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Research Article

Status and Causes of Soil Salinization of Irrigated Agricultural Lands in Southern Baja California, Mexico

Tsuneyoshi Endo,[1] Sadahiro Yamamoto,[1] Juan A. Larrinaga,[2] Hideyasu Fujiyama,[1] and Toshimasa Honna[1]

[1] *Faculty of Agriculture, Tottori University, 4-101 Koyama-Minami, Tottori 680-8553, Japan*
[2] *Centro de Investigaciones Biologicas del Noroeste, La Paz, BCS 23090, Mexico*

Correspondence should be addressed to Tsuneyoshi Endo, endo@muses.tottori-u.ac.jp

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Selected farmlands in southern Baja California, Mexico, were surveyed to determine the levels and the causes of salinization/sodication in irrigated agricultural soil. The salt dynamics observed in profiles differed from farm to farm. Low EC and high pH levels were observed in the profiles of sandy fields, because the salt composition of these soils can easily change when salts are leached by irrigation water that contains carbonates of sodium. On the other hand, high levels of salinity and sodicity were observed in the soils of clayey fields. Soil salinization/sodication is complexly interrelated with soil characteristics, the amount and composition of salts in the soil, the quantity and quality of irrigation water applied, and the irrigation methods used. Our findings indicate that irrigation water in Baja California should be supplied at a rate that is sufficient to meet crop requirements without exacerbating salt accumulation.

1. Introduction

In arid regions, desertification is mainly caused by human activity [1, 2]. Attempts to grow crops in arid inadequate irrigated areas have mainly resulted in the salinization and/or sodication of the soil. Because the irrigation of agricultural lands in arid regions has not yet become a widespread practices a relatively small area has been degraded compared to the areas used for grazing or those in which rain-fed agriculture is carried out. However, irrigation tends to increase productivity in the short term, and the need to produce food for an increasing population might result in the conversion of grazed, rain-fed, and even virgin lands to irrigated fields [3]. Furthermore, the reclamation of salt-affected land that has been irrigated for agricultural purposes has become increasingly important. Reducing the severity and extent of soil salinity is primarily a matter of soil and water management. Good water management involves both preventing water received in the recharge areas from percolating into groundwater and maintaining the water table of the discharge areas at low, safe levels. The most common approach to salinity management is to maintain a prescribed leaching requirement. However, this approach is ineffective when the irrigation water contains significant levels of sodium, carbonates, and bicarbonates. In addition, the surface drainage capacity of these arid soils is usually poor.

The Baja California peninsula was once a part of the North American Plate, of which mainland Mexico remains a part. In southern Baja California, Pliocene to early Quaternary sedimentary formations were deposited syntectonically over a major detachment that is associated with the exhumation of Mesozoic crust [4]. The area has a very dry climate with an average annual rainfall that ranges from less than 100 to 300 mm. Mean temperatures typically range between 18 to 22°C. Rainfall is characterized by its irregularity and variability in both time and space [5]. Though most soils in Baja California are low in organic matter, their levels of plant nutrients (except nitrogen) tend to be high. If sufficient irrigation water is available and temperatures are favourable, these soils can be made highly productive for agriculture. The crops that are most profitable and best adapted to the conditions of the region are grown in La Paz due to economic pressure. These factors result in the cultivation of extensive monocultures, mainly of chilli peppers, frijol beans, and tomatoes. Legume crops are cultivated extensively in the southern part of the peninsula though the number of species that are adapted to the area is limited. The widespread use of commercial fertilizer has led to the recent intensification of agriculture in localised areas of Baja California. In some areas, the indiscriminate use of large amounts of chemical fertilizers and the overexploitation of groundwater has dramatically increased the amount of surface soils affected by salinity. Crop cultivation redistributes water within a landscape by changing the vegetative composition, the amount of water infiltration into the soil, and the amount of runoff, which can in turn aggravate the natural processes of soil salinization.

This study represents the first attempt to scientifically investigate the salinity of agricultural soils in southern Baja California. We hope to provide baseline data against which to compare future measurements of soil salinity and sodicity. The aims of the study were to (1) clarify the physicochemical properties of the soil, (2) evaluate the current state and severity of soil salinity and soil sodicity, and (3) assess the probability of soil salinity levels increasing under the current agricultural land use and management practices. This study was carried out on selected small- and medium-scale farmlands in southern Baja California, where there is little use of subterranean water for irrigation. The physicochemical properties of the cultivated soils were investigated to clarify the profile of salt distribution at the few sites where soils are irrigated. We also evaluated the mechanisms of soil salinization and sodication in soils that are irrigated for agricultural purposes. Finally, the amount of available micronutrients present in the soil was assessed to determine the land's potential for agriculture.

2. Materials and Methods

2.1. Site Descriptions and Sampling Sites. The investigated area was El Carrizal in the suburbs of La Paz, southern Baja California, Mexico (Figure 1). The average annual precipitation is less than 200 mm and the rainfall varies in time and space (Table 1). Both the tropical climate and the location of Baja California in the direct path of Pacific hurricanes ensure that the area receives more tropical cyclones than any other part of Mexico. The rainy season extends from May to October, and most tropical cyclone impacts occur in September. This coincides with the statistical peak of the eastern North Pacific hurricane season, which occurs in late August or early September. The area is characterized as dry, warm, and sunny with a mean annual temperature of 23°C–25°C.

Five farmlands in the village of El Carrizal, where subterranean water is used for irrigation, were selected to assess the status of soil salinization as study sites. Irrigation water was sampled from each farm. There is little use of underground water for irrigation in the investigated area. These farms located between 23°45′ to 23°47′ N and 110°16′ to 110°18′ W were used to represent small- and medium-scale agriculture plots (Figure 1).

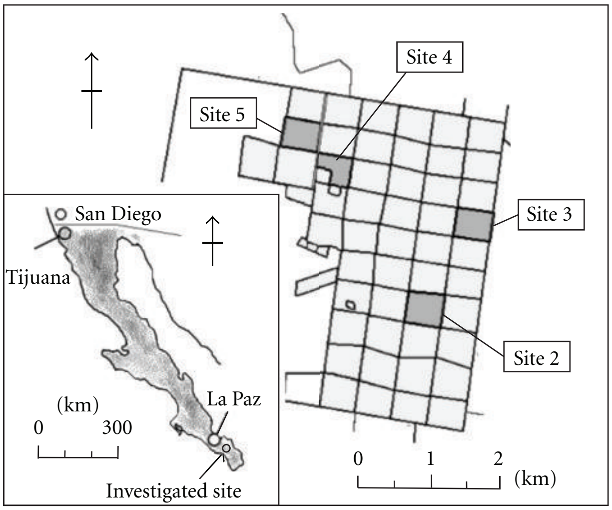

Figure 1: Location of the investigated farmlands. Site 1 is located at about 7 km southeast of Site 2.

Site 1 has been in production for two years. The soil properties before and after cultivation of frijol beans were investigated at this site. Irrigation water was generally applied for three hours every three days by drip irrigation. Site 2 has been in production for two years. Chile guerito was the main crop here. Irrigation water was generally applied three hours every three days by drip irrigation. Site 3 has been farmed for a decade, primarily for the cultivation of Chile guerito. Irrigation water was generally applied for half a day three days per week by drip irrigation. The soil of Sites 1, 2 and 3 were classified as typic torriorthents and aridic arenosols, according to soil taxonomy [6] and WRB classification [7], respectively. Site 4 has been managed for about twenty yeas every ten to fifteen days by driprs, primarily for the cultivation of Chile guerito and frijol beans. Irrigation water was applied here for three-hour irrigation. Site 5 has been managed for a decade, primarily for the culture of frijol bean. Irrigation water was generally applied for five hours every five to six days by drip irrigation. The soil of Sites 4 and 5 were classified as petroargids and sodic solonchaks, according to soil taxonomy [6] and WRB classification [7], respectively. Sites 4 and 5 drew their irrigation water from the same well. The other sites used its own well.

2.2. Analysis of Soil and Irrigation Water. Geostatistics can be defined as a set of tools and techniques to analyze spatial patterns and predict the values of a continuous variable distributed in space or in time at unsampled locations [8–11]. During November 2002 (before cultivation) and November 2003 (after one year cultivation) at Site 1, 80 surface soil samples from 0 to 10 cm depth were collected at 10 m intervals to investigate the spatial variations of pH and electrical conductivity (EC). The pH and EC were determined in a 1 : 5 soil to water ratio. To evaluate the salini-zation and sodication of soils in this site, soil profiles of approximately 1 m in depth were investigated on November 2002 and November 2004. Soil profiles of approximately 1 m in depth

Table 1: Average monthly temperature and rainfall at La Paz, Mexico.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Temperature (°C)	18.0	19.4	20.4	22.6	24.7	27.4	29.8	29.7	28.7	25.6	22.1	19.3
Rainfall (mm)	8	24	0	0	1	6	13	31	33	15	15	25

Table 2: Irrigation water quality in the investigated area.

Sites	pH	EC dS m^{-1}	Cations and anions (mmolc L^{-1})								SAR $(\text{mmol } L^{-1})^{1/2}$
			Ca^{2+}	Mg^{2+}	K^+	Na^+	SO_4^{2-}	NO_3^-	HCO_3^-	Cl^-	
Site 1	7.99	0.96	4.10	2.16	0.09	3.47	0.93	0.58	2.63	4.69	1.96
Site 2	8.02	0.83	2.66	1.94	0.22	4.80	0.87	0.01	2.33	5.76	3.17
Site 3	7.78	1.38	6.06	4.26	0.45	5.11	1.24	0.39	2.12	11.11	2.25
Site 4	7.81	1.74	7.32	5.04	0.63	9.86	1.50	0.00	2.06	15.70	3.97
Site 5	7.81	1.74	7.32	5.04	0.63	9.86	1.50	0.00	2.06	15.70	3.97

were also examined in Sites 2, 3, 4, and 5 on November 2002. Soil samples were collected for laboratory analysis of the soil physicochemical properties.

Soil samples were air-dried, crushed, and passed through a 2-mm sieve. Soil properties known to be influenced by the accumulation of salts and/or those affecting the optical properties of the soil were determined for each prepared sample by standard laboratory methods. These properties were soil particle size distribution, pH, EC, moisture content, soluble salt content, Olsen P, total C, total N, and available micronutrients. Particle size distribution was measured using the pipette method [12] after removal of carbonate salts with 1 M CH_3COONa (pH 5) [13]. Soil texture triangle and distribution percentage measurements were used to define the soil texture of the samples. The ECe was determined from soil saturated water extract using air-dried soil and distilled water. The amount of cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) and anions (SO_4^{2-}, NO_3^-, and Cl^-) present in each of the irrigation water and soil samples were measured using an atomic absorption spectrophotometer (Hitachi, Z-2300) and ion chromatography (Shimadzu, LC-10A). The HCO_3^- (alkalinity) was measured by titration. An Olsen P test was carried out by shaking 5 g of air-dried soil in 100 mL of 0.5 M-$NaHCO_3$ (pH 8.5) for 30 minutes in an end-over-end shaker [14], then measuring the P concentration in the solution using spectrophotometric method. Total C and N levels were determined by dry combustion using a SumiGraph NCH-21 analyzer (Sumika, MT 700). Available manganese (Mn_d), iron (Fe_d), copper (Cu_d), and zinc (Zn_d) were extracted with diethylenetriamine penta-acetic acid (DTPA-PAC) [15] and quantified with ICP (Rigaku, CIROS CCD). The clay mineralogy was determined by X-ray diffraction (Rigaku, RINT2500HF) using Mg- and K-saturated clay. In addition, heat (350°C, 550°C) and glycerol treatments were performed.

3. Results and Discussion

3.1. Properties of the Irrigation Water in the Investigated Area. The quantity of well water that could be obtained for irrigation in the investigated area varied from farm to farm. It depended largely on the financial status of each individual farmer, because it costs the farmer to pump up water from wells. The properties of irrigation water used in the investigated areas are shown in Table 2. The US Salinity Laboratory's diagram [16] is used widely for classifying irrigation water. According to the diagram, the water samples were classified as C3S1, indicating a high salinity and low sodium hazard. However, high concentrations of bicarbonate ion were also observed in the water samples, which can result in high soil pH and may cause deficiencies in iron or other micronutrients [17].

3.2. Morphological Properties and Salt Status of Soils. Pedon descriptions for the soil profiles obtained from the investigated areas are summarized in Table 3. The morphological and physicochemical properties of the soil profiles are shown in Table 4. Here, we described the soil and irrigation properties of each site.

Site 1. 12 mm irrigation water was applied every hour from drip irrigation tube holes at this site. In total, 36 mm of irrigation water was applied to the field every three days. The changes in spatial variations of the salt accumulation status ($EC_{1:5}$) and $pH_{1:5}$ in surface soil from November 2002 to November 2003 are shown in Figure 2. Salts in the soil were redistributed by irrigation and the soil $pH_{1:5}$ increased with the use of the drip irrigation over this one year period. Though the increase in soil $EC_{1:5}$ was slight, the increase in soil $pH_{1:5}$ was remarkable. Because the clay content was low, the soil showed high water permeability. The salt composition of this soil could easily have been changed when salts were leached with irrigation water that contained sodium carbonates. This resulted in the high soil alkalinity, observed [16]. Although soil ECe (electrical conductivity of a saturated paste extract) was low, soil pHe (pH of a saturated paste extract), alkalinity and SAR (sodium adsorption ratio) levels were high. The relative high pHe and low ECe have been due to the fact that the amount of water is controlled and, therefore, limited, while under conventional irrigation, salts and fertilizers were leached out due to the low water retention of the sandy-textured soils.

Table 3: Pedon description.

Soil Horizon	Depth (cm)	Boundary Dis.	Boundary Con.	Structure	Compactness	Roots
Site 1; After cultivation of fulijol beans						
Ap1	0–18	Clear	Smooth	SG	Very loose	VF-f, F-f
Ap2	18–28	Clear	Smooth	SG	Very loose	VF-f, F-f
C1	28–50/58	Difuse	Wavy	SG	Loose	VF-f
C2	50/58–105	Clear	Smooth	SG	Loose	VF-f
C3	105–115+			SG	Loose	None
Site 2; Under cultivation of chille guerito						
Ap	0–16	Clear	Smooth	SG	Very loose	VF-m, F-f
C1	16–40	Difuse	Smooth	SG	Medium	VF-f
C2	40–65/71	Clear	Wavy	SG	Loose	VF-f
C3	65/71–75+			SG	Loose	None
Site 3; Under cultivation of chille guerito						
Ap	0–22	Difuse	Smooth	SBK-F-W, GR-F-W	Very loose	VF-m, F-f
C1	22–45	Difuse	Smooth	SBK-F-W, SBK-M-W	Loose	VF-co
C2	45–65	Difuse	Smooth	SBK-F-W, SBK-M-W	Loose	VF-co
C3	65–75+			MA	Loose	VF-f
Site 4-1; Under cultivation of chille guerito						
Ap1	0–10	Clear	Smooth	SBK-M-W, GR-F-W	Very loose	VF-f
Ap2	10–22	Abrupt	Smooth	SBK-M-Mo, SBK-C-Mo	Very loose	VF-f
Bw	22–35	Clear	Wavy	SBK-M-Mo, ABK-M-Mo, ABK-M-S	Medium	None
Bk	35–46/49	Clear	Wavy	ABK-M-Mo	Compact	None
Bkm	46/49–60+			ABK-M-S	Very compact	None
Site 4-2; Under cultivation of fulijol beans						
Ap1	0–10	Clear	Smooth	SBK-F-W, SBK-M-W	Very loose	VF-f
Ap2	10–20/25	Abrupt	Wavy	SBK-F-W	Very loose	VF-f
Bk	20/25–39/41	Difuse	Wavy	SBK-C-W	Loose	None
BC	39/41–66/71	Clear	Wavy	SBK-M-W	Medium	None
Bkm	66/71–75+			MA	Very compact	None
Site 5; Under cultivation of chille guerito						
Ap	0–17/32	Abrupt	Wavy	SBK-M-W, GR-F-W	Loose	VF-co
Bk1	17/32–55	Difuse	Smooth	MA	Very compact	None
Bk2	55–60+			MA	Very compact	None

[a] Boundary—Dis.: distinctnesss, Con.: configuration. Structure: type-size grade—type: GR: granular, MA: massive, ABK: angular blocky, SBK: subangular blocky, SG: single grain.—size: F: fine, M: medium, C: coarse.—grade: W: weak, Mo: moderate, S: strong. roots, size quantity—size: CO: coarse, F: fine, M: medium, VC: very coarse, VF: very fine. quantity—f: few, c: common, m: many.

Though salt accumulation in the soil was not observed, soil alkalinity was heightened. A significant amount of the sodium carbonate in the irrigation water was transferred to the soil, thereby increasing its soil content. Taking the result as mentioned above, the quantity of irrigation water was reduced to 12 mm every three days, and a moderate amount of diluted sulphuric acid was applied with the drip irrigation. Diluted sulphuric acid was prepared by dilution of sulphuric acid (91%, 34.14 mol L^{-1}) by 5000 times. We added the diluted sulphuric acid solution to the drip irrigation liquid fertilizer used for drip irrigation at the start of irrigation. While ECe and pHe was maintained in the surface soil,

Table 4: Physicochemical properties of soils in the investigated area.

Soil Horizon	Depth (cm)	Particle size distribution (%)				Soil Texure	pH	EC dS m^{-1}	The amount of soluble salts in saturated extract (cmolc kg^{-1})								SAR (mmol L^{-1})$^{1/2}$
		Coarse sand	Fine sand	Silt	Clay				Cations				Anions				
									Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	$SO_4{}^{2-}$	$NO_3{}^{-}$	$HCO_3{}^{-}$	Cl^{-}	
Site 1-1; No cultivation (before application of diluted sulfuric acid)—November, 2002																	
A1	0–10	73.42	22.58	2.91	1.09	S	8.17	0.49	0.07	0.03	0.04	0.04	0.01	0.00	0.19	0.02	1.07
A2	10–20	53.72	39.51	3.38	3.39	S	8.04	0.57	0.08	0.03	0.03	0.07	0.02	0.00	0.15	0.05	1.78
C11	20–30	57.66	36.02	2.21	4.11	S	8.05	0.80	0.13	0.05	0.02	0.05	0.01	0.01	0.20	0.10	1.00
C12	30–40	66.44	26.66	4.63	2.27	S	8.10	0.61	0.03	0.11	0.02	0.04	0.01	0.00	0.13	0.05	0.90
C21	40–50	68.98	25.30	3.50	2.22	S	8.14	0.68	0.15	0.04	0.01	0.05	0.01	0.01	0.16	0.06	0.97
C22	50–60	65.09	30.33	3.55	1.03	S	8.02	0.54	0.02	0.09	0.01	0.06	0.01	0.02	0.15	0.04	1.52
C31	60–80	73.54	22.85	3.11	0.50	S	8.05	0.42	0.06	0.01	0.01	0.04	0.01	0.02	0.08	0.02	1.26
C32	80–90	65.36	29.82	3.28	1.54	S	7.90	0.32	0.04	0.01	0.01	0.03	0.01	0.01	0.06	0.01	1.14
C41	90–105	69.82	26.26	2.85	1.07	S	7.98	0.35	0.01	0.06	0.01	0.05	0.01	0.01	0.13	0.02	1.59
C42	105–115+	70.16	24.82	3.98	1.04	S	7.94	0.31	0.04	0.01	0.01	0.03	0.01	0.00	0.06	0.01	1.14
Site 1-2; After cultivation of fulijol beans (after application of diluted sulfuric acid))—November, 2004																	
Ap11	0–10	60.62	32.17	4.67	2.54	S	7.93	0.70	0.06	0.03	0.03	0.11	0.02	0.00	0.05	0.16	3.09
Ap12	10–18	57.07	35.85	4.02	3.06	S	8.08	0.48	0.06	0.03	0.03	0.05	0.01	0.00	0.04	0.11	1.32
Ap2	18–28	60.68	33.42	3.73	2.17	S	8.00	0.69	0.05	0.02	0.02	0.13	0.03	0.00	0.03	0.18	3.85
C11	28–37	76.15	19.58	2.47	1.80	S	7.78	0.83	0.08	0.04	0.02	0.13	0.03	0.00	0.02	0.20	3.26
C12	37–50/58	62.71	32.60	2.99	1.70	S	5.23	0.77	0.07	0.04	0.01	0.11	0.02	0.00	0.00	0.19	2.69
C21	50/58–62	66.10	30.43	2.70	0.77	S	4.67	0.56	0.04	0.03	0.01	0.09	0.01	0.00	0.00	0.14	2.91
C22	62–80	58.87	37.11	2.47	1.55	S	5.32	0.37	0.02	0.02	0.01	0.07	0.01	0.00	0.00	0.08	2.91
C23	80–105	82.96	15.37	1.39	0.28	S	5.00	0.27	0.01	0.01	0.01	0.05	0.01	0.00	0.00	0.05	3.15
C3	105–115+	79.63	17.45	1.36	1.56	S	7.03	0.18	0.01	0.01	0.01	0.04	0.00	0.00	0.01	0.03	2.15
Site 2; Under cultivation of chille guerito—November, 2002																	
Ap1	0–8	20.94	61.06	8.88	9.12	SL	7.89	2.51	0.32	0.18	0.05	0.36	0.17	0.19	0.04	0.46	4.21
Ap2	8–16	20.18	61.41	9.56	8.85	SL	7.86	1.29	0.16	0.08	0.04	0.20	0.04	0.11	0.04	0.17	3.23
C11	16–29	21.25	59.39	9.82	9.54	SL	7.61	1.08	0.12	0.05	0.05	0.15	0.03	0.16	0.02	0.08	3.08
C12	29–40	24.80	53.10	10.46	11.64	SL	7.58	0.72	0.08	0.03	0.03	0.11	0.03	0.10	0.02	0.08	2.65
C21	40–55	26.99	49.74	10.31	12.96	SL	7.68	0.66	0.08	0.03	0.02	0.10	0.02	0.07	0.02	0.08	2.44
C22	55–65/71	24.74	51.11	9.72	14.43	SL	7.79	0.68	0.09	0.04	0.01	0.11	0.03	0.06	0.03	0.09	2.38
C3	65/71–75+	23.74	51.81	11.21	13.24	SL	8.17	0.66	0.09	0.03	0.01	0.10	0.03	0.02	0.06	0.11	2.48
Site 3; Under cultivation of chille guerito—November, 2002																	
Ap1	0–10	20.99	53.62	9.93	15.46	SCL	7.45	3.13	0.62	0.36	0.04	0.23	0.09	0.94	0.02	0.18	1.76
Ap2	10–22	20.73	53.86	9.09	16.32	SCL	7.89	2.30	0.44	0.24	0.02	0.23	0.14	0.51	0.06	0.15	2.09
C11	22–33	18.95	52.40	10.09	18.56	SCL	7.93	0.99	0.16	0.09	0.02	0.12	0.05	0.08	0.05	0.21	1.77
C12	33–45	18.93	50.25	11.41	19.41	SCL	7.81	0.83	0.13	0.07	0.02	0.15	0.04	0.04	0.04	0.22	2.46
C21	45–55	24.30	46.20	10.74	18.76	SCL	7.69	0.87	0.13	0.07	0.01	0.13	0.04	0.03	0.03	0.22	2.28
C22	55–65	30.29	41.45	10.55	17.71	SCL	7.84	0.79	0.13	0.06	0.01	0.14	0.04	0.01	0.03	0.22	2.48
C3	65–75+	38.40	37.75	8.18	15.67	SCL	7.64	0.89	0.12	0.06	0.01	0.12	0.04	0.01	0.02	0.21	2.35

Table 4: Continued.

Soil Horizon	Depth (cm)	Particle size distribution (%)				Soil Texure	pH	EC dS m^{-1}	The amount of soluble salts in saturated extract (cmolc kg^{-1})								SAR $(mmol\,L^{-1})^{1/2}$
		Coarse sand	Fine sand	Silt	Clay				Cations				Anions				
									Ca^{2+}	Mg^{2+}	K^+	Na^+	SO_4^{2-}	NO_3^-	HCO_3^-	Cl^-	
Site 4-1; Under cultivation of chille guerito—November, 2002																	
Ap1	0–10	3.30	40.68	25.84	30.18	LiC	8.10	5.25	0.70	0.64	0.15	2.36	0.65	0.37	0.17	2.31	11.87
Ap2	10–22	3.01	43.87	25.57	27.55	LiC	8.45	2.93	0.09	0.08	0.07	1.44	0.18	0.51	0.22	0.59	22.03
Bw	22–35	2.79	35.92	25.72	35.57	LiC	8.15	9.45	0.60	0.68	0.24	6.49	2.18	0.20	0.14	5.09	31.23
Bk	35–46/49	1.84	36.28	25.97	35.91	LiC	7.56	42.00	3.94	7.55	0.52	25.03	2.27	0.37	0.11	27.90	41.49
Bkm	46/49–60+	2.12	35.48	25.25	37.15	LiC	7.68	30.50	1.90	4.14	0.71	19.94	2.03	0.00	0.10	19.81	44.10
Site 4-2; Under cultivation of fulijol beans—November, 2002																	
Ap1	0–10	5.83	45.45	21.97	26.75	LiC	7.99	18.15	2.31	0.54	0.37	11.91	4.43	0.36	0.13	9.03	40.89
Ap2	10–20/25	5.47	46.50	22.02	26.01	LiC	8.16	3.97	0.97	0.18	0.10	1.86	1.77	0.26	0.15	0.48	10.49
Bk	20/25–39/41	2.63	41.11	22.96	33.30	LiC	8.22	11.93	1.71	0.25	0.35	10.36	10.76	0.00	0.12	1.30	39.57
BC	39/41–66/71	3.04	42.53	24.65	29.78	LiC	7.93	39.60	0.49	0.22	0.59	27.72	5.27	0.00	0.13	21.18	192.69
Bkm	66/71–75+	2.03	70.87	15.83	11.27	SCL	7.48	66.90	0.50	0.35	0.68	35.48	2.28	0.00	0.05	31.02	268.18
Site 5; Under cultivation of chille guerito—November, 2002																	
Ap1	0–5	9.86	9.09	27.40	53.65	HC	8.15	4.32	0.56	0.40	0.24	1.80	0.16	0.63	0.13	1.69	10.70
Ap2	5–17/32	10.35	9.34	27.51	52.80	HC	8.58	1.81	0.14	0.09	0.10	0.81	0.09	0.36	0.21	0.31	9.78
Bk11	17/32–35	12.93	8.62	23.56	54.89	HC	8.71	1.30	0.05	0.03	0.04	0.66	0.07	0.00	0.21	0.44	14.01
Bk12	35–55	7.05	8.98	25.97	58.00	HC	8.38	6.97	0.30	0.45	0.24	5.07	1.06	0.00	0.23	4.26	29.53
Bk2	55–60+	6.07	8.86	25.91	59.16	HC	8.25	10.50	0.44	0.80	0.28	7.95	1.04	0.00	0.20	7.29	36.23

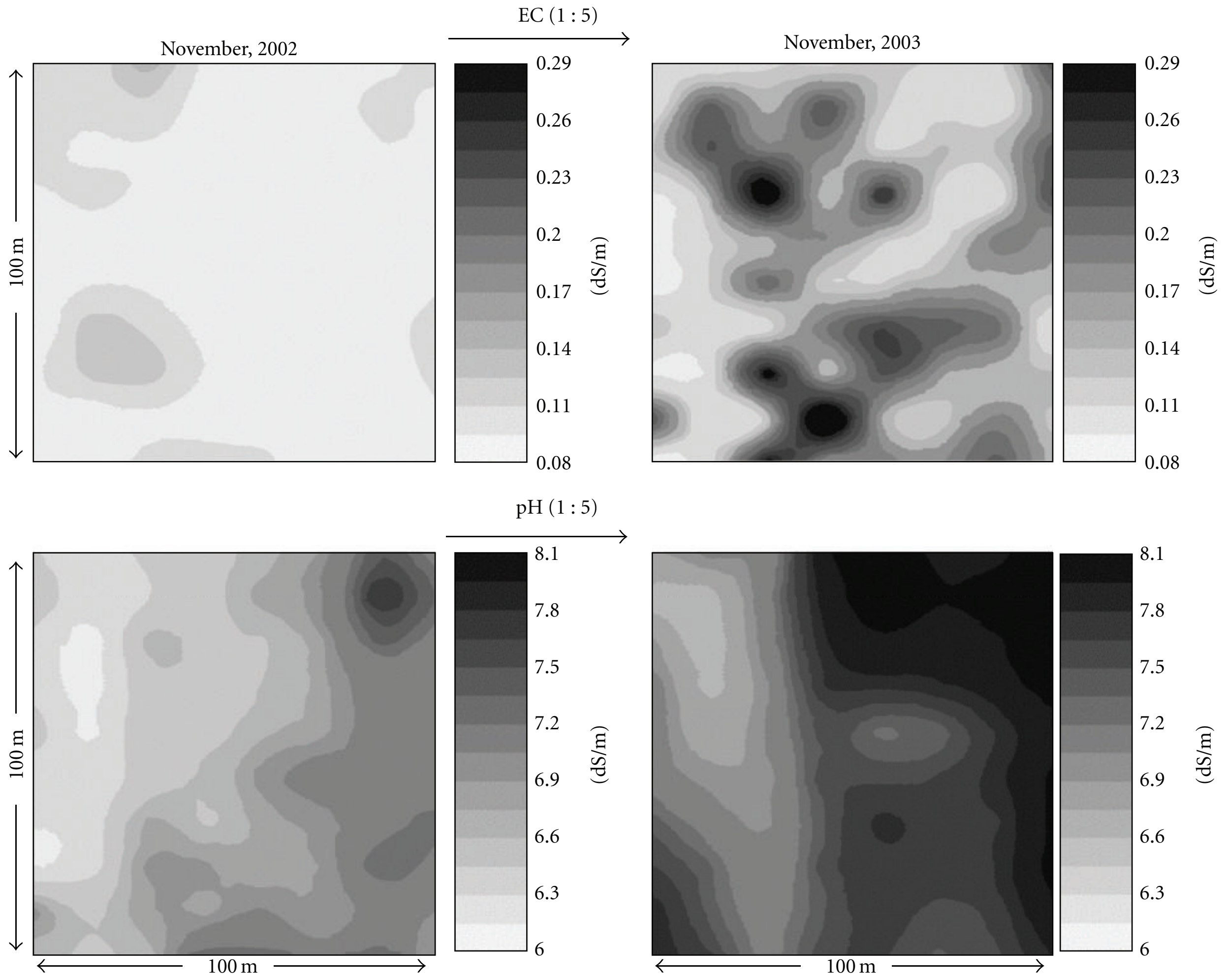

Figure 2: Change in spatial variations of the salt accumulation status ($EC_{1:5}$ and $pH_{1:5}$) in surface soil at Site 1 from 2002 to 2003.

the subsoil pHe decreased (see Table 4). Crop production was maintained in spite of a reduction in the quantity of irrigation water. This suggests that it is possible to use only one third the amount of irrigation water typically to this site.

Site 2. Plant growth in Site 2 was poor compared with that in Site 1. The soil profile of Site 2 showed neither development of soil structure nor differentiation of soil horizon. The ploughed layer was approximately 20 cm thick, and a hardpan layer was observed at a depth of 20 to 40 cm. The root growth of plants was limited by this hardpan layer. 3-4 mm irrigation water was applied every hour from the drip irrigation tube holes at this site. In other words, 9–12 mm of irrigation water was applied to the field every three days. The subsurface was moist, which indicates excessive irrigation. The susceptibility of the soil to salinization was low, because its sandy texture ensured high water permeability; furthermore, the quality of the irrigation water was comparatively high. Crop growth was poor because root zones were limited to the top surface of the soil, and plants could not absorb the fertilizer that passed through the hard subsurface pan.

Site 3. The plant growth at Site 3 was good compared with that of Sites 1 and 2. 3-4 mm irrigation water was applied every hour by drip irrigation at this site. In other words, 36–48 mm of irrigation water was applied to the field every three days. The soil at this site contained a very soft till lower layer, the result of deep ploughing. Roots were observed even in this lower layer. The soil had a sandy texture, and soil salinization was not observed despite excessive irrigation with lower quality water. Plants grew well at this site, because the root zone was wide, allowing more efficient absorbance of nutrients. However, we fear that underground water may become polluted by nitrate leaching, caused by the excessive application of fertilizer and excessive irrigation.

Site 4. At Site 4, most of the salts were accumulated not only in the surface but also in the whole soil profile due to excessive long-term irrigation. 3-4 mm irrigation water was applied every hour by drip irrigation. In other words, 9–12 mm of irrigation water was applied to the field every ten to fifteen days by drip irrigation. This field showed well-defined areas with strong plant growth and other areas with poor plant growth. Surficial precipitation of white was observed in areas where plant growth was poor. This field was not well leveled, and salinization of surface soil was observed at the concave areas. The permeability of the soil was very low, causing a large amount of salt accumulation at a depth of 30 cm below the surface. The salts added by irrigation accumulated at the uneven parts of the soil surface, and water moved gradually to the low layer of the soil profile. Evaporation then caused salts to precipitate at the surface of the soil in these lower parts, resulting in the simultaneous accumulation of salts and salinization and sodication of these lower areas. In addition, concretion of calcium carbonate was increased in the soil layers below 50 cm in the soil profile. The root zone was limited to the ploughed layer, which was one of the causes of poor plant growth. Both plant root growth and water percolation were completely prevented by soil compaction, which triggered further salinization and sodication of the soil.

Site 5. The plant growth at Site 5 was as poor as in Site 4. The soil was dry and very hard from the subsurface to the lower layers. Plant roots were only extending into the ploughed layer (0–17 to 32 cm). Between 2-3 mm of water was discharged every hour, resulting in a rate of irrigation of 10–15 mm every five to six days. Though salt did not accumulate on the surface of the soil, the pHe level was high. Root-like mottling of calcium carbonate was observed in the lower layer of the soil profile. The irrigation water increased the salt concentration and, therefore, the risk of long-term salinization of this field. However, the amount of irrigation water applied was merely a quarter of that used at Site 1. At least once per year, heavy rains caused the fields at this site to flood and remain saturated for several days. The natural flooding of this field appeared to protect the land from soil salinization. Flooding leads to the leaching of salts into lower layers and increases the soil pHe. In other words, the sodium salts were leached, and the overall salt composition was changed by irrigation and rain. Hardpan was formed in the clayey soil as a result of the low salt concentration and high pHe.

The salt dynamics of the profiles of the irrigated soils differed from site to site even in sites that were near one another. It is, therefore, best to consider efficient management methods on a site by site to maximize crop yields using a minimal input of water and fertilizer.

3.3. Analysis of Available Micronutrients in Soils. The available micronutrients in the soils of the investigated areas are shown in Table 5. Total C and total N contents, as well as soil available *P*, were low in all soil profiles. The accumulation of organic material was also low throughout all the soils of the investigated area. The fertility of these soils was very low because of the arid conditions, which slow the decomposition rate of organic matter. Total N and total C content in clay soils were slightly higher than that in sandy soils farms. The clay soil layers under 50 cm in the profile were rich in total carbon because of the significant amount of concretions of calcium carbonate. Moreover, salt accumulated soils showed a tendency to decrease the quantity of available phosphorus; This may result from the formation of insoluble phosphorus complexes.

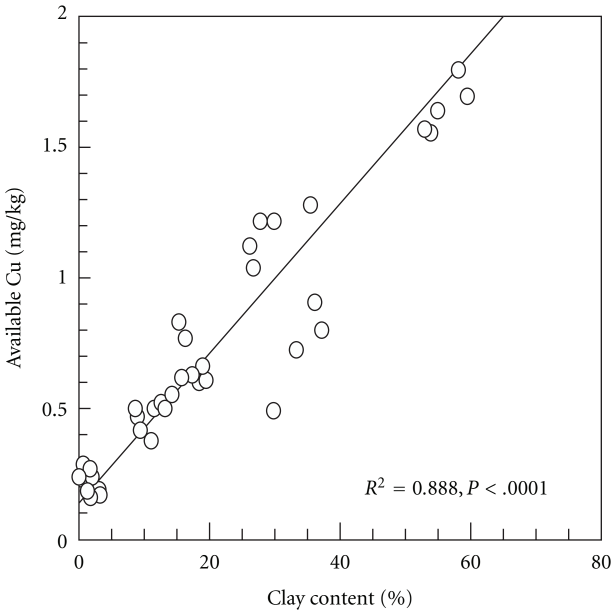

Figure 3: Relationship between clay content and available copper.

Few available micronutrients were observed in the analyzed soil profiles, with the exception of those at Site 1, which had sandy soils and low pHe. Micronutrients were available in the following order: $\mathrm{Mn_d} > \mathrm{Fe_d} > \mathrm{Cu_d} > \mathrm{Zn_d} > \mathrm{Cd_d}$ in all soil layers, except for those at Site 1, where the $\mathrm{Cu_d}$ content was low in all layers and $\mathrm{Fe_d} > \mathrm{Mn_d}$ in the lower layers of the soil profile. The $\mathrm{Cu_d}$ content was proportional to the clay content (Figure 3). In addition, soil layers with low pHe tend to have increased $\mathrm{Fe_d}$ content. It has been suggested that exchangeable Cu in clay was solubilised, and Fe was solubilised at low soil pHe (Figure 4). A high and negative correlation ($r = -0.957$) was observed between the ratio of $\mathrm{Mn_d}$/TAM (total amount of available micronutrients; $\mathrm{Mn_d} + \mathrm{Fe_d} + \mathrm{Cu_d} + \mathrm{Zn_d} + \mathrm{Cd_d}$) and the ratio of $\mathrm{Fe_d}$/TAM in the ratio of each available micronutrient for TAM (Figure 5). Furthermore, a high and negative correlation ($r = -0.969$) between $(\mathrm{Mn_d} + \mathrm{Fe_d})$/TAM and $\mathrm{Cu_d}$/TAM was observed (Figure 6).

3.4. Clay Mineral Compositions in Soils. The primary mineral and clay mineral composition of selected soil layers are shown in Table 6. K-feldspar, plagioclase, biotite, and quartz were observed as the primary mineral components in all sampled sites. Illite and quartz, a small amount of vermiculite, smectite, and kaolinite were also observed. It was suggested that the effect of weathering are reduced by the large amount of K-feldspars in the fine sand fractions, as well as the illite and the small amounts of kaolinite in the clay fraction. However, the degree of weathering at Site 1 was a little higher, because a large amount of 2 : 1 type clay minerals and kaolinite were observed at this site. It appears that the process of soil formation at Site 1 may have been somewhat

Table 5: Available micronutrients in soils under the investigated area.

Soil Horizon	Depth (cm)	T-C ($\mathrm{g\,kg^{-1}}$)	T-N ($\mathrm{g\,kg^{-1}}$)	Available P ($\mathrm{mg\,kg^{-1}}$)	Available micronutrients ($\mathrm{mg\,kg^{-1}}$)			
					Mn	Fe	Cu	Zn
Site 1-1; no cultivation (before application of diluted sulfuric acid)								
A1	0–10	1.15	0.75	0.08	2.81	2.52	0.22	0.22
A2	10–20	1.04	0.66	0.06	2.08	2.32	0.21	0.15
C11	20–30	0.92	0.33	0.08	2.54	2.88	0.19	0.12
C12	30–40	0.55	0.25	0.12	3.65	2.50	0.18	0.12
C21	40–50	0.56	0.31	0.11	3.22	2.03	0.28	0.14
C22	50–60	0.58	0.28	0.15	3.54	1.98	0.21	0.21
C31	60–80	0.56	0.27	0.13	2.95	1.84	0.18	0.18
C32	80–90	0.52	0.22	0.17	2.44	2.32	0.19	0.13
C41	90–105	0.55	0.28	0.15	2.69	2.11	0.21	0.12
C42	105–115+	0.53	0.26	0.17	2.36	1.88	0.19	0.14
Site 1-2; after cultivation of fulijol beans (after application of diluted sulfuric acid)								
Ap11	0–10	2.42	0.89	0.03	2.76	2.54	0.19	0.22
Ap12	10–18	2.62	0.87	0.04	2.37	2.29	0.17	0.20
Ap2	18–28	2.74	0.87	0.06	2.29	2.82	0.16	0.20
C11	28–37	1.73	0.77	0.11	2.73	4.07	0.16	0.19
C12	37–50/58	1.65	0.70	0.57	10.56	13.57	0.24	0.20
C21	50/58–62	1.28	0.47	0.37	10.36	16.90	0.28	0.16
C22	62–80	0.91	0.48	0.38	9.90	11.12	0.27	0.14
C23	80–105	0.81	0.29	0.27	7.20	9.25	0.24	0.13
C3	105–115+	0.58	0.37	0.12	3.11	3.06	0.18	0.10
Site 2; under cultivation of chille guerito								
Ap1	0–8	2.23	0.64	0.28	9.21	3.48	0.46	0.31
Ap2	8–16	2.49	0.50	0.31	10.03	4.05	0.50	0.28
C11	16–29	2.00	0.53	0.36	5.19	3.38	0.42	0.22
C12	29–40	1.70	0.47	0.27	7.12	2.95	0.50	0.19
C21	40–55	1.99	0.85	0.31	7.56	2.43	0.52	0.15
C22	55–65/71	1.84	0.88	0.17	8.32	1.86	0.55	0.14
C3	65/71–75+	1.81	0.81	0.38	6.84	1.80	0.50	0.14
Site 3; under cultivation of chille guerito								
Ap1	0–10	3.02	0.95	0.20	17.49	2.38	0.83	0.22
Ap2	10–22	3.12	1.22	0.17	8.37	2.11	0.77	0.17
C11	22–33	2.09	0.78	0.18	7.02	2.50	0.61	0.10
C12	33–45	1.75	0.79	0.21	7.20	3.19	0.61	0.10
C21	45–55	1.70	0.84	0.18	7.77	3.73	0.66	0.09
C22	55–65	1.50	0.95	0.19	8.42	3.65	0.63	0.07
C3	65–75+	1.45	0.75	0.16	8.46	3.17	0.62	0.09
Site 4-1; under cultivation of chille guerito								
Ap1	0–10	6.60	1.34	0.64	11.78	2.14	1.22	0.30
Ap2	10–22	7.10	1.55	1.06	13.08	2.31	1.22	0.32
Bw	22–35	6.52	1.27	1.20	7.50	2.76	1.28	0.19
Bk	35–46/49	11.32	0.88	0.94	5.92	1.76	0.91	0.17
Bkm	46/49–60+	15.21	0.97	0.55	4.61	1.85	0.80	0.16
Site 4-2; under cultivation of fulijol beans								
Ap1	0–10	11.84	1.17	1.58	6.38	2.13	1.04	0.27
Ap2	10–20/25	11.03	1.23	1.54	6.95	2.81	1.12	0.18
Bk	20/25–39/41	15.96	0.72	0.68	2.23	1.71	0.72	0.11

Table 5: Continued.

Soil Horizon	Depth (cm)	T-C ($g\,kg^{-1}$)	T-N ($g\,kg^{-1}$)	Available P ($mg\,kg^{-1}$)	Available micronutrients ($mg\,kg^{-1}$)			
					Mn	Fe	Cu	Zn
BC	39/41–66/71	11.04	1.06	0.57	3.26	0.99	0.49	0.12
Bkm	66/71–75+	9.87	0.79	0.85	3.20	0.56	0.38	0.09
Site 5; under cultivation of chille guerito								
Ap1	0–5	15.19	1.85	2.56	7.11	3.58	1.56	0.18
Ap2	5–17/32	17.46	2.84	2.36	5.66	3.55	1.57	0.22
Bk11	17/32–35	12.30	1.51	1.09	8.58	3.84	1.64	0.19
Bk12	35–55	11.91	1.12	1.01	10.88	3.67	1.79	0.15
Bk2	55–60+	11.64	1.19	1.28	10.35	3.29	1.70	0.15

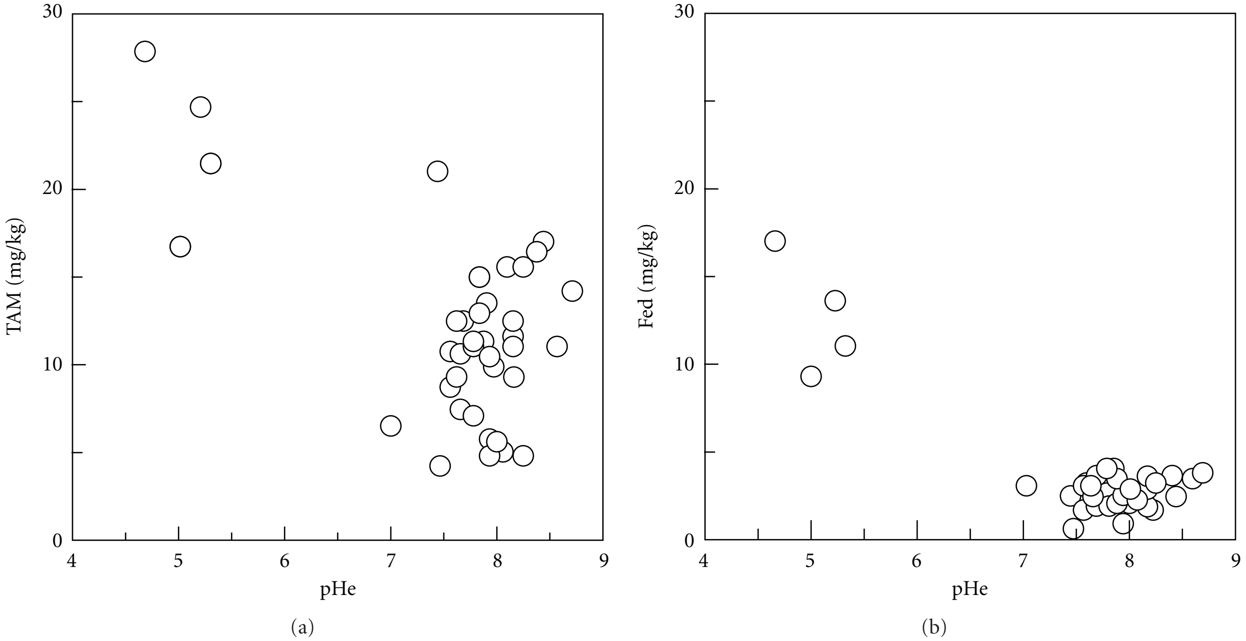

Figure 4: Relationship between pHe and available micronutrients. (a) Relationship between pHe and TAM (%). (b) Relationship between pHe and Fed (%).

different that at the other sites. That is, changes from biotite to kaolinite and from biotite to vermiculite and/or smectite in the clay mineral composition at Site 1 occurred at the first stage of weathering. The diversity of the primary mineral composition ratio is thought to have been caused by heavy rain and flooding that occurs several times each year.

3.5. Soil Management Based on Soil Properties. Soil salinization and sodication are complexly interrelated with many factors such as soil characteristics, amount and composition of salts in the soil, the quantity and quality of irrigation water, and the method of irrigation used. Preventive measures must, therefore, be established against soil degradation, including matching the prevalent soils with suitable crops. A reduction in the application of irrigation water and fertilizer is necessary to prevent soil salinization. Sustainable long-term crop production requires appropriate soil and water management strategies that are specific to the prevalent field conditions. It is important to prevent both the depletion of available water resources and the degradation of soils by salinization. A reduction in the leaching of fertilizer will also minimize underground water pollution. A reduction of water usage can improve crop growth and prevent the salinization and/or sodication of the soil. Moreover, there is a need to take into account the present state of water resources and irrigation efficiency.

4. Conclusion

The salt and water dynamics observed in the soil profiles of irrigated farmlands in southern Baja California are greatly influenced by the prevalent soil characteristics. It is important to understand the distribution and the current state of soil resources and to take soil and water conservation

Table 6: Mineralogical composition of soil.

	Qtz	Bi	Kfs	Pl	Cal	Kln	Ill	Sm	Vt
Site 1									
Surface soil	+	+	++++	++++	tr	+	++	+	+
Subsoil	+++	tr	++	++	tr	+	++	+	+
Site 2									
Surface soil	+++	+	++	++	tr	tr	++	tr	tr
Subsoil	+++	+	+	+	tr	tr	++	tr	tr
Site 3									
Surface soil	+++	+	++	++	tr	tr	++	tr	tr
Subsoil	+++	+	+	+	tr	tr	++	tr	tr
Site 4									
Surface soil	+++	+	+++	+++	tr	tr	++	tr	tr
Subsoil	+++	+	++++	++++	tr	tr	++	tr	tr
Site 5									
Surface soil	++++	+	+	+	tr	tr	++	tr	tr
Subsoil	++++	+	+	+	tr	tr	+++	tr	tr

Qtz: quartz; Bi: biotite; Kfs: K-feldspar; Pl: plagioclase; Cal: calcite; Kln: kaolinite; Ill: illite; Sm: smectite; Vt: vermiculite; tr: trace mineral phase.

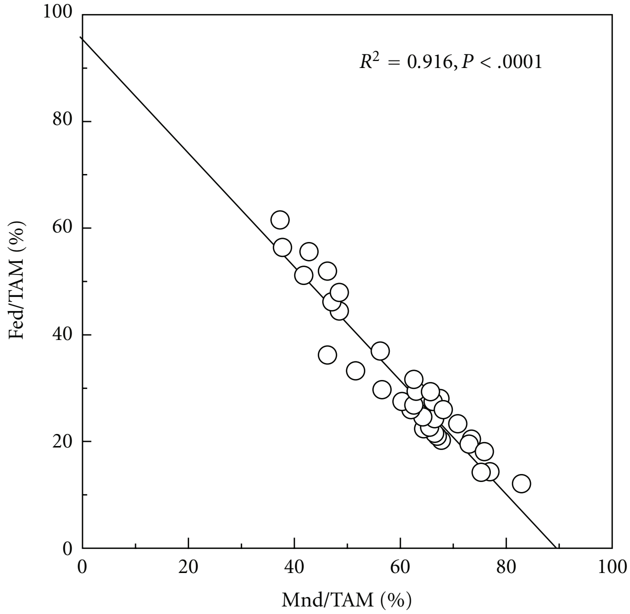

Figure 5: Relationship between Mnd/TAM (%) and Fed/TAM (%). (TAM = total amount of available micronutrients; $Mn_d + Fe_d + Cu_d + Zn_d + Cd_d$).

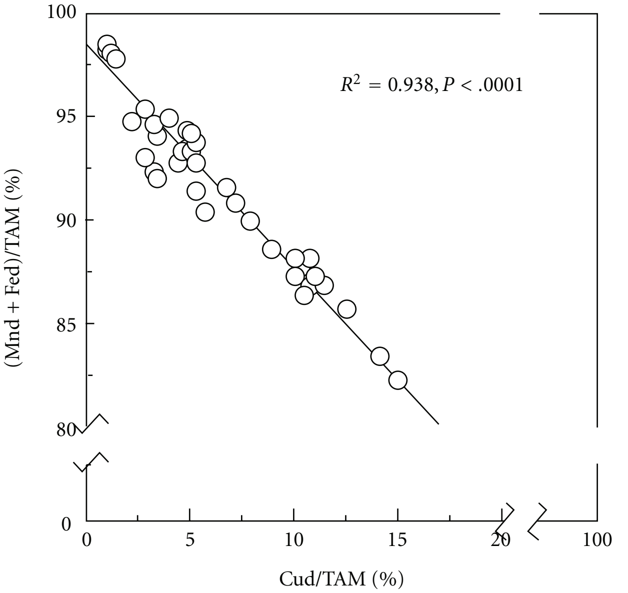

Figure 6: Relationship between Cud/TAM (%) and (Mnd + Fed)/TAM (%). (TAM = total amount of available micronutrients; $Mn_d + Fe_d + Cu_d + Zn_d + Cd_d$).

into consideration when developing sustainable agriculture strategies. This study detailed some of the soil properties of the area, which may provide insight into methods of irrigation management and the specific research needs of different arid soils.

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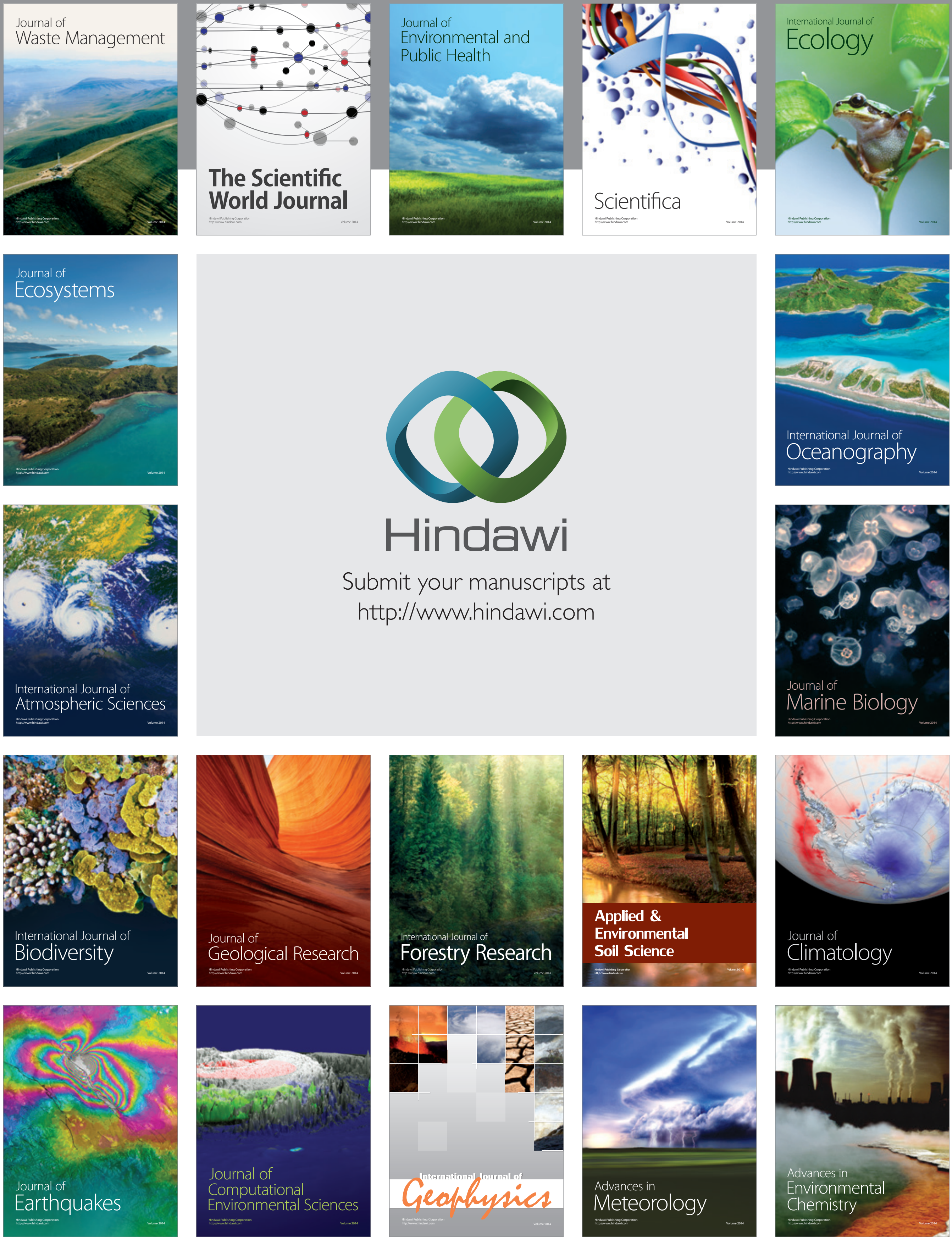
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