Int. J. Environ. Sci. Technol. (2019) 16:1501–1514
DOI 10.1007/s13762-017-1606-6

ORIGINAL PAPER

Effects of irrigation and cultivation on the chemical indices of saline–sodic soils in a calcareous environment

S. Rezapour[1] · **E. Kalashypour**[1]

Received: 7 March 2017 / Revised: 24 September 2017 / Accepted: 11 October 2017 / Published online: 24 October 2017

Abstract Studies on saline–sodic soils have a growing concern during time in many arid and semiarid nations due to human population pressures and need to produce more food and fiber. Nevertheless, little data are available about the quality attributes of the soils when affected by irrigation and cultivation. This study highlights the response of selected chemical indicators of four soil types (Aquic Natrargids, Sodic Aquicambids, Typic Aquisalids, and Typic Halaquepts) associated with calcareous salt-affected soils when changing to cropland. The results revealed a considerable drop in the amounts of soil pH (0.2–0.8 unit), electrical conductivity (69–82%), sodium absorption ratio (62–73%), exchangeable Na (65–90%), and exchangeable sodium percentage (52–69%) following the conversion of saline–sodic soils to cropland, indicating that the processes of desalinization and desodification were promoted by cultivation practices. For the majority of the study soils, an increasing pattern was recorded in the values of organic carbon (15–130%), total N (37–157%), available P (1–7%), exchangeable Ca (20–96%) and Mg (83–94%), and DTPA-extractable Mn (8–85%), Zn (48–85%), Cu (7–75%) with cultivation, whereas the amounts of cation exchange capacity, exchangeable K, available K, and DTPA-extractable Fe were decreased by 1–29, 8–54, 10–60, and 2–54%, respectively. Based on the land productivity index (LPI), 75% of the soils had an increasing trend (a rise of 10–31%) in the LPI [with the improvement of the productive class from average (LPI = 20–34) to good class (LPI = 35–64)] and 25% had a decreasing pattern (a drop of 10%) after cultivation.

Keywords Saline–sodic soil · Cropland · Soil chemical indicators · Soil type · Land productivity

Introduction

Soil salinity/sodicity is the main problem limiting soil and plant production throughout the world particularly in arid and semiarid nations. Salt-affected soils extend in more than one hundred nations and include an area of about 10^6 Mha, of which nearly 38% is saline and 62% saline–sodic/or sodic soils (Tanji 1990). For example, about 375 million ha the total area of Australia, 212 million ha of the North and Central Asia, 129 million ha of South America, 85 million ha of South Asia, 81 million ha of Africa, and 31 million ha of Europe are salt-affected soils (Szabolcs 1989). In Iran, situated in arid and semiarid conditions, these soils are characterized by different levels of salinity/sodicity on some landscape, including irrigated and dry farming areas, and rangeland (Qadir et al. 2008a). Based on the soil map of Iran, soils having slight and moderate salinity/sodicity level occupy about 25.5×10^6 ha (an area of almost 15% of the total area of Iran), whereas the lands with a high salinity/sodicity cover 8.5×10^6 ha (a area of almost 5% of the total area of Iran) (FAO 2000). Such data mean that over 20 the total lands of Iran was affected by salinity/sodicity.

The term saline–sodic soil is described by the presence of high concentrations of both soluble salts [electrical conductivity (EC) > 4 dS m^{-1}] and sodium cation [exchangeable sodium percentage (ESP $> 15\%$) and sodium

Editorial responsibility: Hari Pant.

✉ S. Rezapour
S.Rezapour@urmia.ac.ir

[1] Soil Science Department, Urmia University, P.O. Box 165, Urmia 57134, Islamic Republic of Iran

adsorption ratio (SAR > 13)] along with soil pH less than 8.5 (Qadir et al. 2008b). Such condition is responsible for unbalancing the plant-available nutrients of the soil that in turn can influence plant growth (Mishra and Sharma 2003).

Recent reviews declare that the application of salt-affected soils for food and fiber production will increase with increasing human population growth in the future (Qadir and Oster 2004; Qadir et al. 2008a). In this context, several undesirable impacts may appear concerning the quality of the soil chemical. In general, two positive and negative impacts on soil chemical indices can appear following changing salt-affected soils to croplands. In order to assess such aspects, both soil static or inherent attribute (activities included soil primary capacity to supply essential plant growth) and dynamic attribute (soil properties reflected the changes associated with human management decisions) need to be investigated. For example, increases in soil nutrients and organic carbon are among the most important attributes that change positively, whereas those that change negatively are mainly exemplified as the enrichment soil heavy metals and the depletion of soil organic carbon and soil nutritional compounds, etc. (Rezapour and Samadi 2012; Rezapour et al. 2013). Qadir et al. (2001) and Wong et al. (2010) stated that cropping practices improve the structure and chemistry of salt-affected soils. Studies conducted by Acosta et al. (2011) in SE Sapian showed that the operations of fertilization and the irrigation with low-quality water make a developed salinity load to the soil and hence result in a land degradation aspect in the region.

When saline–sodic soils are used as the agricultural field, plant nutrient supply is a main restricting parameter for plant growth and food production due to relatively low levels of native fertility in these soils. Chemical and fertility problems of these soils have been ascribed to extreme organic carbon poverty and serious unbalance in crop nutrition, which can be developed from deficiency in several elements to high range from toxicity of some nutrients (Qadir et al. 2008a; Singh et al. 2014). Globally, some studies have been accomplished on the response of general soil quality of the salt-affected soils following the application of organic and mineral compounds, elemental S, calcareous and gypsum compounds, and manures (Wong et al. 2009; Rezapour 2014; Singh et al. 2014). Nevertheless, the field researches on salinity and sodicity-associated nutrient options have earned a limited attention, particularly in the different soil kinds under long-time irrigation–tillage practices. In addition, saline–sodic soils occupy a great area of the world's arable land which varies widely from one zone to another; hence, there is a necessity to design works with more details associated with such soils (Qadir and Schubert 2002). Consequently, this work purposed to: (1) examine the impacts of converting saline–sodic soils to irrigated cropland on changes in the soil chemical indices (organic matter, CEC, macro- and micronutrient), (2) assess the most susceptible chemical properties of saline–sodic soils following changing irrigated cropland, and (3) describe the influence of irrigation–cultivation practices on the land capability index (LPI) of saline–sodic soils.

Materials and methods

Region description and soil sampling

This work was undertaken in the Urmia area, the catchment of the Urmia lake, situated in the eastern part of the Urmia city from 37°23′8″ to 37°32′26″N and 45°15′44″ to 45°15′59″E in western Azarbaijan province, northwest of Iran (Fig. 1). The region formed on a flat topography (slope of 0–2%) with an elevation of around 1300–1330 m and a groundwater table that is higher than in adjacent zones.

Based on the Urmia climatology data, a semiarid condition with cold winter and hot summer is presented in the area. Average annual temperature is 12.2 °C and maximum (32 °C) and minimum (−7 °C) average monthly temperatures occur during July–August and January, respectively. The average annual precipitation is 330 mm, of which ~ 80% occurs during the 5-month period between December and April, mainly as snow. In the spring thawing period (May and June), snowmelt results in the infiltration of large amounts of water into the soil. The mean annual reference evapotranspiration is about 1270 mm, with a peak in August–September and a minimum in December to February (MOI 2015). The soil moisture and temperature regimes are aridic borders on xeric and mesic. In general, the water table was present at depths of 100–200 cm from soil surface for periods ranging from 1 to 12 months of the year in all of the soils. Indeed, these soils often have an aquatic condition within the profiles during the wet season, but the groundwater table drops to about more 2 m from the surface during the dry season.

The study area has not been used in any way before 1985. After interviewing with local farmers of the area, it was found that agricultural activities have been started about 20 years ago. Before any agronomical operation, a strong irrigation practice has been used to decrease soil salinity in the root zone for 2 years. Irrigation water, received mainly from two local rivers, has a good quality regarding the pH (5.7–7.6), EC (0.22–0.25 dS m^{-1}), and a sodium absorption ratio (SAR) below 1.0 (Ayers and Westcot 1994). Considering the contents of EC (C) and SAR (S), such irrigation waters were categorized as (C1–S1) [(Richards 1954) (Table 1)].

Agronomical activities are developed with flood irrigation, plowing into different depths to open up the hard

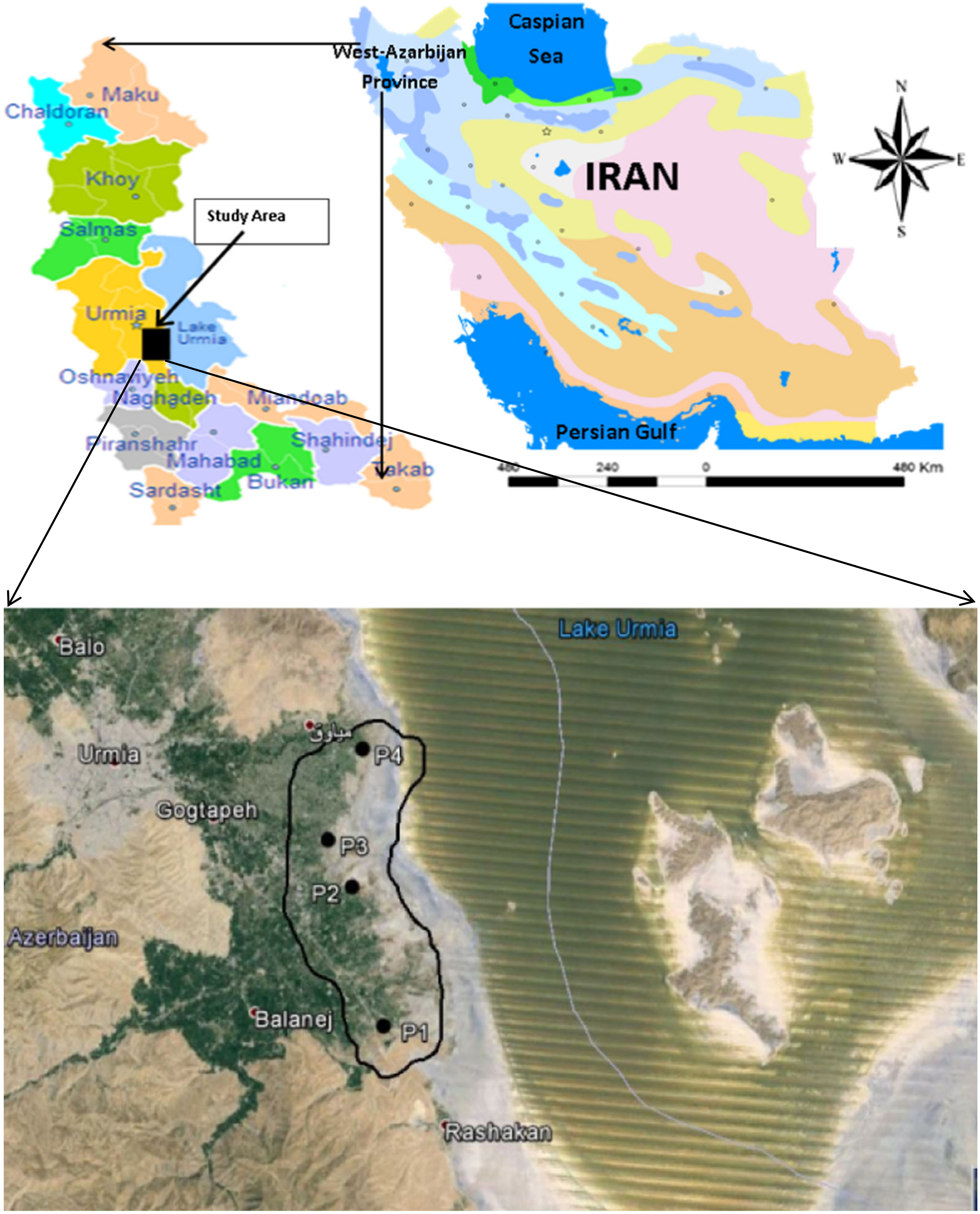

Fig. 1 Location of soil profile sites in the study area (P1, P2… pedon number)

Table 1 Selected chemical composition of the irrigation water applied for the cropped soils from Sept. 2013 until Dec. 2014

River	pH	EC dS m^{-1}	TDS mmol l^{-1}	SAR	$Na^{+1}/\sum Cations$
Shhrchay	7.08	0.22	166.40	0.04	0.10
Barandozchay	7.65	0.24	320.40	0.08	0.14
Mean	7.36	0.23	243.20	0.06	0.13
River	Ca^{+}	Mg^{+2}	Na^{+1} mmol l^{-1}	K^{+1}	$\sum$Cations
Shhrchay	0.60	0.50	0.13	0.01	1.24
Barandozchay	1.2	1.00	0.35	0.03	2.58
Mean	0.9	0.75	0.24	0.01	1.90
River	CO_3^{-2}	HCO_3^{-1}	Cl^{-1} mmol l^{-1}	SO_4^{-2}	$\sum$Anions
Shhrchay	0	0.20	2.00	0.07	2.27
Barandozchay	0	2.00	1.00	0.89	3.89
Mean	0	1.10	1.50	0.50	3.10

EC electrical conductivity, *TDS* total dissolved solids, *SAR* sodium adsorption ratio

soils, and fertilizer inputs irregularly. Consistent with this, a range of about 25–40 ton ha-1 year-1, 200–250 kg ha-1 year-1, and 100–150 kg ha-1 year-1 of manure, urea, and superphosphate have been used, respectively, in the region. Cropping was started by growing forage crops mainly alfalfa (*Medicago sativa* L.) for 5–10 years, followed by planting salt-tolerant crops particularly barley. Cropping is continued by planting salt-tolerant crops in rotation with industrial crops such as sugar beet and wheat in the second phase.

In the field work, two adjoining zones were selected with similar soil classification, drainage, and slope involving (1) tilled soils under rotation cropping (sugar beet, barley, wheat) and (2) nearby untilled soils (saline–sodic soils) as the control. The uncultivated soils are composed of halophilous vegetation such as *Salsola (SP), Salicornia (SP), and Atriplex (SP).* Typically, 64 composite soil samples associated with four soil series and eight profiles (four profiles from the tilled soils and four profiles from the adjoining untilled soils) were collected from surface soil (depth of 0–30 cm). For each profile, subsamples were collected within a radius of 10 m of a central point (surface horizon of each profile). When sampling from each soil series, in addition, tilled and adjoining untilled soils were considered within a distance of 50 m. The analysis was conducted on ground and on the fine earth fraction ($\varnothing < 2$ mm) samples.

Soil physiochemical analyses

Soil textural analysis was conducted by hydrometer method (Bouyoucos 1962). Soil pH and electrical conductivity (EC) were determined in the supernatant of 1:5 soil to 0.01 M $CaCl_2$ and saturated paste extract (Page 1996). The content of organic matter (OM) was estimated with dichromate oxidation (Nelson and Sommers 1982). Titration method was applied to determine calcium carbonate equivalent (CCE) (Nelson 1982). Cation exchange capacity (CEC) was measured by extraction with sodium acetate at a pH 8.2 (Chapman 1965). Total N and available phosphorus were determined by Kjeldahl (Nelson 1982) Olsen methods (Olsen and Sommers 1982). Exchangeable and soluble cations were extracted by 1 N NH4OAc and saturation extract (Thomas 1982), and then, their amount was determined by the complex-metric titration (Ca and Mg) and flame photometer (K and Na). The SAR (sodium adsorption ratio) was estimated as the relation of $SAR = Na^{+}/[(Ca^{+2} + Mg^{+2})/2]^{1/2}$, and the ESP (exchangeable sodium percentage) was estimated by the relation of ESP = exchangeable sodium content × 100/CEC (Salinity Laboratory Staff 1954).

The bioavailable fraction of the investigated metals (Fe, Zn, Cu, and Mn) was extracted by diethylene triamine pentaacetic acid (DTPA), as explain by Lindsay and Norvell (1978), and their concentrations were determined by an atomic absorption spectrophotometer. The repeated analysis of blanks and reference samples was considered for the quality control of chemical analysis.

A relative enrichment (RE) or relative depletion (RD) was estimated by the content of each soil attribute in the tilled soil divided by the content of that attribute in corresponding untilled soil. All statistical analyses were carried out using the program package SPSS 15.

Land productivity index (LPI)

Land productivity is the term given to the capability of land to perform productivity potential based on an evaluation of its physical, chemical, and biological characteristics. This index is greatly important in the management decisions on to accept a type and intensity of land use permanently without long-time degradation (Rezapour et al. 2015).

In the study, a land productivity index (LPI) model created by Khiddir (1986) was applied to demonstrate the effects of long-time irrigation–tillage on the attributes of saline–sodic soils. This index is estimated by the following formula (Sys et al. 1991):

$$\mathrm{LPI} = \mathrm{Rmin} \times \sqrt{\frac{H}{100} \times \frac{D}{100} \times \frac{\mathrm{P}}{100} \times \frac{T}{100} \times \frac{O}{100} \times \frac{\mathrm{A}}{100} \times \frac{M}{100} \times \frac{E}{100} \times \frac{S}{100}}$$

Rmin is average minimum rating, *H*, *D*, *P*, etc., and other ratings. The values of *H*, *D*, *P*, *M*, and *E* were determined in the field (Sys et al. 1991) and the values of *O*, *A*, and *S* were also measured in the laboratory (Page 1996). Each parameter is in relation to a numeric content between 0 and 100, and the outcome index of productivity, also lying between 0 and 100, is set against a scale placing the soil in one or other of five productivity classes as follows: Class I (excellent); LPI = 65–100, Class II (good); LPI = 35–64, Class III (average); LPI = 20–34, Class IV (poor); LPI = 8–19, Class V (extremely poor or nil); LPI = 0–7.

Soil characteristics used to determine the LPI were described as follows:

H refers to soil moisture content with ratings according to the time below the wilting point in the rooting zone. *D* refers to soil drainage with ratings according to water table depth and hydromorphic horizons. In the deep water table (hydromorphic horizon at over 120 cm depth), rating for *D* is 100, for example.

P refers to effective depth of soil with rating value 5–100.

T refers to the texture and structure of the root zone with rating value 10–100. In the angular to crumb structure and medium- to heavy-textured soil (e.g., sandy clay or silty clay loam), rating for *T* is 90, for example.

O refers to soil organic matter in surface horizons (*A* or Ap horizon) with rating value 70–100. In high organic matter content (over 5%), rating for *O* is 100, for example.

A refers to mineral exchange capacity and nature of the clay in the B horizon with ratings according to exchange capacity of clay.

M refers to the reserves of weatherable minerals in B horizon with rating value 85–100. For example, in minerals derived from basic or calcareous rocks, rating for *M* is 95.

E refers to the slope with ratings according to the overall slope. On land with slope of 0–2%, rating for *E* is 100, for example.

S refers to soluble salt content with ratings according to total soluble salts. For example, in total soluble salts less than 0.2%, rating for *S* is 100. For details, see Sys et al. (1991).

Results and discussion

General physicochemical features

Typically, the following soil types belonging to Aridisols and Inceptisols occur in the study region: Aquic Natrargids (AN-A), Sodic Aquicambids (SA-A), Typic Aquisalids (TA-A) and Typic Halaquepts (TH-I) according to Keys to Soil Taxonomy (Soil Survey Staff 2014).

In general, the uncultivated soils of the study region were characterized by the high level of exchangeable Na^+ (mean = 13.4, min = 9, max = 18 $\mathrm{cmol_c\ kg^{-1}}$), pH (mean = 8.17, min = 7.7, max = 8.49), EC (mean = 18.7, min = 5, max = 32 $\mathrm{dS\ m^{-1}}$), SAR (mean = 84, min = 40, max = 125), ESP (mean = 60, min = 44, max = 72%), and CCE (mean = 196, min = 170, max = 240 5 $\mathrm{g\ kg^{-1}}$) that can be classified into calcareous saline–sodic categories (Brady and Weil 1999; FAO/ISRIC/ISSS 2014).

The average content of selected soil physicochemical parameters is presented in Table 2. The conversion of saline–sodic soils to cropland decreased the values of the clay fraction in the range of 5–37%, while the amount of sand was enhanced (an increase of 8–86%) in most soils studied. This can be a result of: (1) clay depletion by runoff and erosion and/or (2) clay movement to subsoil by flooding irrigation (Rezapour and Samadi 2012). Compared to the untilled soils, the amounts of pH dropped ranging from 2 to 9% which can be viewed as a positive change in soil characteristics. Such trend might be due to the movement of salts into subsoil as flooding irrigation (Rezapour et al. 2013), frequent release of H^+ following the uptake of basic compounds by the roots of growing crops, and the effects of $\mathrm{CO_2}$ produced by organic compounds oxidation (Angassa et al. 2012). After cultivation, a drop of 8 (RD = 0.92) to 30% (RD = 0.7) was observed in the content of CCE in all soil types. The movement of carbonates to subsurface horizons as result of dissolution–translocation of native carbonates under irrigation practices and relatively high soil $\mathrm{CO_2}$ partial pressure, caused by the activity of roots and microorganisms, may be the main mechanisms for the decreasing trend of CCE values (Rezapour 2014).

A significant decrease occurred in the amount of EC (a drop of 69–82%) and SAR (a drop of 62–73%) after cropping except the soil type of AN-A. The possible explanation could be because of agronomical activities (e.g., moldboard tillage) and the extent of the root system that improved the topsoil for the percolating soluble salts. Following this process, the salts on the soil surface were promoted to migrate downwards through leaching created by irrigation. Typically, the values of Cl^-, SO_4^{-2}, HCO_3^-, and soluble Na^+ followed the similar trend with EC and diminished after cultivation significantly, whereas a significant rise, in contrast, was recorded in the concentration of soluble Ca^{+2} and Mg^{+2} with cultivation. These outcomes are in accordance with field researches elsewhere (Mishra and Sharma 2003; Qadir et al. 2008b), where a significant reduction in the quantities of soluble Na^+, EC, SAR along with an improvement in the content of soluble Ca^{+2} and Mg^{+2} has been observed following tillage–irrigation activities. The values of ESP and exchangeable Na^+ were found to decrease with cropping, ranging from 52 to 69 and 65 to 90%, respectively, that is in accordance with previous works (Mishra and Sharma 2003). The decreases in the soil ESP and exchangeable Na^+ may be associated with: (1) the mobilization of insoluble carbonates (particularly calcite and dolomite) by the biological processes of around the root zone and the release of organic acids from the decomposition of organic matter, resulting in an increase in the concentration of soluble Ca^{+2} and Mg^{+2}. Such processes probably encouraged the availability of Ca^{+2} to replace excess of exchangeable sodium on the ion exchange complex of the soil, thereby reducing exchangeable Na^+ absorption and ESP of the soil (Qadir and Oster 2002; Singh et al. 2014).

Following irrigation–cultivation practices, AN-A soil type showed different soil properties (mainly in soil pH, EC, SAR, and soluble cations and anions) compared to other soil types. Considering the fact that the drainage status was weaker in the soil type of AN-A compared to other soils, this pattern might be ascribed to the impact of soluble salt motion to the soil surface by evaporation and capillary rise and subsequent salts precipitation.

CEC, OC, and macronutrients

The quantity of CEC, as an indicator of nutrient retention capacity, was medium with a range of 15–26 $cmol_c\ kg^{-1}$ in both tilled and untilled soils, leading those in the level of the Aridisols and Inceptisols to semiarid condition (Table 3). The conversion of saline–sodic soils to the cropland induced some decrease in the values of CEC, ranging from 0.6 (RD = 0.99) to 29% (RD = 0.71). Specifically, this trend was in accordance with the trend of the clay fraction, showing the probable contribution of clay to CEC. Moreover, there was a weak to moderate relationship between CEC and OM ($r^2 = 0.32$, $P \leq 0.01$) and CEC and clay contents ($r^2 = 0.59$, $P \leq 0.01$). These values showed that the content of clay and organic matter contribute significantly to soil CEC, and the role of clay is greater than the role of organic matter. Therefore, any change in the values of clay and organic matter can affect soil CEC following intensive agricultural practices. Such observations are in accordance with the results of Abbasi et al. (2007) and Rezapour and Samadi (2012). There is also a significant relationship between OM and clay contents ($r^2 = 0.56$, $P \leq 0.01$), showing the importance of clay to hold organic matter.

After the cultivation of saline–sodic soils, the amount of organic carbon raised by 15 [a RE (relative enrichment) of 1.15] to 130% (a RE of 2.3) except the soil type of Aquic Natrargids which is in agreement with the observations of Singh et al. (2014). Nevertheless, the quantity of organic matter of the cultivated soils (min = 6 $g\ kg^{-1}$, max = 18.25 $g\ kg^{-1}$, mean = 12.25 $g\ kg^{-1}$) was categorized into various classes from very weak (4–5.95 $g\ kg^{-1}$) to high (16–185 $g\ kg^{-1}$) (Hazelton and Murphy 2007)] probably because of the variety in the soil classification and the distribution pattern of crop residue (Table 3). The amounts of total N enhanced by agronomical operations, similarly, was in parallel with organic carbon in range of 37 (a RE of 1.37) to 157% (a RE of 2.57), implying that the distribution pattern of total N was in accordance with the pattern of organic C as demonstrated by linear correlation between two the parameters ($r = 0.82$, $P \leq 0.01$). The increasing trend in soil organic C and total N in the tilled soils may be explained by the use of organic manure, N fertilizers, and addition of root biomass and crop residues after harvest as well-documented by Rezapour et al. (2013).

A minor increase was observed in the content of available P after cultivation, ranging from 1 to 7% (Table 3). This trend comes as no surprise because of a long history of using chemical P fertilizers and manure on the calcareous soils. There was a decreasing pattern in the values of exchangeable and available K, ranging from 8 to 54 and 10 to 60%, respectively, which can be viewed as a negative response in soil characteries. This pattern may be affected by sheet erosion, runoff, and/or leaching process caused by irrigation, uptake by crops, and the concentration of other cations in the soil solution. The similar findings were stated by other researchers from calcareous soils about the decline

Table 2 Mean ± standard deviation values of selected physicochemical attributes for the cultivated and uncultivated soils (saline–sodic soils)

Property	Cultivated soil	Uncultivated soil	%Change	RD or RE
Aquic Natrargids				
Sand (g kg^{-1})	310.25 ± 0.30	320.91 ± 14.40	−5.00	0.95
Silt (g kg^{-1})	290.58 ± 5.77	310.25 ± 21.00	−5.00	0.95
Clay (g kg^{-1})	390.16 ± 5.77	350.83 ± 24.40	9.00	1.09
pH	8.66 ± 0.19	8.48 ± 0.46	1.88	1.02
CCE (g kg^{-1})	170.00 ± 13.2	180.50 ± 8.06	−8.11	0.92
EC (dS m^{-1})	8.33 ± 3.70	5.30 ± 0.40	57.00**	1.57
Cl^{-1} (mmol l^{-1})	68.00 ± 32.12	21.33 ± 2.40	218.80***	3.19
SO$_4^{-2}$ (mmol l^{-1})	18.32 ± 8.10	5.15 ± 3.44	255.97***	3.56
HCO$_3^{-1}$ (mmol l^{-1})	12.33 ± 7.09	17.33 ± 8.08	−28.85*	0.71
CO^{-2} (mmol l^{-1})	Nil	Nil	–	–
S–Ca (mmol l^{-1})	0.98 ± 0.29	0.75 ± 0.02	31.00	1.31
S–Mg (mmol l^{-1})	0.83 ± 0.17	0.70 ± 0.0.08	18.60	1.19
S–Na (mmol l^{-1})	145.70 ± 45	47.80 ± 4.10	204.68***	3.05
S–K (mmol l^{-1})	0.30 ± 0.18	0.13 ± 0.05	130.76***	2.31
SAR	108.84 ± 40.15	40.40 ± 5.20	169.00***	2.69
Exchangeable Na (cmol$_c$ kg^{-1})	13.84 ± 4.86	9.65 ± 5.09	43.40*	1.43
ESP (%)	64.41 ± 7.05	44.90 ± 3.20	84.52**	1.84
Typic Halaquepts				
Sand (g kg^{-1})	272.5 ± 37.50	160.00 ± 33.00	70.30**	1.70
Silt (g kg^{-1})	376.60 ± 28.80	285.80 ± 14.00	31.80*	1.32
Clay (g kg^{-1})	350.80 ± 64.00	554.00 ± 41.00	−36.60*	0.63
pH	7.71 ± 0.22	8.49 ± 0.36	−9.19	0.91
CCE (g kg^{-1})	215.00 ± 18.00	240.00 ± 10.00	−10.41	0.89
EC (dS m^{-1})	6.03 ± 4.60	25.80 ± 3.59	−76.70**	0.23
Cl^{-1} (mmol l^{-1})	41.70 ± 13.1	168.30 ± 32.53	−75.00**	0.0.25
SO$_4^{-2}$ (mmol l^{-1})	15.31 ± 9.30	22.20 ± 10.60	−31.04*	0.69
HCO$_3^{-1}$ (mmol l^{-1})	3.66 ± 0.57	9.66 ± 0.57	−62.11**	0.38
CO^{-2} (mmol l^{-1})	Nil	Nil	–	–
S–Ca (mmol l^{-1})	2.98 ± 0.29	1.85 ± 0.02	61.00**	1.61
S–Mg (mmol l^{-1})	2.30 ± 0.41	1.66 ± 0.29	38.00*	1.38
S–Na (mmol l^{-1})	48.40 ± 18.50	206.20 ± 51.7	−51.53*	0.48
S–K (mmol l^{-1})	1.12 ± 0.02	1.63 ± 0.42	−31.30*	0.69
SAR	27.39 ± 57.92	109.42 ± 75.76	−62.03*	0.48
Exchangeable Na (cmol$_c$ kg^{-1})	5.92 ± 5.88	17.02 ± 9.15	−65.00*	0.35
ESP (%)	28.45 ± 94.58	70.40 ± 4.40	−52.17*	0.48
Sodic Aquicambids				
Sand (g kg^{-1})	345.8 ± 25.00	320.80 ± 52.00	7.80	1.08
Silt (g kg^{-1})	304.00 ± 23.00	254.00 ± 21.00	19.70	1.20
Clay (g kg^{-1})	350.00 ± 26.00	420.00 ± 36.00	−8.30	0.83
pH	7.30 ± 0.17	7.99 ± 0.24	−8.63	0.91
CCE (g kg^{-1})	128.300 ± 40.00	182.00 ± 21.00	−29.70*	0.70
EC (dS m^{-1})	2.23 ± 1.87	12.20 ± 18.70	−81.72**	0.18
Cl^{-1} (mmol l^{-1})	11.66 ± 6.54	113.30 ± 27.67	−89.70**	0.103
SO$_4^{-2}$ (mmol l^{-1})	6.60 ± 3.03	107.10 ± 8.95	−89.39**	0.106
HCO$_3^{-1}$ (mmol l^{-1})	2.70 ± 1.00	7.20 ± 3.60	−62.00**	0.38
CO^{-2} (mmol l^{-1})	Nil	Nil	–	–
S–Ca (mmol l^{-1})	3.60 ± 0.28	2.75 ± 0.28	118.20***	2.18

Table 2 continued

Property	Cultivated soil	Uncultivated soil	%Change	RD or RE
S–Mg (mmol l^{-1})	2.33 ± 1.15	1.75 ± 0.51	33.14*	1.33
S–Na (mmol l^{-1})	23.50 ± 19.7	138.30 ± 17.80	−83.00*	0.17
S–K (mmol l^{-1})	0.25 ± 0.29	1.85 ± 1.43	−86.48*	0.14
SAR	10.78 ± 10.5	62.73 ± 9.35	−73.25*	0.27
Exchangeable Na (cmol$_c$ kg^{-1})	3.52 ± 0.18	11.05 ± 6.28	−90.53*	0.66
ESP (%)	15.50 ± 16.09	48.50 ± 6.15	−68.00**	0.32
Typic Aquisalids				
Sand (g kg^{-1})	582.5 ± 33.00	312.50 ± 31.00	86.40**	1.86
Silt (g kg^{-1})	212.5 ± 21.00	366.60 ± 36.00	−58.00**	0.58
Clay (g kg^{-1})	205.00 ± 17.00	320.80 ± 19.00	−36.10*	0.64
pH	7.53 ± 0.20	7.70 ± 0.39	−20.20	0.98
CCE (g kg^{-1})	145.00 ± 44.00	176.00 ± 62.90	−18.00	0.82
EC (dS m^{-1})	5.80 ± 4.34	31.50 ± 34.9	−81.60**	0.18
Cl^{-1} (mmol l^{-1})	28.20 ± 19.68	198 ± 86.60	−85.70**	0.14
SO_4^{-2} (mmol l^{-1})	10.13 ± 6.18	89.55 ± 29.15	−88.70**	0.11
HCO_3^{-1} (mmol l^{-1})	2.66 ± 1.52	4.10 ± 1.10	−35.00*	0.65
CO^{-2} (mmol l^{-1})	Nil	Nil	–	–
S− Ca (mmol l^{-1})	3.30 ± 1.54	1.75 ± 1.25	88.60**	1.89
S− Mg (mmol l^{-1})	2.50 ± 1.15	1.65 ± 0.77	51.50*	1.52
S− Na (mmol l^{-1})	86.47 ± 24.10	231.2 ± 46.50	−58.00*	0.42
S− K (mmol l^{-1})	0.42 ± 0.13	5.21 ± 3.27	−91.90*	0.08
SAR	35.80 ± 8.27	124.20 ± 12.79	−69.00**	0.29
Exchangeable Na (cmol$_c$ kg^{-1})	3.52 ± 3.27	15.92 ± 19.84	−77.89**	0.22
ESP (%)	22.52 ± 5.40	72.40 ± 2.40	−69.00**	0.31

EC electrical conductivity, *S* soluble, *SAR* sodium adsorption ratio, *ESP* exchangeable sodium percentage, *RD* relative depletion, *RD* relative enrichment

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ based on paired *t* test results

of soil exchangeable and available K through K uptake by the plants and soil erosion (Rezapour and Samadi 2012; Rezapour et al. 2013). In spite of the fact that the change in sodic–saline soils to the cropland caused a depletion face in the K forms, the K quality of the soils was classified in level of high category, based on the K interpretation scheme of Srinivasarao et al. (2007), regarding both exchangeable and available K.

In general, the values of exchangeable cations were in the rank of $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$ in the majority of the soils. Such pattern may be explained by the strong adsorption energy of Ca^{2+}, creating it effectively more availability abundant as an exchangeable cation than Mg^{2+}, Na^{+} or K^{+} (Angassa et al. 2012). After cultivation, the concentrations of Ca^{2+}, Mg^{2+}, and K^{+} were above their critical limits (Hazelton and Murphy 2007). The mean values of exchangeable Ca in the tilled soils (min = 8, max = 13 cmol$_c$ kg^{-1}) and in the control samples (min = 4, max = 9 cmol$_c$ kg^{-1}) were 11 and 6.5 cmol$_c$ kg^{-1}, respectively, according to which the majority of samples could be classified into moderate (5–10 cmol$_c$ kg^{-1}) to high (10–20 cmol$_c$ kg^{-1}) categories (Hazelton and Murphy 2007). Also, the mean content of exchangeable Mg in the cultivated soils (min = 3.8, max = 7 cmol$_c$ kg^{-1}) and the control samples (min = 2, max = 2.6 cmol$_c$ kg^{-1}) was 4.9 and 2.3 cmol$_c$ kg^{-1}, resulting in a high category (3–8 cmol$_c$ kg^{-1}) for the tilled soils and a moderate category (1–3 cmol$_c$ kg^{-1}) for the control soils (Hazelton and Murphy 2007). Exchangeable Ca^{+2} and Mg^{+2} were observed to

Table 3 Mean ± standard deviation values of selected fertility properties for the cultivated and uncultivated soils

Property	Cultivated soil	Uncultivated soil	%Change	RD or RE
Aquic Natrargids				
OC (g kg^{-1})	5.90 ± 0.40	8.6 ± 0.70	−31.40*	0.69
CEC (cmolc kg^{-1})	20.59 ± 0.52	21.35 ± 0.29	−3.55	0.96
Total N (g kg^{-1})	3.10 ± 0.70	3.40 ± 0.40	−8.80	0.91
Available P (mg kg^{-1})	13.60 ± 3.71	12.86 ± 6.66	5.70	1.06
Available K (mg kg^{-1})	188.70 ± 79.70	278.90 ± 53.44	−32.30*	0.67
Exchangeable Ca (cmol$_c$ kg^{-1})	12.58 ± 2.30	8.61 ± 1.30	21.30	1.21
Exchangeable Mg (cmol$_c$ kg^{-1})	4.58 ± 1.09	2.56 ± 1.18	89.50**	1.9
Exchangeable K (cmol$_c$ kg^{-1})	0.45 ± 0.19	0.70 ± 0.14	−35.70*	0.64
Typic Halaquepts				
OC (g kg^{-1})	1770 ± 0.50	7.70 ± 0.80	129.89***	2.3
CEC (cmol$_c$ kg^{-1})	22.40 ± 3.05	25.23 ± 0.23	−12.00	0.89
Total N (g kg^{-1})	9.00 ± 1.70	3.50 ± 0.20	157.14***	2.57
Available P (mg kg^{-1})	17.80 ± 3.96	17.26 ± 2.34	3.59	1.03
Available K (mg kg^{-1})	579.0 ± 203.30	646.7 ± 74.59	−10.60	0.89
Exchangeable Ca (cmol$_c$ kg^{-1})	11.19 ± 1.20	6.50 ± 2.32	25.35*	1.25
Exchangeable Mg (cmol$_c$ kg^{-1})	6.61 ± 2.30	2.24 ± 1.18	83.40**	1.83
Exchangeable K (cmol$_c$ kg^{-1})	1.37 ± 0.21	1.49 ± 0.23	−8.10	0.92
Sodic Aquicambids				
OC (g kg^{-1})	15.2 ± 4.10	13.20 ± 4.50	15.15	1.15
CEC (cmol$_c$ kg^{-1})	20.70 ± 0.72	20.82 ± 0.26	−0.58	0.99
Total N (g kg^{-1})	7.40 ± 2.70	5.40 ± 1.87	37.03*	1.37
Available P (mg kg^{-1})	13.51 ± 0.50	13.40 ± 1.27	0.82	1.01
Available K (mg kg^{-1})	295.6 ± 119.6	685.30 ± 135.5	−56.9**	0.43
Exchangeable Ca (cmol$_c$ kg^{-1})	11.90 ± 1.98	6.60 ± 4.94	80.30**	1.8
Exchangeable Mg (cmol$_c$ kg^{-1})	4.50 ± 1.14	2.35 ± 1.40	91.00**	1.91
Exchangeable K (cmol$_c$ kg^{-1})	0.73 ± 0.61	1.57 ± 0.49	−53.50*	0.46
Typic Aquisalids				
OC (g kg^{-1})	10.00 ± 2.90	5.70 ± 2.20	75.40**	1.75
CEC (cmol$_c$ kg^{-1})	15.52 ± 0.01	21.79 ± 0.91	−29.00*	0.71
Total N (g kg^{-1})	7.80 ± 0.60	5.10 ± 1.50	52.90*	1.53
Available P (mg kg^{-1})	18.82 ± 2.02	17.67 ± 4.37	6.50	1.06
Available K (mg kg^{-1})	254.30 ± 20.74	628.3 ± 135	−59.53**	0.40
Exchangeable Ca (cmol$_c$ kg^{-1})	8.24 ± 3.30	4.20 ± 2.20	96.20**	1.96
Exchangeable Mg (cmol$_c$ kg^{-1})	3.88 ± 2.80	2.00 ± 1.52	94.00**	1.94
Exchangeable K (cmol$_c$ kg^{-1})	0.61 ± 0.06	1.09 ± 0.15	−44.03*	0.56

OC organic carbon, *CCE* calcium carbonate equivalent, *CEC* cation exchangeable capacity, *RD* relative depletion, *RD* relative enrichment

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ based on paired *t* test results

accumulate in the tilled soils in range of 20 (RE = 1.2) to 96% (RE = 1.96) and from 83 (RE = 1.83) to 94% (RE = 1.94) compared to the untilled soils (Table 3). This might be explained by rhizosphere impacts and organic compounds oxidation during tillage–irrigation–cropping (as previously discussed) which influenced more dissolution of soil calcite and dolomite through the formation of the acidic compounds (Wong et al. 2009).

DTPA-extractable micronutrients

Generally, the mean content of DTPA-extractable micronutrients follows the order of Fe > Mn > Zn > Cu > Cd for both tilled and untilled soils. DTPA Fe ranged between 4.5 and 15 mg kg^{-1} in the tilled soils and between 5.5 and 14.5 mg kg^{-1} in the untilled soils (saline–sodic soils). In all of the soil types, it was above the critical range

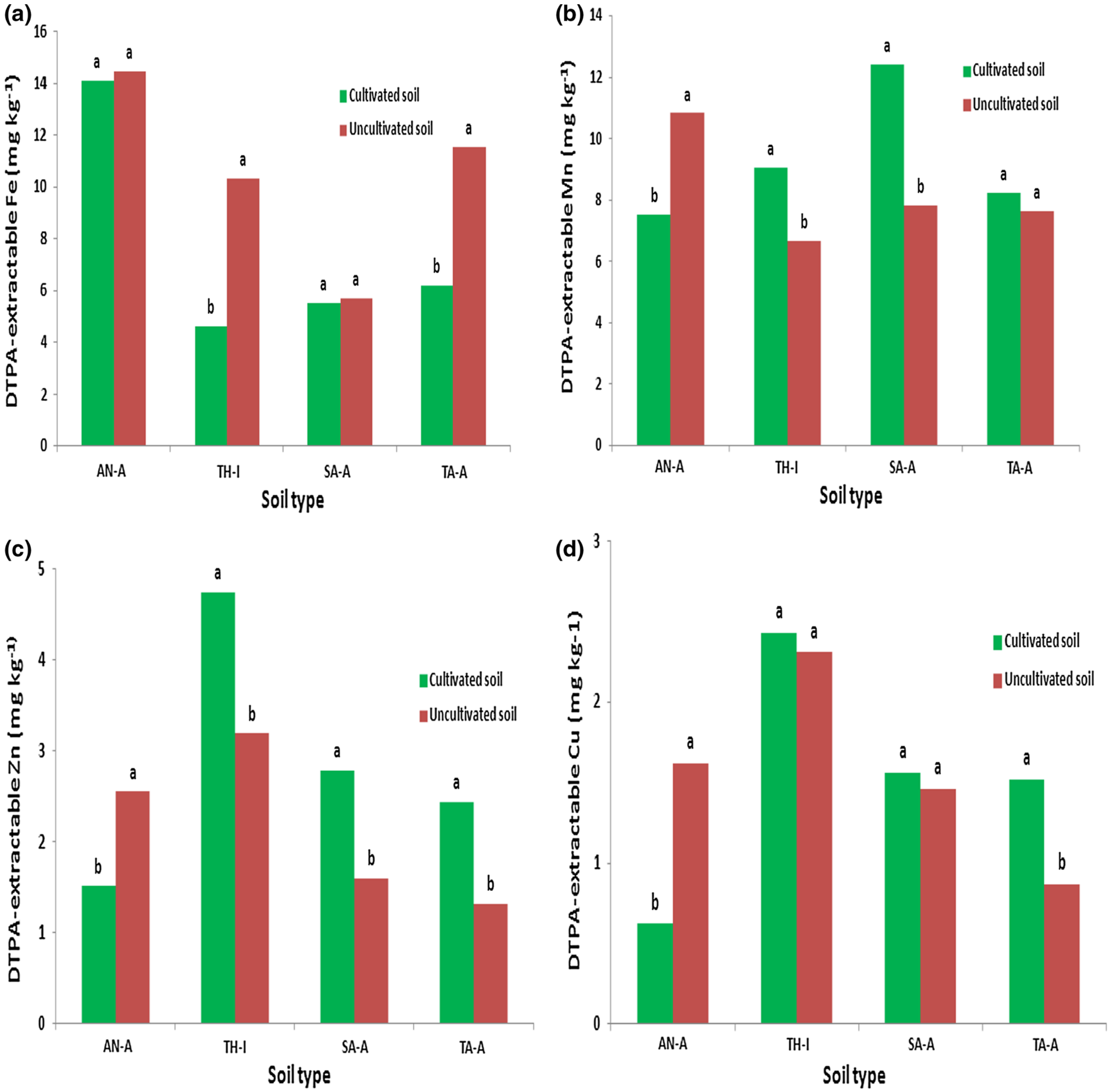

Fig. 2 Comparison of the mean amount of DTPA-extractable Fe (*a*), Mn (*b*), Zn (*c*), and Cu (*d*) in the cultivated soil and the adjacent uncultivated soils (saline–sodic soils) for different soil types. Values followed by the same latter are not significantly different ($P \leq 0.05$)

[(4.5 mg kg^{-1}) Lindsay and Norvell 1978] with respect to the plant nutrient aspects. Besides, the concentration of DTPA Fe was within the allowable maximum ranges regarding soil pollution (Malakouti and Gheibi 2000; Kaur and Rani 2006). There was a remarkable decline in the available Fe with agricultural activities in range of 2–54% (Fig. 2a), which can contribute to crop removal, soil erosion, and Fe motion to the subsoil by tillage–irrigation operation (Rezapour et al. 2013).

A rise of 8–58% was observed in the values of DTPA Mn (Fig. 2b) with the cultivation of saline–sodic soils in the majority of soil types This may be explained by distinct wetting (reducing)–drying (oxidizing) cycles during agricultural activities because of the capability of Mn to change from an oxidized to a reduced condition, thereby causing the increase in DTPA Mn in the tilled soils (Brady and Weil 1999). However, the DTPA concentration of Mn in both tilled ($\min = 7.5$, $\max = 13$, $\text{mean} = 9.3$ mg kg^{-1}) and

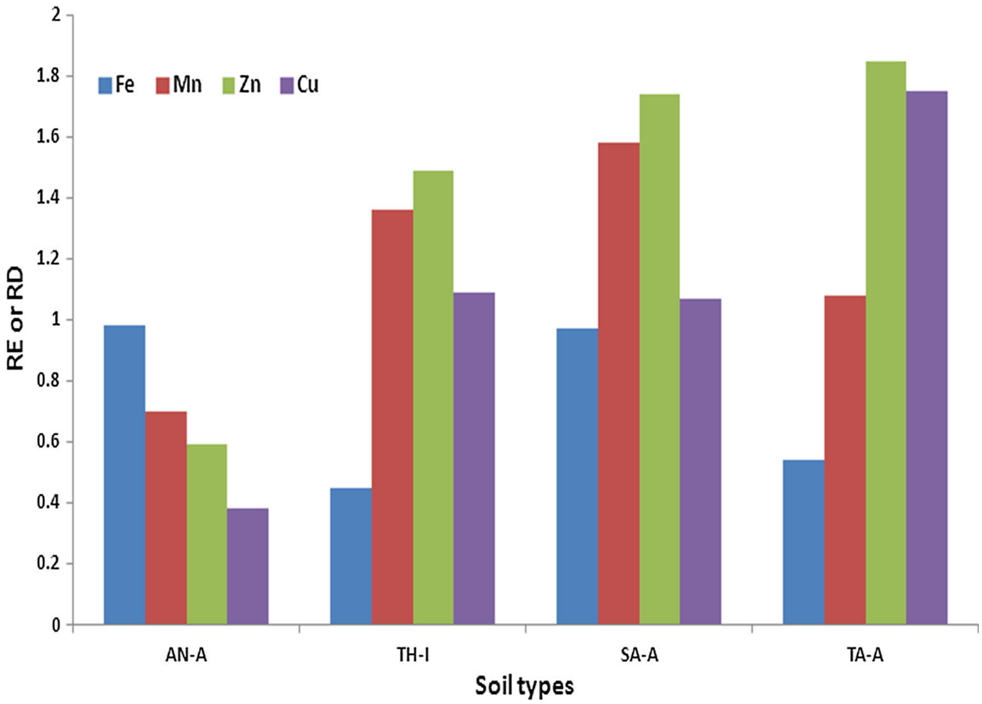

Fig. 3 Relative enrichment (RE) or relative depletion (RD) for DTPA-extractable Fe, Mn, Zn, and Cu in the different soil types. RE and RD are associated with the values of higher and lower than 1, respectively

untilled soils (min = 6.5, max = 11, mean = 8.25 mg kg^{-1}) was well within the allowable maximum ranges of 0–30 mg kg^{-1} (Malakouti and Gheibi 2000).

The DTPA values of Zn and Cu showed an increasing trend with cropping ranging from 48% (a RE of 1.48) to 85% (a RE of 1.85) and from 7% (a RE of 1.07) to 75% (a RE of 1.75), respectively (Fig. 2c, d), for the majority of the soils probably due to the use of various agrochemicals and fertilizers which is in agreement with the researches accomplished in the past. Ramos and Lopez-Acevedo (2004) described that the utilization of composted cattle manure enriched the EDTA and DTPA fraction of Zn in alkaline-calcareous soils from the northeastern Spain. In spite of the patterns mentioned above, the concentration of available Zn and Cu was well within the permitted limits in both tilled and untilled soils (Zn = 0.6–10 mg kg^{-1}, Cu = 0.2–5 mg kg^{-1}) based on national (Malakouti and Gheibi 2000) and international references (Kaur and Rani 2006). In Fig. 3, RE or RD for extractable-DTPA Fe, Mn, Zn, and Cu in various soil types is illustrated.

Land productivity index (LPI)

In order to better showing the impacts of the change in saline–sodic soils to cropland, land productivity index (LPI) was investigated. Land productivity is an important topic in terms of recognizing and predicting land capability for crop production and management options. The data showed that the soil types of TH-I, SA-A, and TA-A tend to the increase the LPI (a rise of 12–31%), whereas Aquic Natrargids reflected a decreasing pattern in the index (a drop of 10%) with cultivation (Fig. 4). Following the conversion of saline–sodic soils to cropland, the categorization of LPI was improved from an average (LPI = 20–34) to good class (LPI = 35–64) in the soil types of TH-I and SA-A, whereas other soil types, categorized as the good class, showed no change in LPI classification with cultivation. In this context, organic C and soluble salts were known as the major factors affecting LPI contents. However, effects of drainage condition, texture and structure, and mineral exchange capacity were not ruled out.

Nowadays, assessment of land productivity has been highlighted as a special operation due to the demand for soil conservation and its ability to retain its functions (De La Rosa 2005). However, it seems that the examined LPI needs to be improved by considering other soil properties mainly biological indicators. In the light of this, some of the soil physicochemical parameters of the LPI (e.g., texture/structure, soil depth, and slope) are very stable and permanent in time, whereas the soil biological attributes are more unstable and susceptible to management activities. In order to better illustrate the impact of tillage–

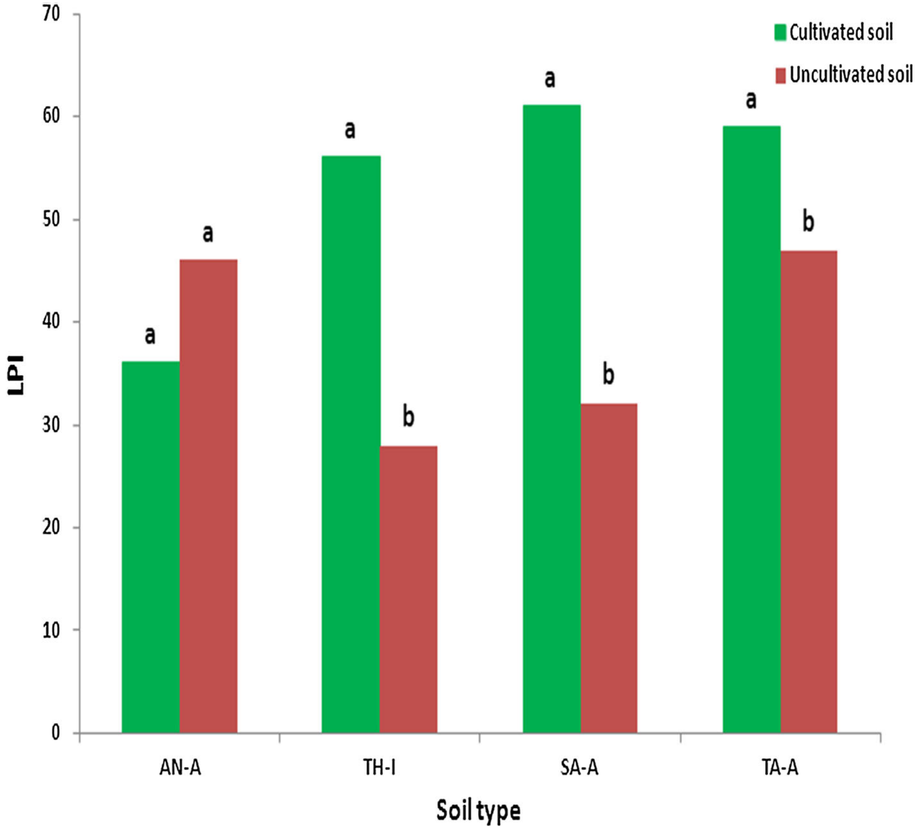

Fig. 4 Comparison of the values of land productivity index (LPI) for the cultivated and adjacent uncultivated soils (saline–sodic soils) of different soil types. Contents followed by the same latter are not significantly different ($P \leq 0.05$)

irrigation–cropping on soil attributes, future studies associated with land productivity indicators can be conducted on the evaluation of soil biological quality and its monitoring.

Conclusion

The majority of soils showed a clear pattern of changes in the soil chemical indices after 2 decades of the cultivation and irrigation. The major changes were as follows: (1) the accumulation of soil organic matter (which is of growing interest and concern), buildup of soil N and exchangeable Ca and Mg; (2) increase in the extractable Mn, Zn, and Cu; and (3) drop in the quantity of EC, SAR, and ESP. Such patterns can be remarked as a positive impact on soil quality of the agricultural ecosystems mainly in the alkaline–calcareous soils. In contrast, cultivation–irrigation caused a remarkable reduction in the values of CEC, K forms, and DTPA-extractable Fe which can be recorded as a negative effect in soil attributes. A rise of 10–31 in the values of LPI, as an important tool for soil management planning, was observed in 75% of the studied soils mainly as a result of the improvement in the organic matter along with the processes of desalinization and desodification. Considering the sensitivity of soil attributes of saline–sodic soils to tillage–irrigation practices as demonstrated in this study, it seems that periodic analysis of the chemical properties of both the irrigation water and the tilled soils is required in order to create the water–soil–crop suitable management options. Such activities can help to prevent agroecosystem degradation and to retain the overall health of these soils.

Acknowledgements The authors wish to thank Urmia University for their support throughout the research.

References

Abbasi MK, Zafar M, Razaq Khan S (2007) Influence of different land-cover types on the changes of selected soil properties in the mountain region of Rawalakot Azad Jammu and Kashmir. Nutr Cycl Agroecosyst 78:97–110. doi:10.1007/s10705-006-9077-z

Acosta JA, Fazb A, Jansen B, Kalbitz K, Martínez-Martínez S (2011) Assessment of salinity status in intensively cultivated soils under semiarid climate, Murcia, SE Spain. J Arid Environ 75:1056–1066. doi:10.1016/j.jaridenv.2011.05.006

Angassa A, Sheleme B, Oba G, Treydte AC, Linstädter A, Sauerborn J (2012) Savanna land use and its effect on soil characteristics in southern Ethiopia. J Arid Environ 81:67–76. doi:10.1016/j.jaridenv.2012.01.006

Ayers RS, Westcot DW (1994) Water quality for agriculture irrigation and drainage. Paper No. 29. FAO, Rome

Bouyoucos GJ (1962) Hydrometer method improved for making particle size analysis of soils. Agron J 54:464–465. doi:10.2134/agronj1962.00021962005400050028x

Brady NC, Weil RR (1999) The Nature and Properties of Soils. Prentice-Hall, Inc, Upper saddle river

Chapman HD (1965) Cation exchange capacity. In: Black CA (ed) Methods of soil analysis, part 2. American Society of Agronomy, Madison, pp 891–900

De La Rosa D (2005) Soil quality evaluation and monitoring based on land evaluation. Land Degrad Dev 16:551–559. doi:10.1002/ldr.710

FAO (2000) Global network on integrated soil management for sustainable use of salt-affected soils. Country Specific Salinity Issues—Iran. Rome, Italy

FAO/ISRIC/ISSS (2014) World reference base for soil resources. Food and Agriculture Organization of the United Nations, World Soil Resources reports no. 106, ISRIC and ISSS, Rome, Italy

Hazelton PA, Murphy BW (2007) Interpretation of soil test results (what do all the numbers mean?). CSIRO publishing 150 Oxford Street (PO Box 1139) Collingwood VIC 3066, Australia

Kaur R, Rani R (2006) Spatial characterization and prioritization of heavy metal contaminated soil-water sources in peri-urban areas of national capital territory (NCT), Delhi. Environ Monit Assess 123:233–247. doi:10.1007/s10661-006-9193-x

Khiddir SM (1986) A statistical approach in the use of parametric systems applied to the FAO framework for land evaluation. Ph.D. thesis State University Ghent, Belgium

Lindsay WL, Norvell WA (1978) Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci Soc Am J 42:421–428. doi:10.2136/sssaj1978.03615995004200030009x

Malakouti MJ, Gheibi MN (2000) Determination of critical levels of nutrients in soils, plant, and fruit for the quality and yield improvements of Iran's strategic crops. Applied Agricultural Science Publishers, Tehran **(In Persian)**

Mishra A, Sharma SD (2003) Leguminous threes for the restoration of degraded sodic wasteland in Eastern Uttarpradesh, India. Land Degrad Dev 14:245–261. doi:10.1002/ldr.544

MOI (Meteorological Organization of Iran) (2015) Climatology reports of Iran, 2000–2015

Nelson RE (1982) Carbonate and gypsum. In: Page AL (ed) Methods of soil analysis, part 2. American Society of Agronomy, Madison, pp 181–197

Nelson DW, Sommers LE (1982) Total carbon, organic carbon, and organic matter. In: Page AL (ed) Methods of soil analysis, part 2. American Society of Agronomy, Madison, pp 539–580

Olsen SR, Sommers LE (1982) Phosphorus. In: Page AL (ed) Methods of soil analysis, part 2. American Society of Agronomy, Madison, pp 403–430

Page AL (1996) Methods of soil analysis, part 2. American Society of Agronomy, Madison

Qadir M, Oster JD (2002) Vegetative bioremediation of calcareous sodic soils: History, mechanisms, and evaluation. Irrigation Sci 21:91–101

Qadir M, Oster JD (2004) Crop and irrigation management strategies for saline–sodic soils and waters aimed at environmentally sustainable agriculture. Sci Total Environ 323:1–19. doi:10.1016/j.scitotenv.2003.10.012

Qadir M, Schubert S (2002) Degradation processes and nutrient constraints in sodic soils. Land Degrad Dev 13:275–294. doi:10.1002/ldr.504

Qadir M, Schubert S, Ghafoor A, Murtaza G (2001) Amelioration strategies for sodic soils: a review. Land Degrad Dev 12:357–386. doi:10.1002/ldr.458

Qadir M, Tubeileh A, Akhtar J, Larbi A, Minhas PS, Khan MA (2008a) Productivity enhancement of salt affected environments through crop diversification. Land Degrad Dev 19:429–453. doi:10.1002/ldr.853

Qadir M, Qureshi AS, Cheraghi SAM (2008b) Extent and characterisation of salt affected soils in Iran and strategies for their amelioration and management. Land Degrad Dev 19:214–227. doi:10.1002/ldr.818

Ramos MC, Lopez-Acevedo M (2004) Zinc levels in vineyard soils from the Alt Penedes-Anoia region (NE Spain) after compost application. Adv Environ Res 8:687–696. doi:10.1016/S1093-0191(03)00041-8

Rezapour S (2014) Effect of sulfur and composted manure on SO_4-S, P and micronutrient availability in a calcareous saline–sodic soil. Chem Ecol 30:147–155. doi:10.1080/02757540.2013.841896

Rezapour S, Samadi A (2012) Assessment of inceptisols soil quality following long-term cropping in a calcareous environment. Environ Monit Assess 184:1311–1323. doi:10.1007/s10661-011-2042-6

Rezapour S, Taghipour A, Samadi A (2013) Modification in selected soil attributes as influenced by long-term continuous cropping in a calcareous-semiarid environment. Nat Hazard 69:1951–1966. doi:10.1007/s11069-013-0786-8

Rezapour S, Najari S, Ghaemian N (2015) The impacts of long-term intensive agriculture on the Vertisol properties in a calcareous region. Environ Monit Assess. doi:10.1007/s10661-015-4453-2

Richards LA (1954) Diagnosis and improvement of saline and alkali soils. US Salinity Laboratory, US Department of Agriculture Handbook 60, California

Salinity Laboratory Staff (1954) Diagnosis and improvement of saline and alkali soils. In: Agriculture handbook, vol 60. U. S. Department of Agriculture, Washington

Singh K, Mishra AK, Singh B, Singh RP, Patra DD (2014) Tillage effects on crop yield and physicochemical properties of sodic soils. Land Degrad Dev 27:223–230. doi:10.1002/ldr.2266

Soil Survey Staff (2014) Keys to soil taxonomy. U.S. Department of Agriculture, National Resources Conservation Service

Srinivasarao CH, Vittal K, Tiwari KN, Gajbhiye PN, Kundu SU (2007) Categorisation of soils based on potassium reserves and production system: implications in K management. Aust J Soil Res 45:438–447. doi:10.1071/SR07024

Sys C, Van Ranst E, Debaveye J (1991) Land evaluation. Part 2. Methods in land evaluation. Agricultural publication-No 7, G.A.D.C., Brusscle, Belgium

Szabolcs I (1989) Salt-affected soils. CRC Press, Boca Raton

Tanji KK (1990) Nature and extent of agricultural salinity. In: Tanji KK (ed) Agricultural salinity assessment and management. Manuals and reports on engineering practices no. 71. American Society of Civil Engineers, New York, pp 1–17

Thomas GW (1982) Exchangeable cations. In: Page AL (ed) Methods of soil analysis, part 2. American Society of Agronomy, Madison, pp 159–166

Wong VNL, Dalal RC, Greene RSB (2009) Carbon dynamics of sodic and saline soils following gypsum and organic material additions: a laboratory incubation. Appl Soil Ecol 41:29–40. doi:10.1016/j.apsoil.2008.08.006

Wong VNL, Greene SB, Dalal RC, Murphy BW (2010) Soil carbon dynamics in saline and sodic soils: a review. Soil Use Manag 26:2–11. doi:10.1111/j.1475-2743.2009.00251.x