Wetlands (2014) 34:1229–1239
DOI 10.1007/s13157-014-0585-3

ORIGINAL RESEARCH

Evaluating Abiotic Influences on Soil Salinity of Inland Managed Wetlands and Agricultural Croplands in a Semi-Arid Environment

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Received: 6 June 2014 / Accepted: 25 September 2014 / Published online: 7 November 2014

Abstract Agriculture and moist-soil management are important management techniques used on wildlife refuges to provide adequate energy for migrant waterbirds. In semi-arid systems, the accumulation of soluble salts throughout the soil profile can limit total production of wetland plants and agronomic crops and thus jeopardize meeting waterbird energy needs. This study evaluates the effect of distinct hydrologic regimes associated with moist-soil management and agricultural production on salt accumulation in a semi-arid floodplain. We hypothesized that the frequency of flooding and quantity of floodwater in a moist-soil management hydroperiod results in a less saline soil profile compared to profiles under traditional agricultural management. Findings showed that agricultural croplands differed (p-value<0.001, df=9) in quantities of total soluble salts (TSS) compared to moist-soil impoundments and contained greater concentrations (TSS range = 1,160–1,750 (mg kg-1)) at depth greater than 55 cm below the surface of the profile, while moist-soil impoundments contained lower concentrations (TSS range = 307–531 (mg kg-1)) at the same depths. Increased salts in agricultural may be attributed to the lack of leaching afforded by smaller summer irrigations while larger periodic flooding events in winter and summer flood irrigations in moist-soil impoundments may serve as leaching events.

Keywords Semi-arid wetlands · Soil salinity · Moist-soil management · Typic torrifluvent · EC · SAR

Introduction

Alluvial wetlands of semi-arid environments provide important resources for migratory waterbirds worldwide (Kingsford et al. 1999; Taylor and Smith 2005). However, hydrologic modifications to these ecosystems, such as constructed levees for floodplain control and increased water consumption for agriculture, have resulted in altered hydroperiods of adjacent wetlands (Jolly et al. 2008). As a result, maintaining food resources for migratory waterbirds requires intensive management. Wildlife management in these ecosystems commonly use controlled flooding to support moist-soil management and traditional irrigations in agriculture croplands (herein referred to as *croplands*) to produce food resources for migratory birds (Kang et al. 2000; Taylor and Smith 2003, 2005). Moist-soil management is the creation of exposed, saturated soils in wetland impoundments by irrigation or drawdown during the growing season to promote germination, growth, and seed production of high energy wetland plants that is of high-value to waterbirds (Haukos and Smith 1993). However, in some systems, modifying the hydrology through repeated flooding and duration can result in increased concentrations of soluble salts within the soil (Crawford et al. 1993; Morway and Gates 2012), which can have adverse effects on plant productivity by decreasing the osmotic water potential in the soil to a point that water is inhibited from being absorbed by plant roots (Hoffman 1986).

The abiotic processes that drive soil salinity are complex. Increased soil salinity can result through multiple processes

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including: evapotranspiration that exceeds precipitation (Domingo et al. 2001); a hydrologic regime that is incapable of leaching salts through the soil (Ayers and Westcot 1985); capillary wicking of a shallow, saline groundwater table (Northey et al. 2006); or application of irrigation water that has high levels of soluble salt concentrations (Costa et al. 1991). As a result, abiotic changes within salinized soils may indirectly jeopardize waterbird food resources. The success of both moist-soil management and agricultural production in semi-arid regions is partially dependent on the control of soil salinity and sodicity in the rooting zone.

Moist-soil management and agricultural production practices have unique hydrologic regimes that differ in quantity, quality, timing, and duration of applied water that likely influence soil salt concentrations. Common agricultural practices, such as those used in field corn (*Zea mays*) production, irrigate to meet the transpirational needs of the crop, but do not inundate (i.e., pond surface water) the field. In contrast, moist-soil management practices use repeated flooding events during the growing season that inundate impoundments for several hours to 3 days or more. Moist-soil managed impoundments also receive extended periods of inundation (i.e., up to 3 months) during the dormant season (i.e., winter) (Fredrickon and Taylor 1982; Taylor and Smith 2005), which is in contrast to a dry, fallow period for croplands. Because mean evapotranspiration rates diminish during the winter, solute concentrations are diluted and result in lower electrical conductivity of applied river water. Thus, impoundments are flooded for long periods with water possessing low solute concentrations. Therefore soil salinity under moist-soil managed impoundments and irrigated croplands have the potential to be different in their capacities to accumulate or remove salts and influence vegetative production.

Much of the work regarding the remediation and regulation of saline soils has been in the context of agriculture and little information is available on soil salinity under moist-soil management practices in semi-arid environments. As water availability becomes more limiting for these systems, a conceptual model that depicts the dynamics of soil salinity associated with wetland management practices can assist in developing future management practices for these water-dependent ecosystems. As such, the objective of this study is to evaluate the effect of moist-soil management on soil salinity and sodicity compared with common cropland irrigation practices by monitoring soil salinity in the upper portion of the soil in moist-soil impoundments and croplands after applications of flooding and irrigation treatments. We hypothesize that the flooding frequency, water quantity, and hydroperiod used on moist-soil managed impoundments will result in less soil salinity compared with soils under common irrigation agricultural practices.

Study Site and Methods

This study was conducted at Bosque del Apache National Wildlife Refuge (refuge) (33° 48′, 106° 53′), which is south of San Antonio, New Mexico in Socorro County. The refuge lies within the Middle Rio Grande Basin (MRGB) along the Rio Grande River and is a primary wintering location for sandhill cranes (*Grus canadensis*), snow geese (*Chen caerulescens*), and waterfowl within the central flyway (Crawford et al. 1993). As is the case throughout much of the MRGB, the active floodplain of the Rio Grande River within the boundaries of the refuge is restricted by earthen levees. However the refuge manages approximately 3,862 ha of the inactive floodplain (i.e., floodplain area protected by levees) by diverting water to create seasonal wetlands that are under moist-soil management practices, to irrigate fields for agricultural crop production, and to stimulate the growth of riparian forests. The vast majority of water used in these practices is diverted surface flow from the Rio Grande River; however groundwater can be pumped as a supplemental water source. In our study, only diverted surface flow from the Rio Grande River was used.

The BdANWR is characterized by high evapotranspiration (Class A evaporation pan 250 cm per year) (WRCC 2013) and low precipitation (Johnson 1988). Collective annual rainfall is approximately 25 cm (WRCC 2013). Much of this rainfall occurs during the monsoon season from the months of July to October when convective winds bring moisture up from the Gulf of Mexico.

Soils within the Rio Grande basin are derived from alluvial and clastic sediments (Crawford et al. 1993). For this research, moist-soil impoundments and cropland study sites were restricted to a single soil series to help limit variability in soil properties and chemistry (e.g., hydraulic conductivity, salinity). The soil evaluated in this study was the Gila loam, classified as a Coarse-loamy, mixed, superactive, calcareous, thermic Typic Torrifluvents (Soil Survey Staff 2014) and is located within the Southern Desertic Basin, Plains, and Mountains Major Land Resource Area 42 (USDA NRCS 2006). The Gila soil series is common throughout the Rio Grande alluvial valley and represents soil types that have moderate hydraulic conductivity and drainage. The saturated hydraulic conductivity (Ksat) of the Gila soil series is estimated at 6.88 μm/s (Soil Survey Staff 2014).

Three fields under moist-soil management (*moist-soil impoundments*) and three fields under continuous agricultural production mapped as the Gila soil series (Johnson 1988) were selected for intensive study from May to August 2012.

Selected moist-soil impoundments have been under common wetland management practices for at least 20 years, receiving rotational disking approximately every 4 years. Selected croplands have been under agricultural production since 1993 and rotate between alfalfa (*Medicago sativa*) and field corn, subjected to disking during production phases of each crop. Both moist-soil-impoundments and croplands received river water from a central interior diversion canal that runs parallel to the Rio Grande through the managed portion of the refuge.

Four sites were randomly selected within each impoundment and cropland. To determine initial soil salinities entering the growing season, and after the period of winter inundation in moist-soil impoundments, a hydraulic soil probe (Giddings Machine, Inc.) was used to extract one meter deep soil cores from each site on 10 May, 2012. Cores were placed in PVC pipe for protection and wrapped with plastic wrap.

Starting at the soil surface, each soil core was segmented into 10-cm portions, dried, and ground to pass through a 2-mm sieve. Samples of the soil were sent to the Louisiana State University AgCenter Soil and Plant Laboratory for analysis. Samples of soil were prepared in a 1:2 soil to water ratio, shaken for 1 hour and then filtered through a #42 Whatman filter paper screen (Rhoades 1996). The dynamic nature of soil salinity is caused by the effects and interactions of varying edaphic factors such as soil permeability, water table depth, and geohydrology (Rhoades et al. 1999). We choose this method of soil preparation as it is serves as a standardized approach to hold influencing factors constant while making an assessment of soil salinity. Extracts were then analyzed for pH and water soluble Ca, Cl, Mg, and Na using inductively coupled plasma (ICP) spectroscopy. The sodium adsorption ratio was determined from concentrations of assayed soils (U.S Salinity Laboratory Staff 1954). Extracts also were used to measure soil electrical conductivity (EC_s) and TSS with a temperature-compensating conductivity electrode (Horiba D-54) standardized to 25 °C. Subsequently, 1:2 electrical conductivities were converted to saturated paste electrical conductivity equivalents using the regression equations of Hogg and Henry (1984) and particle size analysis determined by hydrometer via method per Gee and Bauder (1986).

Data collected from a United States Geological Survey stream gauge (USGS 08355490) was used to monitor changes in electrical conductivity of the Rio Grande River (EC_r). The stream gauge was located approximately 13 km north (upstream) of the refuge in San Antonio, New Mexico. Weekly measurements of EC_r of the water used to flood and irrigate the moist-soil impoundments and croplands were taken from 10 May 2012 to 1 August 2012 using a portable temperature-compensating electrode (YSI 85) standardized to 25 °C.

Six moist-soil impoundments and six croplands were selected for the installation of groundwater monitoring wells alongside their perimeter edges. A total of 16 monitoring wells (32 total; U.S. Army Corps of Engineers 2005) were installed to a depth of 250 cm alongside both moist-soil impoundments and croplands. Monitoring wells were constructed of 4-cm diameter Schedule 40 polyvinyl chloride (PVC) pipe following U.S. Army Corps of Engineers (2005). The total pipe length was 300-cm constructed of a 150-cm piece of solid PVC connected to 150 cm of 0.025-cm slotted PVC well screen with a drainable end-cap.

Measurements of water-levels in the monitoring wells began in May 2012 and were taken manually with an in-situ electric dip tape (Solinst 101 P7) in the morning, three times a week until 1 August 2012. Electrical conductivity of the groundwater was measured using a portable temperature-compensating electrode (YSI 85) standardized to 25 °C. The dates of water application were recorded for each moist-soil impoundment or agricultural cropland; however, some dates relating to the time of applied water in croplands were unavailable.

SAS 9.3 software (SAS Institute, Inc., Cary, NC) was used for all statistical analyses (SAS Institute, Inc. 2011). Differences in measured variables of each 10-cm portion of sampled soil were evaluated using a nested analysis of variance to evaluate changes in soluble salts with depth and by depth within treatments using Proc Mixed. Sampled soils were nested by treatment within depth and core and field were blocking variables.

Previous studies have indicated strong relationships between clay content and EC_s due to the negatively charged clay particulates that attract positively charged ions. Therefore the percentage of clay in the soil at each depth was assigned as a random effect in the model. Depth to groundwater and groundwater electrical conductivity (EC_g) were evaluated for differences between moist-soil impoundments and croplands. The amount of variability in each treatment was determined by calculating the total range (Δ) in values throughout the measured period, where:

$$\Delta = \text{Maximum value–Minimum value}$$

Calculated Δs were then analyzed in an analysis of variance model where treatment was assigned as a fixed effect. Mean depth to groundwater and EC_g for the measured periods were calculated for groundwater wells in each treatment. Means were analyzed in an analysis of variance model where treatment was assigned as a fixed effect. A significance level of 0.05 was used for all statistical tests.

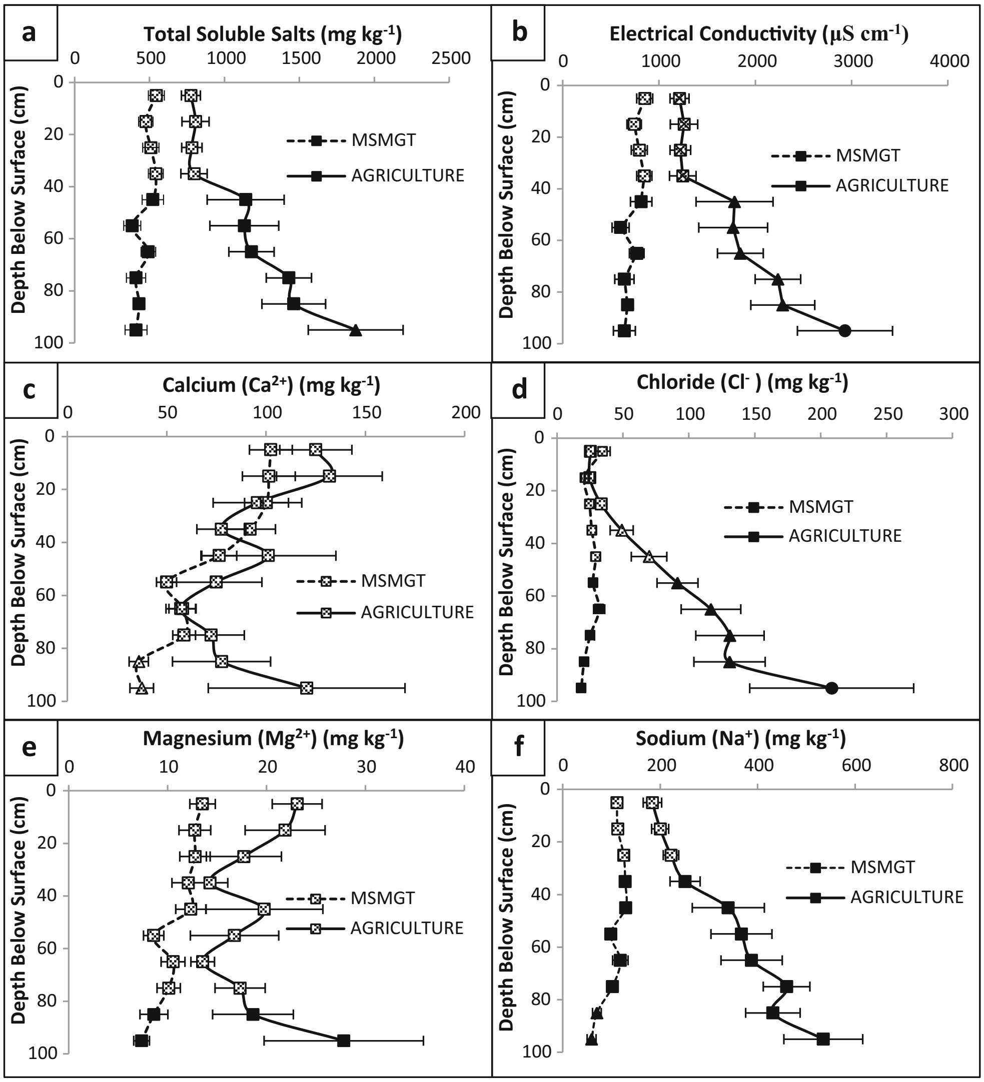

Fig. 1 Mean values and standard error for total soluble salts (**a**), electrical conductivity (**b**), calcium (**c**), chloride (**d**), magnesium (**e**), and sodium (**f**) concentrations in sampled soil profiles from 0 to 100 cm taken at Bosque del Apache National Wildlife Refuge (33° 48′, 106° 53′), 10 May 2012 in the Gila soil series (Typic Torrifluvent). Soil profiles were divided into 10 cm segments and point markers (n= 12) represent the midpoint of each section. Point markers that share the same shape within treatments represent similar groups ($p\leq$ 0.05). Depths with checkered point markers represent no difference in values between treatments. Depths with solid fill point markers represent differences in values between treatments

Results

Soil Cores

Within croplands, the range of mean values in total soluble salts (Fig. 1a) and electrical conductivity (Fig. 1b) in cores of croplands ranged from 776 to 1,875 mg kg^{-1} and 1,210 to 2,931 µS cm^{-1}, respectively. Although mean values of total soluble salts and EC$_s$ increased with depth, only the 95 cm depth differed statistically and was greater than the remaining profile. Within moist-soil impoundments, the range of mean values in total soluble salts and EC$_s$ ranged from 385 to 545 mg kg^{-1} and 600 to 853 µS cm^{-1}, respectively. No differences in mean values were detected by depth. Between moist-soil management and agricultural treatments, a treatment and depth interaction was revealed for EC$_s$ and total soluble salts (Table 1). Croplands had greater concentrations of total soluble salts and EC$_s$ than did moist-soil impoundments in the 45 to 95 cm portion of the profile.

Within croplands, Cl (Fig. 1d), Na (Fig. 1e), sodium adsorption ratio (Fig. 2a), and pH (Fig. 2b) differed by depth, whereas within moist-soil impoundments, only pH, Ca (Fig. 1c), and Na differed by depth. Among treatments, a treatment and depth interaction was observed for Cl, Mg (Fig. 1e), Na, and the sodium adsorption ratio.

Water Quality of Applied Irrigation Water

Electrical conductivity of river (EC$_r$) water varied from 420 to 1,080 µS cm^{-1} in 2011 (Fig. 3a), and 335 to 2,950 µS cm^{-1} in 2012 (Fig. 3b). In both 2011 and 2012, EC$_r$ was highest during the summer months and lowest during the winter (Fig. 3a and b). The 7 year daily discharge mean (Fig. 3c) depicts a peak in discharge in spring and a period of low discharge throughout the summer with return flows during the winter.

Within the refuge, EC$_r$ of water taken from an interior irrigation canal during the growing season had a mean value

Table 1 Estimate of fixed effects from Nested Analysis of Variance of measured variables in moist-soil impoundments and croplands from Bosque del Apache National Wildlife Refuge (33° 48′, 106° 53′), 10 May 2012, in the Gila soil series (Typic Torrifluvent)

Estimate of fixed effects					
Variable	Effect	Numerator DF	Denominator DF	*F* Value	Pr>F
Total soluble salts	Treatment	1	196	200.53	<0.0001*
	Depth	9	196	1.16	0.325
	Interaction	9	196	4.87	<0.0001*
Soil Electrical Conductivity (EC_s)	Treatment	1	196	200.3	<0.0001*
	Depth	9	196	1.16	0.3226
	Interaction	9	196	4.87	<0.0001*
Calcium	Treatment	1	196	2.86	0.0922
	Depth	9	196	6.21	<0.0001*
	Interaction	9	196	1.3	0.2388
Chlorine	Treatment	1	195	126.51	<0.0001*
	Depth	9	195	6.46	<0.0001*
	Interaction	9	195	8.39	<0.0001*
Magnesium	Treatment	1	196	60.15	<0.0001*
	Depth	9	196	2.08	0.0329*
	Interaction	9	196	1.79	0.0721
Sodium	Treatment	1	196	407.84	<0.0001*
	Depth	9	196	1.96	0.0461*
	Interaction	9	196	10.92	<0.0001*
Sodium adsorption ratio	Treatment	1	196	386.95	<0.0001*
	Depth	9	196	8.03	<0.0001*
	Interaction	9	196	8.68	<0.0001*
pH	Treatment	1	196	0.8	0.3713
	Depth	9	196	8.39	<0.0001*
	Interaction	9	196	0.59	0.8012

(*) represents differences in means at the alpha ≤0.05 level

of 896 µS cm^{-1}±36 µS cm^{-1} and ranged from 813 to 1,210 µS cm^{-1} from 1 May 2012 to 1 August 2012. In late May, 2012, the refuge was faced with a temporary shortage in water supply causing water levels in the irrigation canal to become very low. A spike in EC_r during this time period is likely a result of concentrated salts in the remaining water. Normal water levels returned within a week and EC_r values returned closer to the mean.

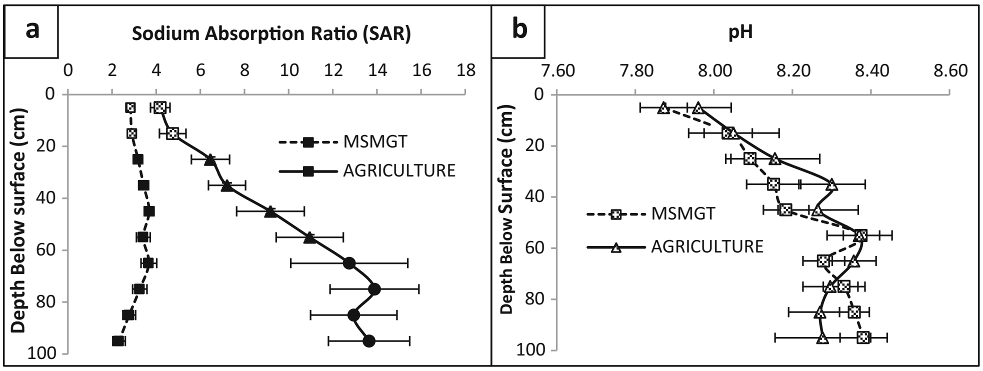

Fig. 2 Mean values and standard error for sodium adsorption ratio (**a**), and pH (**b**)concentrations in sampled profiles from 0 to 100 cm taken at Bosque del Apache National Wildlife Refuge (33° 48′, 106° 53′), 10 May 2012 in the Gila soil series (Typic Torrifluvent). Soil profiles were divided into 10 cm segments and point markers (n=12) represent the midpoint of each section. Point markers that share the same shape within treatments represent similar groups (p≤0.05). Depths with checkered point markers represent no difference in values between treatments. Depths with solid fill point markers represent differences in values between treatments

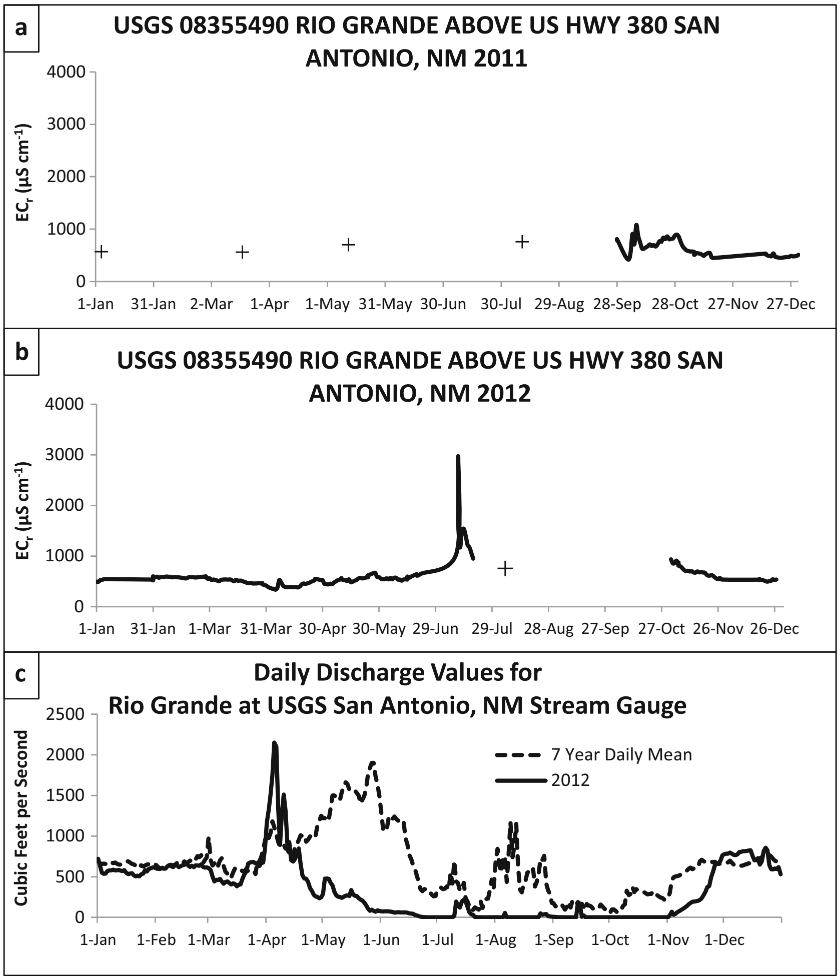

Fig. 3 River electrical conductivity (EC_r), 2011 (**a**), 2012 (**b**) and daily discharge (**c**) data collected from the USGS monitoring station (08355490) (33° 55′, 106° 51′) on the Rio Grande River located approximately 13 km north of the Bosque del Apache NWR. + point markers represent an individual observation recorded during a period when data was otherwise not collected by the data logger. The extreme peak in mid-July is likely a result of the drying out of the river. This peak and subsequent period of uncollected data in August, September, and October corresponds with the no to little observed discharge during those months in Fig. 3c

Effect of Hydroperiod on Depth to Groundwater and Groundwater Electrical Conductivity

Flash-flood irrigation events in moist-soil impoundments during the summer growing season resulted in a temporary decrease [mean (standard error) = 60 (4) cm] in depth to groundwater. Initial irrigations caused a temporary increase in EC_g [mean (S.E) = 300 (23) $\mu S\ cm^{-1}$], but subsequent irrigations tended to cause a temporary dilution of solutes in groundwater (Fig. 4).

No data are available on dates of irrigation in croplands although irrigations are known to have occurred during the monitoring period. Irrigation in croplands tended to have a less pronounced effect on depth to groundwater and EC_g based on the low variability in groundwater depths throughout the growing season (Fig. 5).

Moist-soil impoundments and croplands differed in mean depth to groundwater and overall variability of depth to groundwater during the course of the growing season (Table 2). Depth to groundwater was deeper (≈152 cm) in croplands compared to moist-soil impoundments (≈111 cm) and tended to deepen over the course of the growing season. Differences also existed in variability of EC_g among treatments (Fig. 6). Mean values in depth to groundwater and EC_g in croplands were greater than in moist-soil impoundments (Fig. 6).

Discussion

The results of this study indicate that depth to groundwater is influenced differently under treatments of moist-soil management and cropland irrigations and can be an indication of evidence of connectivity between applied surface water and groundwater that moves salts. In this study, depth to groundwater in moist-soil impoundments was less than that of croplands. Furthermore, variability in depth to groundwater was greater in moist-soil impoundments than croplands. The timing of increases suggests that flooding events associated with moist-soil management are responsible for shallower groundwater depths in these sites. Irrigation events associated with agriculture appear to have little effect on groundwater

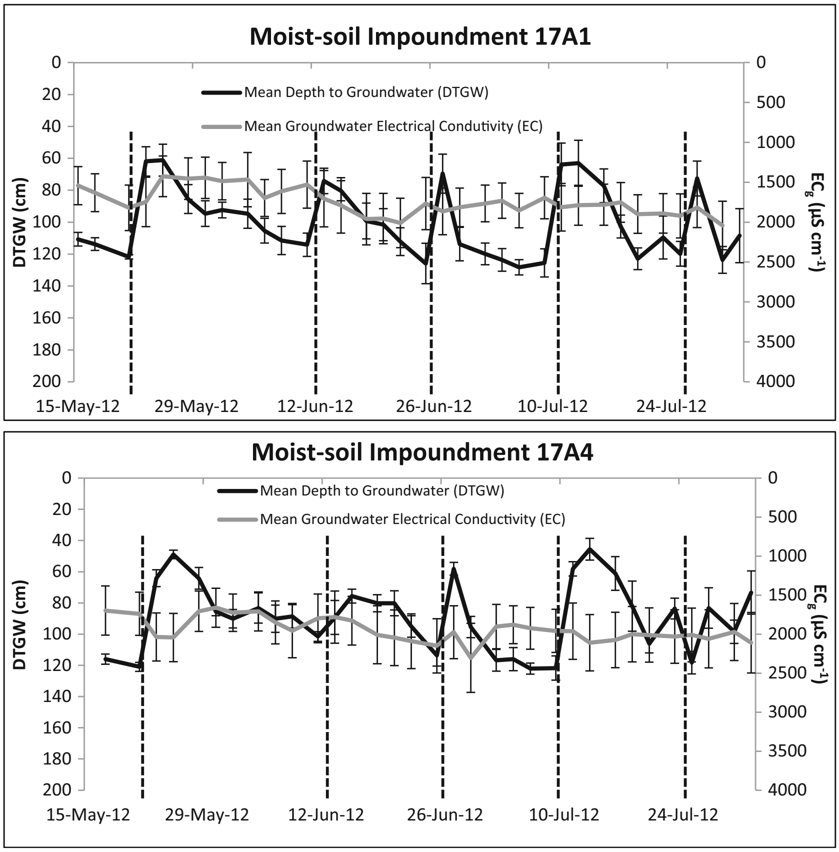

Fig. 4 Changes in depth to groundwater and groundwater electrical conductivity (EC_g) in two randomly selected moist-soil impoundments during the growing season at Bosque del Apache National Wildlife Refuge (33° 48′, 106° 53′), 2012, in the Gila soil series (Typic Torrifluvent). Dashed vertical lines represent recorded flash flood irrigations. Corresponding lines represent the mean (*n*=4) and standard error depth to groundwater and groundwater electrical conductivity in response to irrigation events of individual groundwater monitoring wells located on the northeast (*NE*), northwest (*NW*), southeast (*SE*), and southwest (*SW*) corners of the moist-soil impoundment. Complete data set can be found in Fowler (2013)

levels in croplands resulting in deeper, more stable groundwater levels throughout the growing season.

Differences in overall soil salinities and variability in depth to groundwater between treatments are likely related to differences in the volume and quality of water applied in irrigation, as well as the season of application. Moist-soil impoundments had lower overall soil salinities than croplands. In moist-soil management, summer irrigation events caused a rise in the groundwater level accompanied either by a temporary increase in EC_g in initial flooding events followed by a temporary decrease in EC_g from subsequent flooding events. This suggests that summer moist-soil management flooding is capable of serving as a leaching mechanism that can flush salts from the upper portion of a soil, with moderate hydraulic conductivity, and perhaps enhance/restore wetland vegetation productivity. In this study, the EC_r of applied water [mean (S.E) = 896 (36) µS cm^{-1}] was lower than mean EC_g (range: 1,542–2,993 µS cm^{-1}). Therefore, it is likely that initial increases in EC_g are a result of salts flushed out of the soil profile and into the groundwater. However, subsequent irrigations tended to temporarily dilute EC_g as few soluble salts remain in the soil profile to be leached.

The seasonality and duration of flooding in hydrologic regimes likely affected differences of soluble salt concentrations between treatments. Water used to flood moist-soil impoundments and irrigate croplands varied in solute concentration throughout the year. Peaks in solute concentration occurred during the summer months when evapotranspiration and water demand were high and were lowest during winter months characterized by reduced evapotranspiration. Moist-soil impoundments additionally received a period of prolonged flooding during the winter with water containing a lower concentration of solutes (Fig. 3b). Previous studies have shown that ponding of water can be an effective tool to remove salts (Oster et al. 1984). The low mean values in soluble salts analyzed from soil cores in moist-soil impoundments are likely a reflection of the effects of prolonged winter flooding. Salt concentrations measured prior to initial summer flood-up in moist-soil impoundments showed no differences in concentration by depth throughout the entire profile. Additionally, concentrations were low enough to be considered non-saline (Chhabra 1996) and would be expected to have no biological impact on common wetland plants found in moist-soil management production.

In contrast, soils under agricultural production received irrigations only during those months when crops were cultivated (April-September). Hydrographs in croplands revealed less variability and both mean depth to groundwater and EC_g was larger in croplands (Fig. 6). Because of growing season water limitations, agricultural managers try to minimize the amount of water that moves through the root zone and is reflected in common calculated leaching requirements

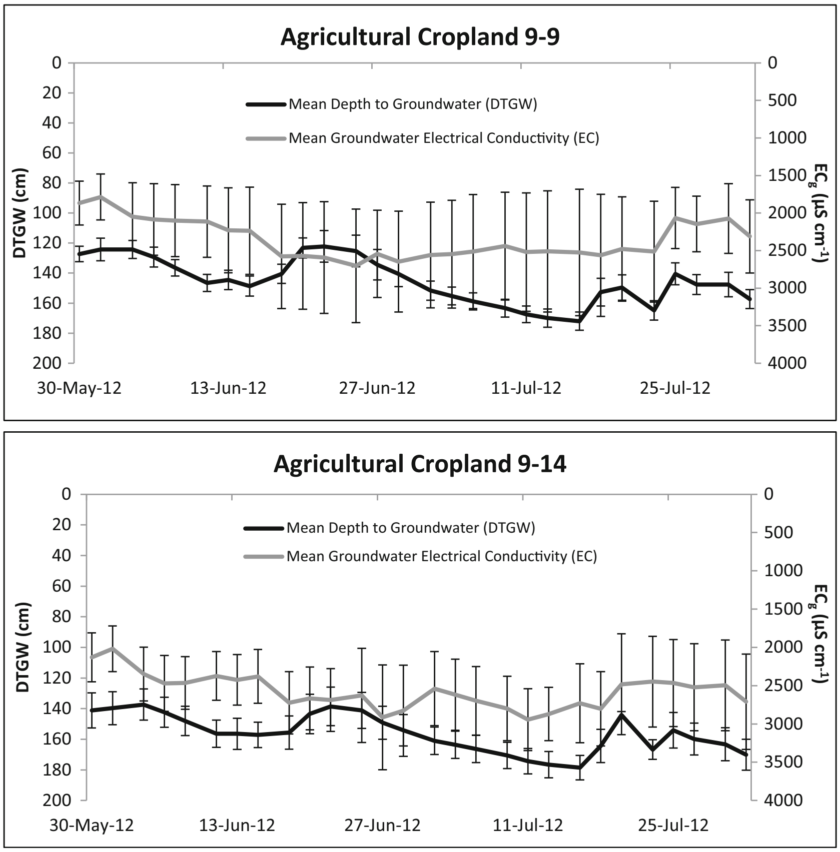

Fig. 5 Changes in depth to groundwater and groundwater electrical conductivity (EC_g) in two randomly selected croplands during the growing season at Bosque del Apache National Wildlife Refuge (33° 48′, 106° 53′), 2012, in the Gila soil series (Typic Torrifluvent). No data was available on dates of irrigations, although irrigations were known to occur. Corresponding lines represent the mean (n=4) and standard error depth to groundwater and groundwater electrical conductivity in response to irrigation events of individual groundwater monitoring wells located on the northeast (*NE*), northwest (*NW*), southeast (*SE*), and southwest (*SW*) corners of croplands. Complete data set can be found in Fowler (2013)

(Corwin et al. 2007). The limited leaching fractions, and the high solute concentrations of applied water, result in increasing concentrations of salt with depth in croplands. As a result, a considerable portion of the applied water in agricultural irrigations may be lost to evapotranspiration and serves to deposit additional solutes within the soil.

Although solute deposition likely occurred in the croplands, soil salinity concentrations, at least at the time measured, presented no limitations for the successful production of field corn. Salinity concentrations in the root zone (0–35 cm) prior to planting and pre-irrigation were below the threshold tolerance of 1,700 µS cm^{-1} for field corn (Maas et al. 1983). Low levels in the root zone could be explained by three potential possibilities. First, water solute concentrations used for irrigation at the refuge is relatively low compared to other studies (Amer 2010; Yazar et al. 2003) that experience loss of biomass production in field corn as a result of soil salinity. In a similar semi-arid floodplain used for agricultural production, Morway and Gates (2012) found that mean sampled soil profiles had soil electrical conductivities of 4,100 µS cm^{-1} and 6,200 µS cm^{-1} when irrigated with water at 1,300 µS cm^{-1} and 3,000 µS cm^{-1}, respectively. In our study, mean EC_r of applied water was 890 µS cm^{-1} (±36 µS cm^{-1}). A second possibility that explains low salinities in our study was the amount of snow and rainfall (9.7 cm) recorded during the 2011–2012 winter. This precipitation may have served as an additional freshwater input that leached salts further down the profile. A third explanation for the relatively low presence of soluble salts in croplands may lie within the constructs of the sampling design of this study and may have underestimated the adverse effects of soil salinity on agricultural production. Samples were extracted in early May while fields were laser-leveled. After sampling, rows were created and then irrigated prior to planting. Anecdotal evidence suggest that salts

Table 2 Estimate of fixed effects for ANOVA of variability and mean values of depth to groundwater and groundwater electrical conductivity (EC_g) in two treatments: moist-soil impoundments and croplands at Bosque del Apache National Wildlife Refuge (33° 48′, 106° 53′), May through August 2012, in the Gila soil series (Typic Torrifluvent)

Estimate of Fixed Effects

Variable	Effect	Numerator DF	Denominator DF	F Value	Pr>F
Δ DTGW[a]	Treatment	1	39	169.75	<0.0001
Mean DTGW	Treatment	1	39	151.71	<0.0001
Δ EC_g	Treatment	1	39	818.65	<0.0001
Mean EC_g	Treatment	1	39	1,295.32	<0.0001

Treatment type was used as a fixed effect

[a] Depth to Groundwater

[b] Groundwater Electrical Conductivity

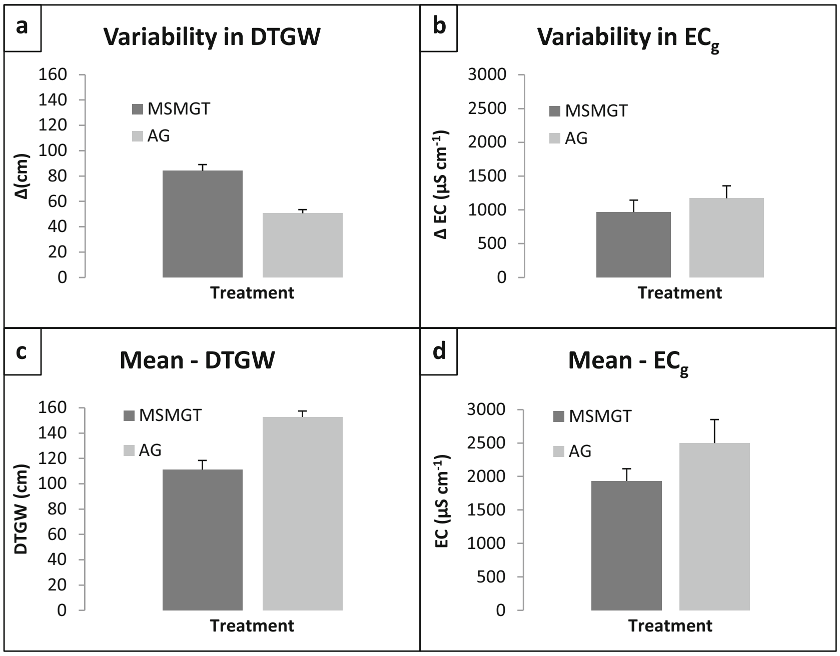

Fig. 6 Mean values between (**a**) variability in depth to groundwater, (**b**) variability in groundwater electrical conductivity (EC_g), (**c**) depth to ground water, and (**d**) groundwater electrical conductivity within moist-soil impoundments ($n=6$) and croplands ($n=6$) at Bosque del Apache National Wildlife Refuge (33° 48′, 106° 53′), from 15 May 2012 to 1 August 2012, in the Gila soil series (Typic Torrifluvent). Means sharing a letter do not differ ($P>0.05$)

brought in from applied water as well as salts pre-existing in the soil were mobilized and concentrated on the tops of the rows as a result of capillarity and ET. These observations are consistent with previous literature (Bernstein et al. 1955; FAO 1988) that documents this effect in furrow irrigated agricultural systems. Elevated salinity levels prior to planting could subject seedlings to osmotic stress and incur injury during its most sensitive stage to soluble salts.

While salinities were not adverse in the root zone, EC_s increased with depth and Na was the prevalent soluble cation causing soil to approach sodic conditions at depths >55 cm. Soils where Na excessively outweighs the concentrations of Mg and Ca are deemed *sodic* (Agassi et al. 1981). Sodicity can lead to negative effects on the soil structure as a result of clay deflocculation and thereby reduce soil air and water permeability (Rengasamy and Olsson 1991). Sodic soils are typically defined by a sodium adsorption ratio >13, soil electrical conductivity <4,000 $\mu S\ cm^{-1}$, and a pH>8.5; however, it is important to note that deleterious effects can occur before these defined limits (Chhabra 1996). While soils under moist-soil management had a relatively consistent SAR of 3 throughout the sampled soil zone, lower portions (>55 cm) of irrigated cropland soil closely approach sodic conditions (Fig. 2) because of low Ca and Mg, and high Na. These soils influenced by sodicity may contribute to further salinization through water logging of poorly permeable soils or enhanced capillarity of saline groundwater.

Broader Considerations

While the results from our study suggest that moist-soil management may have a greater capacity to flush salts from soils relative to agricultural management, limitations may exist as large quantities of applied surface water may result in salinization from a rising saline groundwater table. Little research has been conducted on soil salinity in moist-soil management, but the integrated relationships among surface flooding, groundwater, and salt accumulation in moist-soil impoundments are similar to those observed in semi-arid natural wetlands (Jolly et al. 2008). Flood pulses in natural wetlands in semi-arid environments can recharge groundwater and flush salts stored in the soil into the groundwater (Cramer and Hobbs 2002). However, flood events may contribute to a rise in the groundwater table shallow enough to result in an upward flux of saline groundwater (Hutmacher et al. 1996). Crosbie et al. (2009) demonstrated that wetting and drying cycles in semi-arid floodplain wetlands can alter the function of the wetland from a recharge system to a discharge system, respectively. During flood periods, flooding results in recharge, but in non-flooded periods with high groundwater the wetlands function as discharge systems. In the Canadian prairies, Nachshon et al. (2013) observed greater salt concentrations in and around discharge wetlands compared to nearby recharge wetlands. Similar processes could occur in moist-soil management, although our data are insufficient to unequivocally document these processes in our study. The results of non-published data from Fowler (2013) indicate that soil salinity concentrations were greater near the surface relative to concentrations at 1 m deep in the profile at the time of summer flood irrigations. This suggests the possibility that moist-soil impoundments may at some periods function as discharge systems and display an inverted soil profile as a result of capillary upward flux of saline groundwater.

While our study determined differences in salt concentrations among treatments as a result of differences in hydrologic regimes, it is important to note the variability within treatments of the same soil type. Within treatments, depth to groundwater and groundwater conductivity varied in magnitude among installed groundwater wells. These variations are likely a function of the alluvial floodplain environment in which our study was conducted. Floodplain soil environments are highly variable due to the geomorphic processes from which they are derived (Jacobson et al. 2011). Historic depositional events and shifting meandering channels can create preferential pathways, such as sand lenses, for the movement of subsurface water (Makaske 2001) or impermeable clay layers. Therefore the effect of an implemented hydrologic regime is likely to have differential impacts on soil and groundwater salinity throughout the spatial landscape. In areas that have poor drainage, applied surface water may infiltrate slowly and contribute little to influencing groundwater or leaching. In contrast, the successive applications of large quantities of water on highly porous soils may serve to permanently raise the groundwater table and encourage alternative processes of salinization such as capillary upward flux. An understanding of site specific soil and water characteristics would improve predictions of water management applications.

Lastly, while moist-soil management practices are common throughout regions of the United States (including the southeast, mid-west, and western US regions), continued use in semi-arid environments is contingent on the future availability of an adequate water supply. Current high consumptive rates for agriculture and growing municipal demands (Li et al. 2005) will present challenges to its continued use and warrant further research on how limited or reduced flooding applications will affect salt dynamics in soils under moist-soil management.

Conclusions

Differences in the timing, volume, and quality of artificial hydrologic regimes influence the degree of salt accumulation in semi-arid environments. Flooding regimes under moist-soil management reduced soil salinities from the sampled one meter portion of the soil profile. Inundation during the winter, when applied water has its lowest annual concentration of solutes, enables a large portion of salts to be removed from the soil prior to the growing season. Flash floods in the summer growing season tend to serve as leaching and recharge events that may keep soil salinity accumulation to a minimum. In contrast, soils under long term agricultural production seem to lack a fraction of water capable of moving salts out of the profile and this has led to the greater accumulation of salts, particularly in the lower portions of the profile (>55 cm) that have sodic-like conditions. While salinity levels measured in the root zone (0–35 cm) of agricultural profiles were below salt tolerance thresholds for field corn, over winter flooding may be a technique utilized if root zone salinities are high. While the remediation of sodic soils likely requires the addition of chemical amendments such as gypsum, the incorporation of a seasonal leaching fraction similar to that found in moist-soil management may be a solution that discourages the further accumulation of soluble salts and soil degradation. A tradeoff exists between repetitive flushing of salts into the groundwater that can lead to water table rise and enhanced salinization via capillary rise versus the buildup of high levels of salts in the profile, potentially jeopardizing the success of desired crops and wetland vegetation. Nevertheless, given adequate consideration to tradeoffs, a rotational use of moist-soil management flooding within wetlands may be a tool to restore or enhance seasonal wetlands degraded by high salt concentrations.

Acknowledgments This project was supported by the U.S. Fish and Wildlife Service, Bosque del Apache National Wildlife Refuge, and the United States Geological Survey with support also from the Friends of the Bosque. We thank J. Vradenburg, J.A. Nyman, and R. Finocchiaro for their critical insights. In addition, we extend gratitude to M. Kaller for statistical assistance. We also thank two anonymous reviewers for their helpful suggestions. The use of trade, product, or industry firm names or products is for informative purposes only and does not constitute an endorsement by the U.S. Government.

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