) methodology to develop SLM indicators that address the five pillars of the FESLM. Knowledge from the farmers gained through 58 questionnaires held with them in suite and many publications concerning the investigated area was used as well. The SLM indicators (Figure 2) were developed along the five pillars of FESLM, i.e., productivity, security, protection, viability and acceptability. The SLM indicators threshold, their quantitative and ratings were defined according to Rais et al. (1997). SLM indicators had all values ranging between 0 and 1. Sustainability index was obtained by the multiplication of the five pillar indicators. Obviously the multiplication result had a value between 0 and 1; values closer to 1 meant the higher degree of sustainability. The obtained multiplication results, which reflect the degree of the agriculture sustainability were divided into four sustainability classes, namely:

(1) land management practices meet sustainability requirements (between 1 and 0.6)
(2) land management practices are marginally above the threshold for sustainability (between 0.6 and 0.3)
(3) Land management practices are marginally below the threshold for sustainability (0.3 and 0.1), and
(4) Land management practices do not meet sustainability requirements (< 0.1).

Sustainability indicators of DSS-SLM model were studied and evaluated for soil mapping units received via geostatistical analysis.

2.5 Integration of DSS-SLM model with GIS

To generate an effective and user-friendly decision support tool for sustainability in El-Tina plain, DSS-SLM model was integrated with GIS using ArcGIS v. 9.3. The ArcGIS Model Builder environment and other data processing tools in ArcMap were used. In Model Builder, the user can design and use a GIS model to automate data processing by dragging process tools and data layers into a visual diagram of the model (ESRI 2008). Several steps had to occur outside the Model Builder due to the limitations of Model Builder. The first step in DSS-SLM model was to make the sustainable indicators for five pillars comparable by standardizing the indicator data using the sustainability criteria (Rais et al. 1997; El-Nahry 2001). Then all the indicator tables were used to make a new map layers containing all the indicator data The next step was to apply the DDS-SLM model built in Model Builder to the indicator data. This produced a sustainability score for each of soil mapping units, which is the weighted summation of all the indicators. It also produced a score for the Productivity, security, protection, social and economic pillars from the weighted summation of their respective indicators. Each of these scores were then mapped separately to show the variation in sustainability and Productivity, security, protection, social and economic condition across the region. Finally, the sustainability map was produced by weighted overlay of the maps of the five pillars.

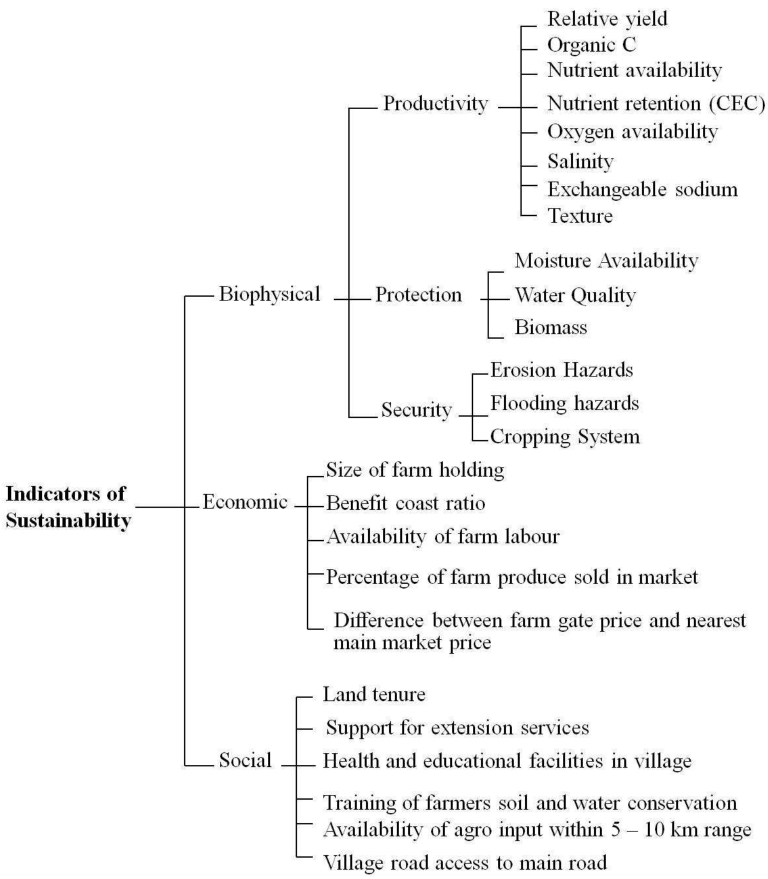


Figure 2: Indicators of sustainability for El-Tina plain

3. Results and discussion

3.1 Soil mapping units

Soil mapping units were the final result of mapping soil in El-Tina plain based on geostatistical approach (Nawar et al. 2011). Soil mapping units were used as the basis for sustainability assessment in the study area. Soils of the study area consisted of four main soil types, fine texture with water table alternative between deep to medium, coarse texture with water table alternative between deep to medium, fine to medium texture with subsurface coarse texture and fine texture with subsurface salipan. The four main types involved eighteen soil mapping units (Figure 3). Soil texture differed from clay, silty clay, silty clay loam and clay loam to sandy loam, on the other hand coarse texture ranges between sand to loamy sand. In addition, soil salinity varied from slightly saline to very strongly saline. The obtained data revealed that The obtained data revealed that these soils were characterized by alternative pattern of sedimentation and their sediments originated from different parent materials i.e., fluvio-marine, lacustrine and aeloian deposits The studied soils were classified according to Soil Taxonomy (2006) into two orders; Entisols and Aridisols that included eight subgreat group; i.e., Typic Aquisalids, Typic Haplosalids, Aquic

Torriorthents, Typic Torriorthents, Aquic Torripsamments, Typic Torripsamments, Gypsic Aquisalids and Gypsic Haplosalids. Soil mapping units were used as the level of sustainability assessment in the study area.

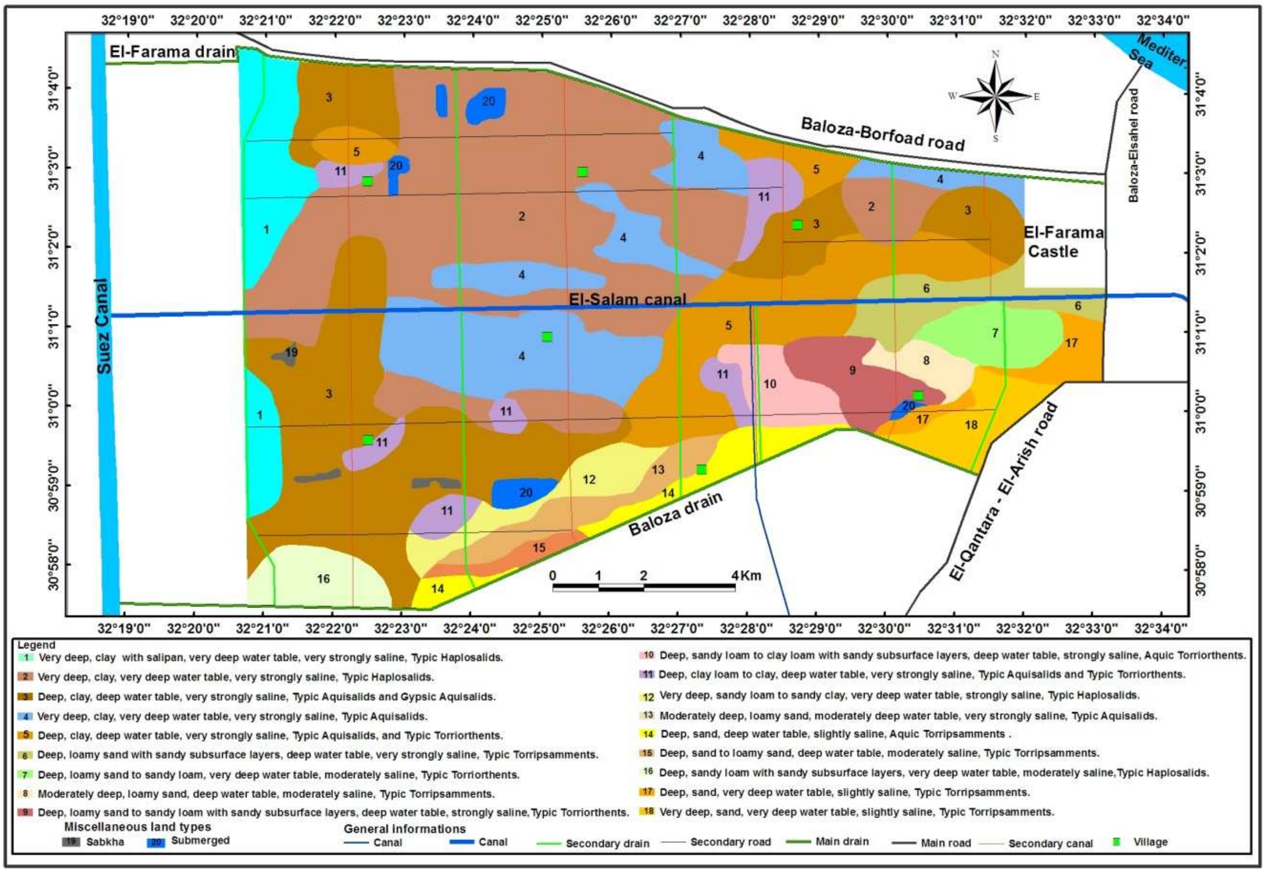
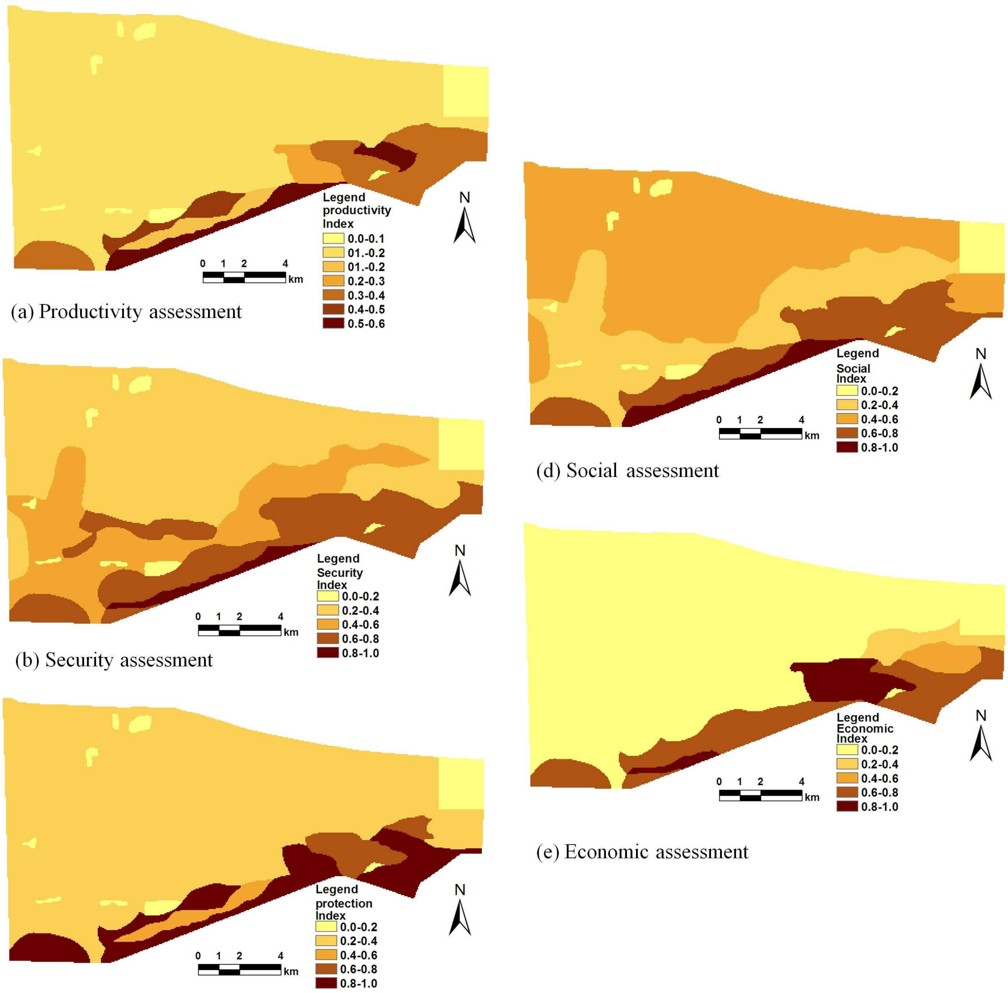


Figure. 3: Soil map of El-Tina plain

3.2. Sustainability assessment El-Tina plain region

DSS-SLM was used to produce a series of maps showing five pillars of FESLM: productivity, security, protection, social and economic conditions, and finally the final sustainability index across the soil mapping units in study area. An examination of these maps (Figure 4) showed that there was variation in pillar conditions across the soil mapping units in the region. This result suggests that the model would be useful for supporting decision making to progress sustainability.

As would be anticipated with the large number of environmental indicators included in the model, biophysical condition displayed variations across the soil mapping units in the region (Figure 4a, b, c). The soil mapping units with the highest biophysical scores, and thus, best biophysical condition were those in the southern region (8, 10, 12, 14, 15 and 18) while those in the northern region (1, 2, 3, 4, 5 and 6) had the lowest scores. The soil mapping units in the southern region all had higher scores for the majority of biophysical indicators, particularly in terms of high relative yield, low salinity, light texture and cropping system. This is because a large amount of land in this area is cultivated. The northern region had low values of biophysical indicators, particularly with high salinity, heavy texture and high exchangeable sodium percentage



(a) Productivity assessment
(b) Security assessment
(c) Protection assessment
(d) Social assessment
(e) Economic assessment

Figure 4: The five pillars of DSS-SLM model in El-Tina plain

The map of social conditions (Figure 4d) shows their variation in soil mapping units, lower than for other pillars. The region is achieving relatively well with most soil mapping units reaching scores of 0.40 or above.Social acceptability index reaches its maximum in the mapping unit 14 and 15 (0.95) followed by mapping units 8, 9, 10, 11, 12, 13, 14, 15, 16, 17 (0.76). The Social acceptability of zero value refers to the abandoned mapping units. The low values of these indicators are mainly due to the shortage in health and educational facilities in the studied area because there is no or not enough training for land users on soil and water conservation.
There is significant variation in soil mapping units economic condition (Figure 4e), similar to biophysical condition assessment. This map display a relatively good economic performance in soil mapping units in southern region, receiving a score of 0.80 or more. The remaining soil mapping units all scored less than 0.20. The highest ranked soil mapping units were 7, 8, 9, 10, 12, 13, 14, 15, 16, 17 and 18, all which had intensive farming. The soil mapping units with the lowest economic scores referred to the uncultivated

soil mapping units. The low values of these indicators are mainly due to the shortage in infrastructure and the low of biophysical conditions

The sustainability map (Figure 5) demonstrates that there is a significant variation in sustainability across the region. Soil mapping units with high relative sustainability are easily distinguishable from those with relatively low sustainability. Assessment of sustainable land management in the investigated area resulted in four sustainability classes, which reflect the degree of agriculture sustainability are listed as follows:

1. Class I - none of the soil mapping units in the study area is found to meet the requirements of this class.
2. Class II - units 8, 10, 12, 14, 15, and 18.
3. Class III - units 7, 9, 13, 16 and 17.
4. Class IV - units 1, 2, 3, 4, 5, 6 and 11.

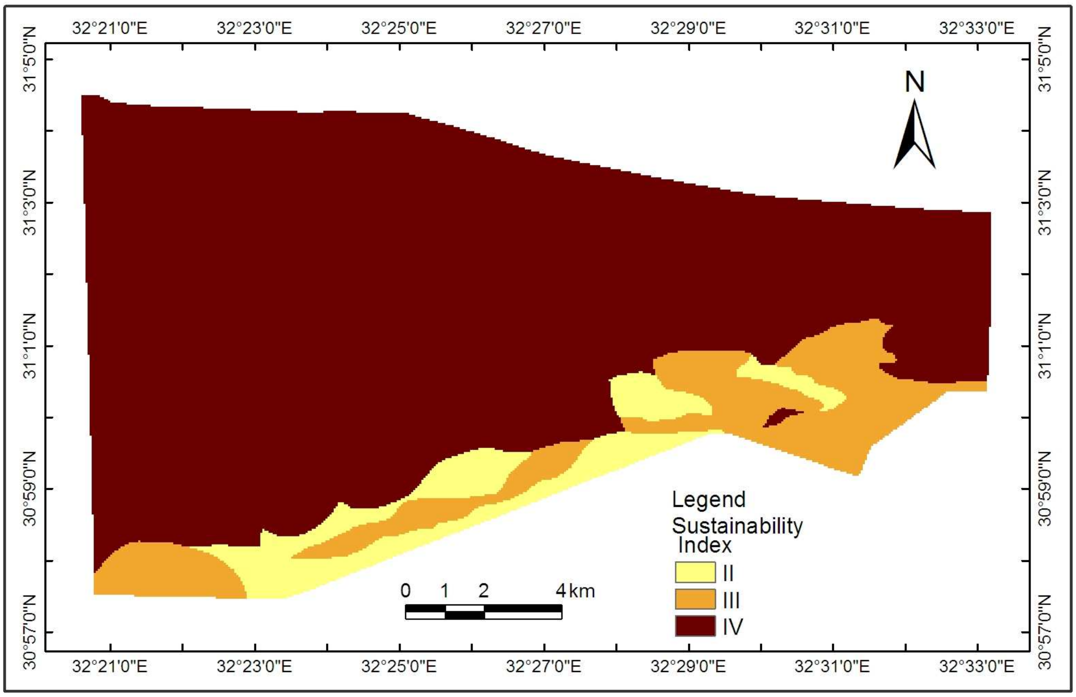


Figure 5: Sustainability assessment map in El-Tina plain

Thus, the map is able to highlight soil mapping units most in need of sustainability initiatives to progress sustainability, helping managers to prioritise soil units in study area. The highest sustainability scores had the soil mapping unit 12 (0.39), followed by units 10 and 14 (0.37), all in the southern region. The soil mapping units with the lowest sustainability scores were 1, 2, 3, 4, 5 and 6. The sustainability of the soil mapping units in the southern region were higher than for those in the northern region of the study area suggesting that land use in this region is having a major impact on the biophysical condition and sustainability. This suggests that sustainability in El-Tina plain is intimately linked to biophysical quality, and thus, management actions to improve biophysical quality are needed to improvement the overall region sustainability.

This assessment of El-Tina plain demonstrates that DSS-SLM could highlight the differences in sustainability across the region, as well as indicate aspects of the soil mapping units were improvements are needed to progress sustainability. Thus, it is a valid decision support tool for monitoring sustainability and evaluation of arrangements to progress sustainability at El-Tina plain region.

4. Conclusion

This paper has demonstrated that the using of geostatistical analysis and spatial modeling to generate accurate soil maps and DSS-SLM model, produces an effective decision support tool for sustainability assessment in El-Tina plain region. DSS-SLM is a user-friendly means of monitoring sustainability, as it uses an easy step by step method that is able to produce maps that show the variation in sustainability across the region, as well as biophysical, social and economic conditions. The testing of the model proved that it is a sensitive method of sustainability assessment. Its ability to show differences in sustainability and pillar conditions across the region could help managers farms in terms of their need for sustainability initiatives and other management actions, making it a useful decision support tool for progressing sustainability. If used regularly in the consequent years, it might also be useful for sustainability monitoring and evaluation of the efficiency of sustainability strategies by illustrating changes in soil units sustainability over time. Thus, this paper has been able to support sustainability assessment in the study area by producing a GIS-based multi criteria analysis tool that is a fully integrated sustainability assessment, which is also easy to use, clear and useful for helping managers make decisions to progress sustainability.

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