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Assessment of soil degradation and resilience at northeast Nile Delta, Egypt: The impact on soil productivity

W.A.M. Abdel Kawy [a], **R.R. Ali** [b,*]

[a] *Soils Science Department, Faculty of Agriculture, Cairo University, Egypt*
[b] *Soils and Water Use Department, National Research Centre, Dokki, Cairo, Egypt*

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Abstract In Egypt, the soil degradation is the main constraint to the development of agricultural sector. In the last few decades, the farmers and the government have made a great effort to resist soil degradation. The resistance of soils to degradation processes by human positive actions is known as soil resilience. This study aims to assess the soil degradation and resilience at northeast Nile Delta and evaluate their impact on the soil productivity. To fulfill these objectives, Landsat ETM+ images and digital elevation model were processed using ENVI 4.7 software to identify the main physiographic units in the area. The recognized units comprised; lacustrine, marine, and alluvial deposits. Twelve soil profiles were undertaken to represent the different mapped units, the locations of the soil profiles were selected to be the same sites previously studied by the Research Institute of Soils and Water (RISW) in 1976. Changes in soil properties and productivity index during the last 35 years (1976–2011) were identified. The status of soil degradation was evaluated; the results indicate that the most active soil degradation processes are water logging salinization, and alkalinization. The soil resilience against salinity, alkalinity and water logging was assessed. It was found that the soil productivity index reflects the balance between soil degradation and resilience. The soil degradation processes overcome the soil resilience in most of the study area where the soil productivity index was decreased in 45.82% of the total area.

1. Introduction

Soil degradation is defined as the process, which lowers (quantitatively or qualitatively) the current and/or the potential capability of soil to produce goods or services. Soil degradation implies deterioration in soil productivity and land capability, (Mashali, 1991; Ayoub, 1991; UNEP, 1992; Wim and Elhadji, 2002). The food gap due to increasing population puts more pressure on the use of land. The intensification of agriculture as well as poor management accelerates the rate of land degradation. Food supply situation will be worse in the future

* Corresponding author. Address: Soils and Water Use Department, National Research Centre, El Buhoth Street, Dokki, Cairo 12311, Egypt. Tel.: +20 2 33371362; fax: +20 2 33370931.
E-mail addresses: dr_wael_kawy@yahoo.com (W.A.M. Abdel Kawy), bediertop@yahoo.com (R.R. Ali).

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if the current trend of land degradation does not change drastically. The livelihoods of more than 900 million people in some 100 countries are now directly and adversely affected by land degradation (United Nations, 1992). Although climatic conditions, such as drought and floods, contribute to degradation, the main causes are human activities. Land degradation is a local problem in vast number of locations, but it has cumulative effects at regional and global scales. The countries of the developing world, and particularly those in the arid and semi-arid zones, are the most seriously affected, (UNEP, 1986).The status of soil degradation is an expression of severity of the process. The severity of the processes is characterized by the degree in which the soil is degraded and by the relative extent of the degraded area within a delineated physiographic unit (UNEP, 1991). In Egypt the main land degradation types in irrigated agriculture are salinization, alkalization and water logging (El-Kassas, 1999). The resistance of soils to degradation processes by human positive actions is known as soil resilience. Soil resilience has been defined as the capacity of a soil to recover its functional and structural integrity after a disturbance (Pimm, 1984; Eswaran, 1994; Lal, 1997; NRCS, 2005). The rate of soil degradation depends on both soil properties, and land management practices (Shepherd and Soule, 1998), land with low resilience is permanently damaged by degradation (Eswaran et al., 1999). So the soil resilience may be the way that can be used as an operational basis for combating soil degradation (Blum, 1994). The factors of climate, topography, land use, soil type, technological innovations and input management have a direct effect on soil resilience (FAO, 1985; Seybold et al., 1999; Herrick et al., 1996; Greenland and Szabolcs, 1994). The effect of land use on soil resilience is demonstrated by the data from dryland, the proportion of highly resilience soils in world's dryland areas is about 28% in rangelands, 54% in rainfed crop lands, and 70% in irrigated crop lands. It can therefore be inferred that the soil resilience in dry lands is enhanced by the intensive agricultural land use and technological input, and ecologically appropriate land use to alleviate ecological stresses (Rozanov, 1994). Also the soil resilience is affected by both inherent and dynamic soil characteristics and, thus, will vary substantially from one area to another (MacEwan, 1997), e.g. under similar climate conditions, clayey soils are more resilient than sandy (Prasad and Power, 1997). A close relationship exists between climate and soil resilience. The drier the climate, the less resilient soil systems are following various disturbances (Lal, 1997). The human activity is an important driving factor behind the soil formation that may have either positive or negative effects on soil productivity (John et al., 2006). This study aims to assess the soil degradation and resilience and evaluate their impact on soil productivity during the last 35 years at northeast Nile Delta.

2. Materials and methods

2.1. Study area

The studied area is located at the North Eastern part of the Nile Delta between longitudes 31°12″ and 32°18″E and latitudes 30°35″ and 31°32″N (Fig. 1). The River Nile "Damietta branch" separates it into two parts surrounded by the Mediterranean Sea to the north, Al-Manzala Lake to the east, and the Nile Delta flood plain to the south and the west. It covers an area of 5161.44 km^2 and has a population of approximately six million inhabitants. This area belongs to the late Pleistocene era which is represented by the deposits of the neonile. The north eastern parts of the study area include fluvio-marine fluvio-lacustrine deposits, which were originally transported and deposited by both the river, sea and Lake El Manzala, and which are composed of clay and silty clay inter-layered with lenses of quartz sand, and highly enriched with salts. The northern parts of the area include eolian deposits, which are distributed as sand sheets developed into hummocks or sand dunes of variable size. While the western parts include Nile deposits which are composed of medium and fine silt (Said, 1993). The area is characterized by a climate of Mediterranean Sea with hot arid summer and little rain winter. The mean temperatures are especially high in the dry season when

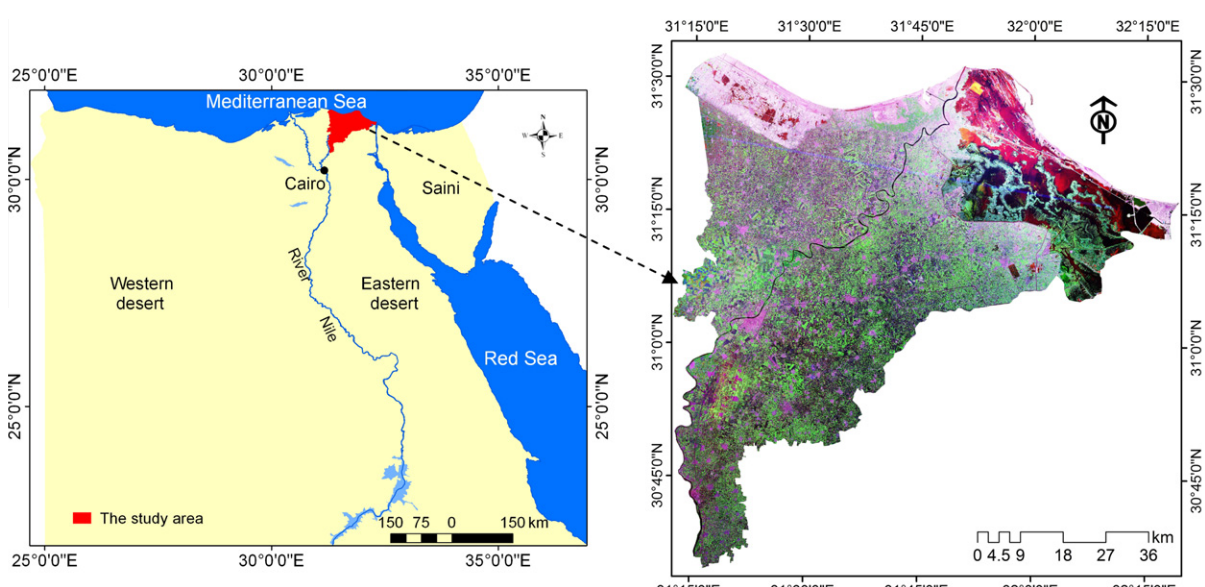

Figure 1 Location of the study area on Egypt map (left) and the Landsat ETM+ image (bands 7, 4, 2) of the year 2009 (right).

they range between 25 and 30 °C with average temperature, 22 °C and the difference between the average temperature in summer and winter is 6 °C (Climatological Normal for Egypt, 2011). According to the keys to soil taxonomy (USDA, 2010), the soil temperature regime of the studied area is defined as Thermic and soil moisture regime as Torric.

2.2. Image processing

Digital image processing was executed for two Landsat ETM+ satellite images (path 176, row 38 and path 176, row 39) with spatial resolutions of 28.50 meters acquired in 2009 using ENVI 4.7 software (ITT, 2009). The Landsat 7 Enhanced Thematic Mapper Plus (ETM+) scan line corrector (SLC) failed on May 31, 2003, causing the scanning pattern to exhibit wedge-shaped scan-to-scan gaps. The ETM+ has continued to acquire data with the SLC powered off, leading to images that are missing approximately 22% of the normal scene area (Storey et al., 2005). To improve the utility of the SLC-off data, the original SLC-off image has been replaced with estimated values based on histogram-matched scenes. Data were calibrated to radiance using the inputs of image type, acquisition date and time. Images were stretched using linear 2%, smoothly filtered, and their histograms were matched according to Lillesand and Kiefer (2007). Images were atmospherically corrected using FLAASH module (ITT, 2009).

2.3. Physiography and soil mapping

The different landforms were initially determined from the satellite image and the digital elevation model extracted from the available contour maps at scale 1:25,000, following the methodology developed by Dobos et al. (2002).

2.4. Field work and laboratory analyses

The interpretation of satellite images and digital elevation model generates a preliminary physiographic map which was checked through 50 field observation points. A semi detailed survey was done throughout the investigated area in order to gain an appreciation on the soil patterns, the land forms and land use/cover. Twelve soil profiles were taken to represent different physiographic units; the locations of the soil profiles were selected to be the same sites previously studied by the Research Institute of Soils and Water (RISW, 1976). The morphological description of these profiles was carried out according to the guidelines edited by FAO (2006). Representative disturbed soil samples have been collected and analyzed using the soil survey laboratory methods manual (USDA, 2004; Klut, 1986) the analyses include, particle size distribution, soil pH, organic matter %, $CaCO_3$ %, electric conductivity (dS/m), cation exchange capacity (meq/100 g soil) and exchangeable sodium percentage. Using the field work and laboratory analyses data, the soils were classified on the basis of the keys to soil taxonomy (USDA, 2010).

2.5. Soil degradation assessment

This study is based on comparing between the data extracted from RISW (1976) report, and the data obtained from this study. The severity of the processes is characterized by the rate, degree and extent in which the soil is degraded. Rate and hazard or degree (Tables 1 and 2) were defined and described by using the methodology described by FAO (1979) and UNEP (1991), the extent was estimated by extracting the degraded areas within delineated geomorphologic units using ArcGIS9.2 software.

2.6. Assessment of soil resilience

Quantification of soil resilience has been achieved using the methodology developed by Lal (1994a, 1997), as the following.

2.6.1. The rate of soil degradation process

Soil resilience can be computed from the rate of change in soil quality, as shown in the following equation:

Table 1 Classes of soil degradation rate.

Type	Indicator	Degradation rate			
		I	II	III	IV
Salinization	Increase in (EC) per dS/m/year	< 0.5	0.5–3	3–5	> 5
Alkalinization	Increase in ESP per percent/ year	< 0.5	0.5–3	3–7	> 7
Compaction	Increase in bulk density per (g/cm^3/year)	< 0.1	0.1–0.2	0.2–0.3	> 0.3
Water logging	Decrease in water table in cm/year	< 1	1–3	3–5	> 5

(I) Non to slight, (II) moderate, (III) high, (IV) very high.

Table 2 Classes of soil degradation hazard (degree).

Hazard type	Indicator	Unit	Hazard class			
			Low	Moderate	High	Very high
Salinization	EC	dS/m	< 4	4–8	8–16	> 16
Alkalinization	ESP	value	< 10	10–15	15–30	> 30
Compaction	Bulk density	g/cm^3	< 1.2	1.2–1.4	1.4–1.6	> 1.6
Water logging	Water table level	cm	> 150	150–100	100–50	< 50

$$Sr = -dSq/dt$$

where (Sq) is soil quality and (t) is time, the negative value of the change refers to degradation.

2.6.2. The rate of soil restoration

In contrast to degradation, the rate of soil restoration can be used to assess soil resilience. It can also be related to changes in soil quality as shown in the following equation:

$$Sr = +dSq/dt$$

where the positive value of the change refers to resilience.

2.6.3. Modeling soil resilience

The following model was used (Lal, 1994a):

$$Sr = Sa + \int_0^t (Sn - Sd + Im)dt$$

where Sa is the rate of the initial or the antecedent condition, Sn is the rate of soil renewal, Sd is the rate of soil degradation, and Im is the management input rates.

The rate of soil property changes (salinity, alkalinity and water logging) was estimated using the data extracted from the report of after Research Institute of Soils and Water (RISW, 1976) and the data of this study. The quantification of soil resilience was worked out using the rating of the antecedent condition of the soil according to soil quality rating (effective soil depth, salinity and alkalinity) after Erian (1989), the rate of soil renewal and management input, after Lal (1994b) as shown in Tables 3 and 4. The soils have been grouped into five classes according to their degree of soil resilience as shown in Table 5.

2.7. Soil productivity index

The soil productivity index (PI) was estimated for the years 1976 and 2011 using the model produced by Riquier et al. (1970) as:

$$PI = (H/100 * D/100 * P/100 * T/100 * S/100 * O/100 * A/100 * M/100) * 100$$

where PI is the productivity index, H is the moisture availability, D is the drainage, P is the effective depth, T is the texture/structure, S is the soluble salt concentration, O is the organic matter content, A is the mineral exchange capacity/nature of clay, M is the mineral reserve in B horizon.

3. Results and discussion

3.1. Physiography and soils

Digital elevation model analysis, satellite images interpretation and land surveying data indicated that, the study area includes

Table 3 Soil quality rating.

Rating	Effective soil depth (cm)	Salinity EC (dS/m)	ESP	Limitation
1	< 150	> 2	> 10	Non
2	100–150	2–4	10–15	Slight
3	100–80	4–8	16–20	Moderate
4	80–50	8–15	21–30	Strong
5	> 50	< 15	> 30	Very strong

Modified after Erian (1989).

Table 4 Soil renewal and management rating.

Rating	Soil renewal rate (cm/year)	Management input	Limitation
1	> 0.1	Chemical fertilizer and organic mater addition with improvement in irrigation and drainage systems	Very high
2	0.06–0.1	Chemical fertilizer and/or organic mater addition with improvement in drainage systems	High
3	0.01–0.05	Chemical fertilizer or organic mater addition	Moderate
4	< 0.01	No management input	Low

Modified after Lal (1994b).

Table 5 Status and description of soil resilience classes.

Class	Resilience status	Description
0	Highly resilient	Rapid recovery, high buffering
1	Resilient	Recovery with improved management
2	Moderately resilient	Sow recovery with high input
3	Slightly resilient	Slow recovery even with change in land use
4	Non-resilient	No recovery even with change in land use

Modified after Lal (1994a).

Table 6 Physiographic and soil map legend of the investigated area.

Landscape	Relief	Land form	Map unit	Profile no.	Area (km^2)	Area (%)	Soil sets	Type of soil sets
Lacustrine plain	Almost flat to gently undulating	Clay flats						
		Relatively high	CF1	1	99.21	1.92	*VTf*	Cons.
		Relatively low	CF2	2	502.63	9.74	*VTf*	Cons.
		Fish ponds	FP	–	63.89	1.24	–	–
		Gypsiferrous flats	GF	–	132.47	2.57	–	–
		Swamps	S	–	251.46	4.87	–	–
Eolian plain	Gently undulating	Coastal sand bar	CS	–	138.34	2.68	–	–
		Hammocks	H	–	64.00	1.24	–	–
		Sand sheets						
		High elevated	OS1	3	222.30	4.31	*TTp*	Cons.
		Low elevated	OS2	4	241.63	4.68	*TTp*	Cons.
		Wetlands	WL	–	61.68	1.20	–	–
Flood plain	Almost flat to gently undulating	River terraces						
		Relatively high	T1	5	525.10	10.17	*TTf*	Cons.
		Relatively low	T2	6	509.75	9.88	*VTf*	Assoc.
		Decantation basin						
		High elevated	DB1	7	269.99	5.23	*VTf*	Cons.
		Low elevated	DB2	8	396.54	7.68	*TNa*	Assoc.
		Over flow basin						
		High elevated	OB1	9	175.88	3.41	*TTf*	Cons.
		Low elevated	OB2	10	524.09	10.15	*TTf*	Cons.
		Over flow mantle						
		Almost flat	OM1	11	171.86	3.33	*VTf*	Cons.
		Gently slope	OM2	12	207.01	4.01	*VTf*	Cons.
Water bodies	–	–	–	–	602.26	11.67	–	–
Island	–	–	–	–	1.63	0.03	–	–

VTf: Vertic Torrifluvents; TTp: Typic Torripsamments; TTf: Typic Torrifluvents; TNa: Typic Natrargids; Cons.: consociation; Assoc.: association.

three main landscapes, (a) lacustrine plain with five landforms i.e., clay flats, fish ponds, gypsiferrous flats and swamps; (b) marine plain including coastal sand bar, hammocks and sand sheets (high and low elevated), and (c) flood plain containing overflow mantle, overflow basins, decantation basins and river terraces. Table 6 and Fig. 2, represent the main physiographic units and its soil sets in the investigated area, the obtained data reveal the following:

3.1.1. Soils of lacustrine plain

Soils of this landscape are represented by relatively high clay flats and relatively low clay flats (CF1 and CF2). The laboratory analyses of the year 2011 showed that the soil depth of the clay flat units ranged between 60 and 90 cm, and the soil texture class is clayey. Soils are moderately compacted where the bulk density reaches to 1.40 g/cm^3. Soil reaction (pH) values are slightly alkaline (8.00 and 8.31). The electric conductivity (EC) values are high as it ranging between 11.40 and 15.45 dS/m. The $CaCO_3$ content is high ranging between 10.12% and 12.30%. This high values of $CaCO_3$ may be due to abundance of shell fragments (inert $CaCO_3$). Organic matter content is relatively sufficient for agricultural production under the aridity conditions recording a range of 1.9–2.1%. Cation exchange capacity is high, where it ranged between 57.56 and 60.65 meq/100 g soils reflecting the high amount of clay content (62.56–67.45%). Exchangeable sodium percentage (ESP) is high to very high where it ranges between 17.82 and 25.42. Gypsum content is high especially in relatively low clay flats (5.23–7.34%). The macro nutrients represented by N, P and K are insufficient amounts 93.23, 32.35 and 296.34 ppm, respectively. The soils of these units (CF1 and CF2) were classified as *Vertic Torrifluvents*.

3.1.2. Soils of marine plain

This landscape includes coastal sand bar, hammocks, relatively high sand sheets (OS1) and relatively low sand sheet (OS2). The soils of marine plain represent the sand sheet landforms (OS1 and OS2), the analytical data showed that the depth of these units ranged between 110 and 1240 cm and the soil texture class is sandy. Soil reaction (pH) values ranged between 7.7 and 8.00. The EC values are high ranging between 17.40 and 20.34 dS/m. The $CaCO_3$ content is low as it ranges between 1.23% and 2.30%. Organic matter content is low recording a range of 0.25–0.45%. Cation exchange capacity is very low reflecting the low amounts of clay and organic matter as it ranges between 4.54 and 7.23 meq/100 g soils. The exchangeable sodium percentage is low where it lays around 12.0. Gypsum content is low ranging between 1.34% and 1.98%. The macro nutrients represented by N, P and K are insufficient in these soils. The soils of these units (OS1 and OS2) were classified as *Typic Torripsamments*.

3.1.3. Soils of flood plain

This landscape includes four landforms i.e., overflow mantle (OM), overflow basin (OB), decantation basin (DB) and river terraces (T). The analytical data showed that the soil depth in

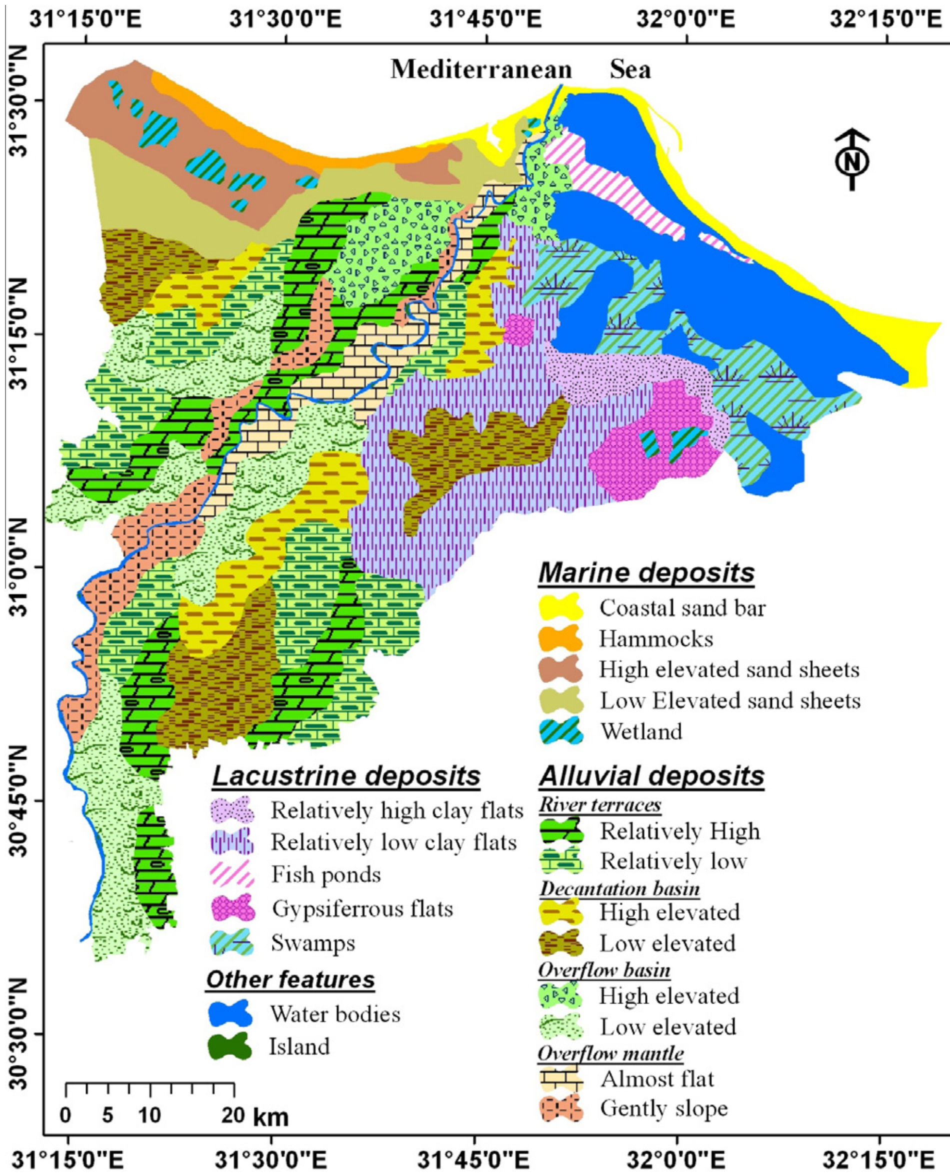

Figure 2 The main physiographic units in the study area.

the flood plain soils ranged between 100 and 150 cm and the soil texture is clayey. The soil reaction (pH) values range between 7.5 and 8.30. The EC values are widely varied ranging between 1.48 and 12.53 dS/m. The $CaCO_3$ content is low ranging between 0.35% and 1.23%. Organic matter content is sufficient recording a range of 1.34–1.95%. Cation exchange capacity is high where it ranges between 33.56 and 55.15 meq/100 g soils reflecting the high amount of clay content (38.89–60.54%). Exchangeable sodium percentage (ESP) is high where it ranges between 10.14 and 22.41. The *Argilic* horizon was identified clearly in the low elevated decantation basin (DB2). Soil compaction was noticed in some fields with low management practices in the DB2 soils where the bulk density reaches to 1.50 g/cm^3. The gypsum content is rather low (0.98–1.01%) and the macro nutrients represented by N, P and K are sufficient in the flood plain soils. The soils of this landscape were classified into *Vertic Torrifluvents*, *Typic Torrifluvents* and *Typic Natrargids*.

3.2. Soil degradation

The soil degradation parameters were investigated for the different soils to assess water logging, compaction, salinization, and alkalinization process in the studied areas. The rate of land degradation was estimated by comparing the main soil characteristics as studied in 1976 and 2011 (Table 7). The obtained data reveal that the annual increases of EC, ESP, and bulk density ranges from 0.01 to 0.14, 0.01 to 0.05 dS/m and from 0.0 to 0.01 g/cm^3 per year, respectively, and the water table level decreased by 0.0 to 1.11 cm per year. The rate of soil degradation in general is slight except for the water logging in the soils of the CF2 where the water table was decreased from 100 to 60 cm between 1976 and 2011. These values refer to the low rate of degradation in the different landforms in the study area. The degree of land degradation was estimated in relation to the present value of electric conductivity, exchangeable sodium percentage, bulk density and the depth of water table.

Table 7 Changes of water table, bulk density, EC and ESP between 1976 and 2011.

Profile no.	Mapping unit	Water table level (cm)		Bulk density (g/cm^3)		EC (dS/m)		ESP	
		1976	2011	1976	2011	1976	2011	1976	2011
1	CF1	110	90	1.35	1.40	10.36	15.45	24.31	25.42
2	CF2	100	60	1.35	1.40	7.92	11.40	16.17	17.82
3	OS1	130	110	1.12	1.14	14.89	20.34	11.36	12.82
4	OS2	140	120	1.10	1.13	11.26	17.40	11.62	12.96
5	OM1	130	115	1.35	1.42	8.41	11.62	9.37	10.14
6	OM2	150	130	1.36	1.45	9.17	12.53	17.26	19.34
7	OB1	150	140	1.25	1.40	1.40	2.57	14.80	16.18
8	OB2	130	120	1.20	1.37	2.74	4.68	13.42	14.17
9	DB1	150	150	1.30	1.45	1.30	3.71	8.41	10.23
10	DB2	150	150	1.30	1.50	2.84	5.17	20.16	22.41
11	T1	120	120	1.10	1.18	0.76	1.48	10.18	11.10
12	T2	110	100	1.25	1.33	5.11	6.75	12.19	13.25

Bulk density, EC and ESP were calculated for the upper 100 cm of the soil profile.

The degree (hazards) of the different types of soil degradation differs from low to very high, where the values of EC, ESP, bulk density and the depth of water table ranges between 1.48 and 20.34 dS/m, 10.23% and 25.42%, 1.13 and 1.50 g/cm^3 and 60–150 cm, respectively. The high and very high degree of salinization (EC > 8 dS/m) affect the soils of clay flats (CF1 and CF2), sand sheets (OS1 and OS2) and overflow mantle (OM1 and OM2) representing 40.70% of the total area. The

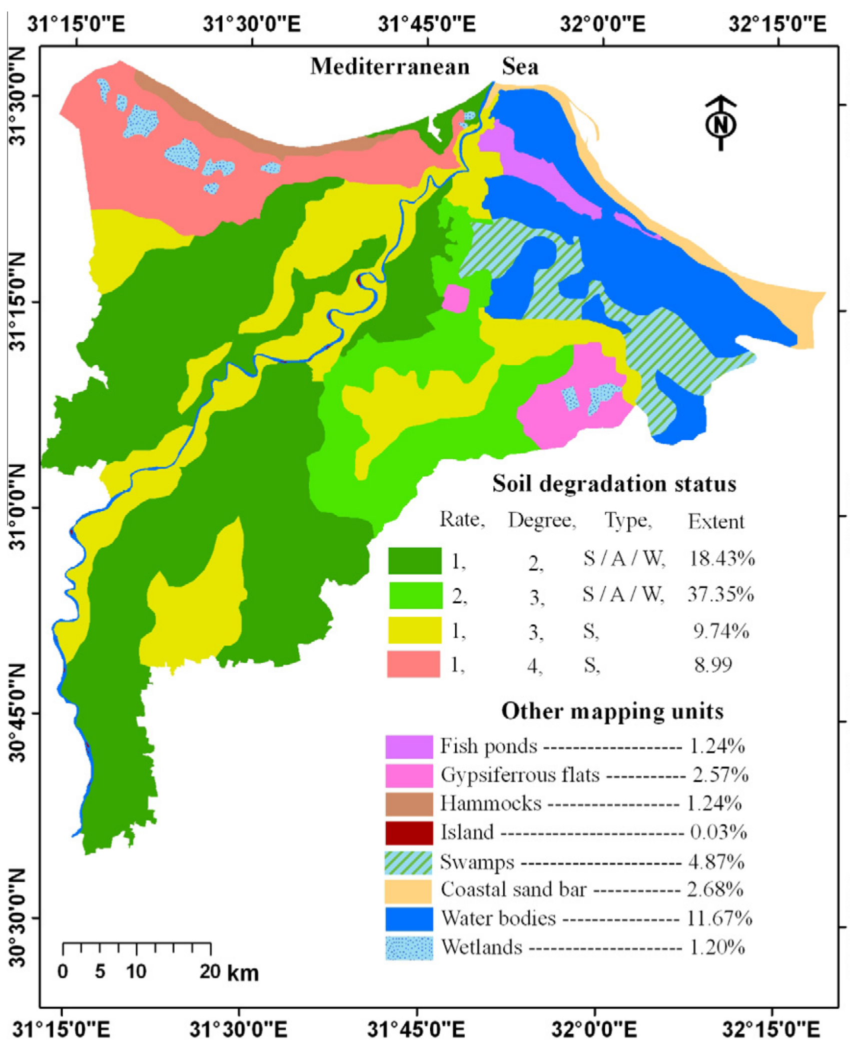

Figure 3 Soil degradation status in the study area, (S) salinization, (A) alkalinization, (W) Water logging.

high degree of alkalinization (ESP > 15) affects 40.33% of the total area distributed in the soils of clay flats (CF1 and CF2); overflow mantle (OM2); overflow basin (OB1) and decantation basin (DB2). The high degree of water logging (soil depth < 100 cm) affects 11.66% of the area exhibiting the clay flats soils. The moderate degree of soil compaction (bulk density $\geqslant$ 1.40 g/cm^3) affects the soils of over flow mantles (OM1 and OM2), clay flat (CF1 and CF2), and decantation basins (DB1 and DB2), respectively. The extent of each type of soil degradation in the studied area was estimated based upon the correlation between the geomorphology and soils. Fig. 3 illustrates the status of soil degradation in the area under investigation. The given data of the rate, degree, and extent indicate that the areas of slight rate of degradation with moderate salinization/alkalinization and water logging classes represent 18.43% of the total mapped area. Areas affected by high degree of salinization/alkalinization and water logging with moderate rate of degradation represent 37.35% of the total area. The soils threatened by high and very high degree of salinization cover 9.74% and 8.99% of the area, respectively. The low rate and high degree of degradation in the different landforms indicate the initial state of degradation in the studied soils due to the arid climate and their location near to Mediterranean Sea and Manzala Lake.

3.3. Soil resilience

The soil resilience in the studied area was estimated based on the correlation between the rate of soil degradation (Sr.deg), the rate of soil restoration (Sr.rest.) and the modeling (Sr.mod.). Table 8, represents the soil resilience according to the rate of degradation in the main soil units of the study area. The obtained data reveal that, soil resilience classes are high in the soils of overflow mantle (OM), overflow basin (OB), decantation basin (DB), and river terraces (T), representing 53.86% of the total area. The moderate resilience class dominates the soils of clay flats (CF) and sand sheets (OS), with an area of 1065.77 km^2, i.e. 20.65% of the investigated area. The soil resilience according to the rate of soil restoration is shown in Table 9. The data indicate that the soils of OM, OB and T are characterized by rapid recovery and high buffering as they are highly resilient. On the other hand the soils of DB (moder-

Table 8 Soil resilient according to the rate of soil degradation.

Mapping unit	Profile no.	dSw/dt	dSz/dt	dSa/dt	dSc/dt	Limiting factor	$-dSq/dt$	Sr.deg.
CF	1	−1	−1	0	0	*w*, *z*	−1	Moderate
OS	3	−1	−1	0	0	*w*, *z*	−1	Moderate
OM	5	0	0	0	0	–	0	High
OB	8	0	0	0	0	–	0	High
DB	10	0	0	0	0	–	0	High
T	12	0	0	0	0	–	0	High

High = 0, moderate = 1; *Sq* is soil quality, *w* is the effective soil depth, *z* is salinity, *a* is alkalinity, *c* is compaction, *t* is time, and Sr.deg. is the soil resilient according to the rate of soil degradation. The negative value of the change refers to degradation.

Table 9 Soil resilient according to the rate of soil restoration.

Mapping unit	Profile no.	dSw/dt	dSz/dt	dSa/dt	dSc/dt	Limiting factor	$+dSq/dt$	Sr.rest.
CF	1	1	1	1	0	*w*, *z*, *a*	0	Non to slight
OS	3	1	1	1	0	*w*, *z*, *a*	0	Non to slight
OM	5	0	0	0	0	–	2	High
OB	8	0	0	0	0	–	2	High
DB	10	0	0	0	1	*c*	1	Moderate
T	12	0	0	0	0	–	2	High

High = 2, moderate = 1, non to slight = 0, *Sq* is soil quality, *w* is effective soil depth, *z* is salinity, *a* is alkalinity, *c* is compaction, *t* is time and Sr.rest. is the soil resilient according to the rate of soil restoration. The positive value of the change refers to resilience.

Table 10 Soil resilient according to model.

Mapping unit	Profile no.	*Sa*	*Sn*	*Sd*	*Im*	Sr.mod.
CF	1	2	3	1	3	Non to slight
OS	3	2	3	1	4	Non to slight
OM	5	3	3	1	1	Moderate
OB	8	3	3	1	1	Moderate
DB	10	3	3	1	1	Moderate
T	12	3	3	1	4	Non to slight

Sa is the rate of the initial or the antecedent condition, *Sn* is the rate of soil renewal, *Sd* is the rate of soil degradation, *Im* is the management input rates and Sr.mod. is the modeled soil resilient.

ate resilience) are slow recovery with optimum management practices. The non to slight soil resilience units (CF, OS) have no recovery even with land use changes. According to the modeled soil resilience (Table 10), the area under investigation is only characterized by two types of resilience i.e. non to slight and moderate. The soil resilience is moderated in the mapping units OM, OB and DB with an area of 1745.37 km^2 (i.e. 33.82%) while it non to slight exhibiting the soils of CF, OS, and T with an area of 2100.62 km^2 (i.e. 40.70%). The non to slight resilient soils have a low management input and were low soil quality in the antecedent condition, including the uncultivated area. The concluded soil resilience in the area was obtained from matching the three above mentioned resilience indices (Sr.deg, Sr.rest. and Sr.mod.) as shown in Table 11 and Fig. 4. The data refer that the highly resilient soils (class 0) in the investigated area have high (Sr.deg), high (Sr.rest.) and moderate (Sr. mod.). It is presented in the soils of OB and OM, in these units the water table is deep (130–150), the electrical conductivity ranges from 2.57 to 12.53 dS/m, the exchangeable sodium percentage differs from 10.14% to 19.34%. These areas also have high management input as chemical fertilizer, manure additions and improved drainage network. The resilient soils (class 1) have high (Sr.deg), moderate (Sr.rest.) and moderate (Sr.mod.). It is presented in the

Table 11 Concluded soil resilience classes.

Mapping unit	Profile no.	Sr (degradation)	Sr (rest)	Sr (model)	Sr (class)	Sr concluded
CF	1	Moderate	Non to slight	Non to slight	3	Slightly resilient
OS	3	Moderate	Non to slight	Non to slight	3	Slightly resilient
OM	5	High	High	Moderate	0	Highly resilient
OB	8	High	High	Moderate	0	Highly resilient
DB	10	High	Moderate	Moderate	1	Resilient
T	12	High	High	Non to slight	2	Moderately resilient

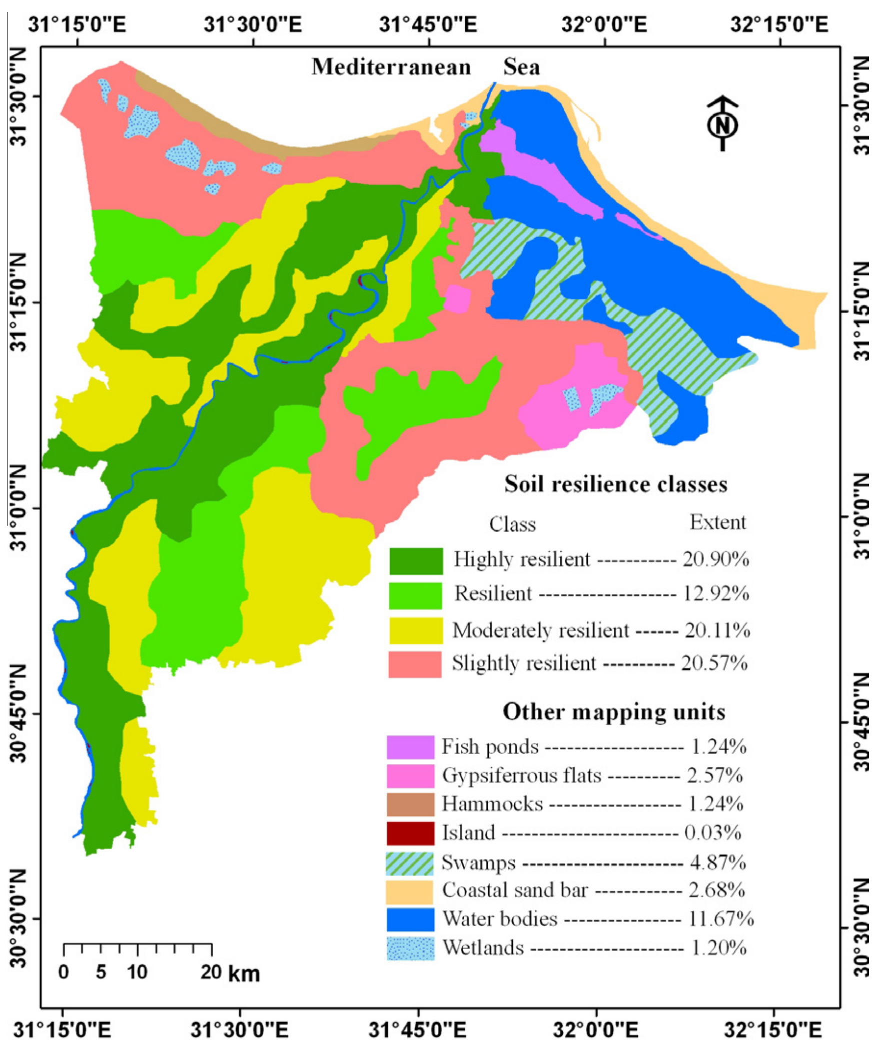

Figure 4 Soil resilience classes in the study area.

mapping unit DB, which is characterized by deep water table, electrical conductivity ranges between 3.71 and 5.17 dS/m and ESP ranges between 10.23 and 22.41. These soils have high management input as chemical fertilizers, manure additions and improved drainage systems. The moderately resilient soils (class 2) have high (Sr.deg), high (Sr.rest.) and slight (Sr.mod.). It is presented in the soils of river terraces (T), where the water table is deep; the electrical conductivity ranges between 1.48 and 6.75 dS/m, the exchangeable sodium percentage ranges between 11.10 and 13.25. These soils also have a traditional management input as chemical fertilizer, manure additions and improved in the irrigation and drainage systems. The slight resilient soils, class3 have moderate (Sr.deg), slight (Sr.rest.) and slight (Sr.mod.). It is presented in the mapping units of CF and OS. In theses mapping units the water table range from moderately to deep, the electrical conductivity differ from 11.40 to 20.34 dS/m; the exchangeable sodium percentage ranges between 13.82 and 25.42. These mapping units have low management input as chemical fertilizer and insufficient drainage network, some areas in these units are new cultivated and some others still barren.

3.4. Soil productivity changes

The soil productivity index was calculated for the years 1976 and 2011; the results are illustrated in Table 12. It is found that the soil productivity index was increased from 27.85 (III) to 34.82 (II) in the landforms of T2 (9.88% of the total area) which have a moderate soil resilience and moderate degree of soil degradation. The productivity index has no changes (class II, in 1976 and 2011) in the soils of OB1, DB1 and T1 landforms representing 18.81% of the total area. These results reflect the suitable land management practices, land use pattern and the positive action of drainage enhancement project which started in the beginning of 1970 at the north Nile Delta. The soil productivity index was decreased in the landforms of CF, OS, OM, OB2, and DB2 (45.82%), where the soil resilience is slight to high and the degree of soil degradation is usually high. The data indicate that after continuous land uses the soil productivity reflects the balance between soil degradation and resilience. Fig. 5 illustrates an ideal relation between soil degradation/resilience and productivity in the landforms of CF, OS, DB and T. It is noticed that the soil productivity

Table 12 Changes of soil productivity index between 1976 and 2011.

Productivity index (PI)	Mapping unit											
	CF1	CF2	OS1	OS2	OM1	OM2	OB1	OB2	DB1	DB2	T1	T2
Value												
1976	19.6	26.1	2.8	4.2	43.5	43.5	43.5	43.5	43.5	43.5	54.4	27.9
2011	7.3	11.0	1.8	2.8	20.9	21.8	43.5	34.8	43.5	34.8	54.4	34.8
Grade												
1976	IV	III	V	V	II	II	II	II	II	II	II	III
2011	V	IV	V	V	III	III	II	III	II	III	II	II
Changes	–	–	0	0	–	–	0	–	0	–	0	+

−: decreased, 0: no change, +: increased.

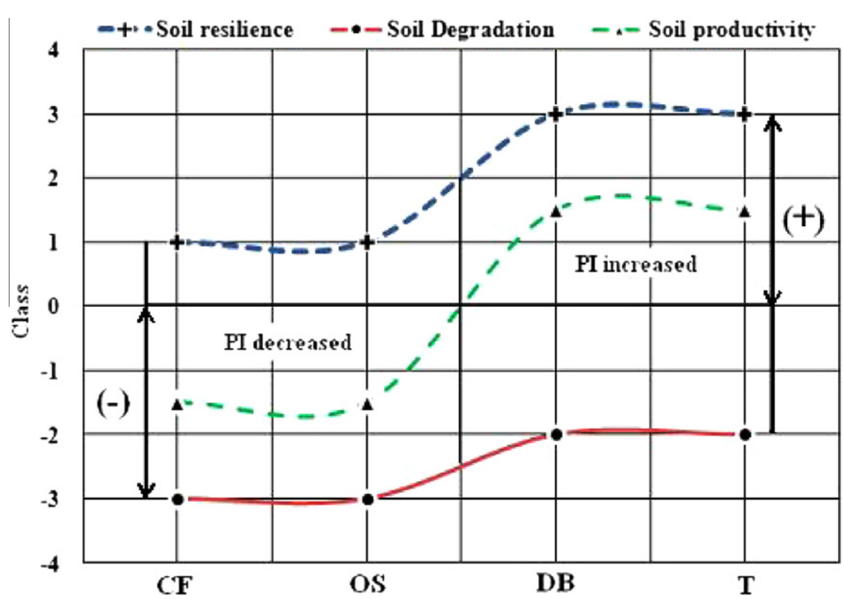

Figure 5 Relation between soil productivity and soil degradation/resilience in some landforms, the degradation classes represented by negative values (−), the soil resilience is represented by positive values (+), the positive difference between degradation and resilience indicate the increase in soil productivity.

index decreased during 1976 and 2011 when the difference between soil degradation and resilience is negative (−) as found in the CF and OS landforms. On the other hand the soil productivity index was increased at the same period in the landforms of DB and T where the difference between the soil degradation and resilience is positive (+).

4. Conclusion

The soil degradation processes are dominating the study area as a result of arid climate, geographical location and the human negative impact. The study area is considered as unstable ecosystem due to active degradation process, i.e. salinization, alkalinization and water logging. The changes in soil properties over the last 35 years in the study area show that the rate of degradation is low. The present values of soil depth, bulk density, electric conductivity and exchangeable sodium percentage show that the degree of soil degradation is in general high. This indicates the initial state of soil degradation which encouraged by negative human impact in the study area. The soil resilience of lacustrine and marine landforms is low; and this corresponds with the decrease of soil productivity index in these landforms during the period of (1976–2011). Although the high soil resilience of the alluvial plain it is noticed that the productivity index was decreased in some areas due to the over irrigation, improper use of heavy machinery and the absence of conservation measurements. In general, after continuous land use, the balance between soil degradation and resilience can be reflected from the soil productivity and human activities.

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