Sediment Accumulation in Semi-arid Wetlands of the Texas Southern High Plains

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ABSTRACT

The purpose of this study was to evaluate the effects of watershed management system on sediment deposition in playa wetlands, depressional geomorphic features that serve as watershed runoff catchment basins which are thought to be focal points for High Plains (Ogallala) aquifer recharge. Three pairs of cropland/grassland playa wetlands in Briscoe, Floyd, and Swisher counties of Texas were selected for the study. Watershed and annulus slopes, tillage index, shape indices, and watershed to wetland area ratio were used to evaluate the effect of watershed management on sediment deposition in playa wetlands. Sediment depth was directly related to watershed land use with more sediment accumulating in playa wetlands with cropped watershed than in grassland watersheds. Tillage index suggests that cropland watershed increased wetland sediment accumulation compared to grassland watersheds. The maximum slope in the annulus surrounding the wetland was positively correlated (0.959) to wetland sediment accumulation. Shape indices suggest that the more "circular" the watershed the less sediment accumulated. Slope of the annulus was significant while shape indices and the ratio of watershed to wetland areas were not significant in predicting wetland sediment accumulation.

Keywords: Watershed Management, Playas, Post-cultural Sediment, Annulus Slope

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INTRODUCTION

The Southern High Plains (SHP) of Texas was native short-grass prairie when initially fenced for cattle. Ranching, while not dramatically altering the ecosystem, increased the grazing pressure by replacing migrating buffalo herds with cattle. Greater changes began in the 1880s when homesteaders began to occupy the area and broke the sod to plant row crops (Gibson 1932). This large influx of homesteaders dramatically changed the SHP vegetation. By the early 1900s, plows were destroying native sod. While the SHP soils are eolian in origin, plowing exposed the soil surface which was left extremely vulnerable to detachment by the wind and severe erosion. The drought of the early 1930's left little vegetative cover which in turn led to the dust bowl (Weaver et al. 1935; Weaver and Albertson 1936). It follows that the adoption of irrigation in the 1950s (Musick et al. 1990) along with the adoption of other agricultural practices mitigated such wind erosion problems (Stout and Lee 2003) and transformed the SHP into one of the most productive cropland regions in the world. While the U.S. Dust Bowl was associated with soil movement by wind, irrigation from the underlying Ogallala (High Plains) aquifer has increased water-transported sediments due to overland water flow. The regional scale land-use change to intensive row crop production has also altered the SHP ecosystem and increased overland flow of sediments to playa wetlands (Luo et al. 1997, 1999).

Playas are natural ephemeral wetlands embedded within closed-system watersheds that are the repository for runoff from the surrounding upland SHP soils. Freshwater playa wetlands and watersheds in the SHP are relatively circular in nature, giving them a "compactness" (Ebdon 1977) that is not associated with wetlands along a river. Due to a semi-arid climate and high evaporation, playas are dry for much of the year (Haukos and Smith 1994). Freshwater playa wetland topology is frequently thought of as being similar to that of a dinner plate; with a flat shallow basin surrounded by a relatively steeply angled annular region which leads up to a wide gently sloping area. These three correspond to the playa lake bottom, annulus, and the upland watershed or "interplaya region", respectively (Gurdak and Roe 2009). The playa basins generally consist of Randall soils (Fine, smectitic, thermic Ustic Epiaquerts) (https://soilseries.sc.egov.usda.gov/OSD_Docs/R/RANDALL.html) that occur within the basin floor (Zartman et al. 1996).

Watershed characteristics play an important role in determining playa geomorphology because these depressional playa wetlands naturally only receive watershed runoff. For managed playa ecosystems, irrigation or other anthropogenic runoff can also influence playa water budgets. Beasley (1972) and Tsai et al. (2007) noted that watershed slope and shape, infiltration, tillage, and vegetative cover all influence runoff into playa wetlands. Watershed-soil properties affect playa wetland sediment characteristics and sediment transport by wind less in grassland watersheds than in cropland watersheds due to the reduced wind speed caused by to permanent vegetation. The regional watershed surface exhibits increased soil-clay content from the south to north of the SHP, a distance of about 400 km (about 250 miles). Texture zones have been defined and range from the southernmost "coarse soils", those soils having sandy surface layers with sandy or loamy subsoils; through the "medium soils", those having loamy surface layers with mostly loamy subsoils; to the northernmost "fine soils," those with loamy surface layers and with clayey subsoils. (Gustavson et al. 1995; Sabin and Holiday 1995). For purposes of this paper, "sediments" are defined as post-cultural deposits that were caused by land-use practices. Sediment depth and total volume were directly related to land-use and soil texture zone (Luo et al. 1997). In the medium texture zone, cropland playa sedimentation rates averaged 9.7 mm/year while native grassland rates averaged 0.67 mm/year (Luo et al. 1997). The coarser soils had higher sedimentation rates. Hydrological events, such as rainfall or irrigation runoff, erode watershed soils (Luo et al. 1999). Cultivation decreased aggregate stability and increased sediment transport.

Due to the uses and important function of playa wetlands for Ogallala aquifer recharge, it is important to understand sedimentation processes. Sediments may be responsible for "clogging" natural drains through the basin floor, which potentially retards water infiltration into the Ogallala aquifer (Bolen et al. 1989). As deposition increases, wetland surface area increases and results in higher potential evaporation losses and a decreased playa "hydroperiod", time in which one of these ephemeral lakes exhibits ponding. Recent studies, however, have reported that sediment in cropped playas may increase seepage which could also provide a mechanism for hydroperiod shortening (Ganesan 2010; Tsai et al. 2010). Sedimentation is associated with increasing numbers of exotic and xeric plants which leads to altered plant community composition and productivity (Smith et al. 2011). The direct effect of sedimentation of soil texture on plant community composition, or of sediment loading of water on macro invertebrates is difficult to separate from hydroperiod reduction; and so has not been studied. Nevertheless, sedimentation clearly provides mechanisms for hydroperiod shortening and so is a major threat to native playa biota and ecosystem services (Haukos and Smith 1994; Smith et al. 2011).

The objective of this study was to evaluate sediment accumulation within the medium-textured zone for three sets of paired playa wetlands of the SHP. Specific objectives were to evaluate sediment accumulation as influenced by watershed management system (cropland or grassland) using: (1) annular and watershed slopes, (2) tillage index [index of the percent of the watershed under cultivation], (3) shape indices, and (4) watershed to wetland area ratio. Information gained from this study should help understanding how watershed crop management influences sediment accumulation in SHP playa wetlands.

MATERIALS AND METHODS

Playa wetlands were selected for evaluation in Briscoe, Floyd, and Swisher counties in Texas. Two playas were selected in each county, which comprised a total of three playa pairs. Paired playas within a county were chosen to have similar watershed, slope, shape, and infiltration (soil texture), but to have different watershed management (cropland versus grassland). Playa basin watersheds are characterized by a playa floor surrounded by a narrow, sloping ring of soil called the annulus. Playa-basin watersheds were considered to be the remaining area beyond the playa wetland and annulus. Terrain elevation maps were created using digital elevation models (TauDEM extension for ArcGIS [ESRI Inc. Redlands, Ca. Version 9.2]) on a pixel by pixel basis (Tarboton 1997). Watersheds were delineated using contour lines and 3D surface grids along with other surface feature maps, such as slope percent and aspect. Transects were defined which were arranged as evenly spaced spokes of a wheel radiating outward from the playa center. In practice, these were defined by using the digital elevation information, computing eight transects from the outer annulus to the center of the wetland and an additional eight transects from the outer edge of the watershed to the center of the playa. These data comprised 16 outer basin to inner basin to playa wetland basin slope segments.

The three playa wetland and watershed pairs are depicted in Figures 1-3. Wetland extent was delineated using Randall clay mapped at each of the six locations (Soil Survey Staff 2010). All playas evaluated were located in areas having a dominant Olton (Fine, mixed, superactive, thermic Aridic Paleustolls) clay loam watershed soil. The playa wetlands (inner rings) are embedded in watersheds (outer polygons) within the "medium" soil textural zone of the southern high plains described as having "loamy surface layers and mostly loamy subsoils" (Gustavson et al. 1995; Sabin and Holiday 1995). Olton clay loam is characterized as a "medium" (Allen et al. 1972) textured playa watershed soil and is generally characteristic of the soils in this zone, and of these counties in particular.

(a) (b)

Figure 1. Briscoe County, Texas (a) Cropland Playa [inner polygon] and Associated Watershed [outer polygon] and (b) Grassland Playa [inner polygon] and Associated Watershed [outer polygon].

Watershed to playa wetland area ratios were determined using the areas quantified in Table 1. For specific information on playa description and selection, see Villarreal et al. (2012). Briefly, Villarreal et al. (2012) chose three paired playas in the medium-textured soil zone of the SHP having either cropland or grassland dominated watersheds. Aerial photos were used to determine the quantity of tilled and untilled land for the watersheds (NAIP, 2012). Using pixel counts to determine the tilled and untilled watershed areas, the "Tillage Index" was computed using the criteria of Tsai et al. (2007). That tillage index is computed as follows:

$$Tillage\ Index = \frac{\text{Tilled landscape} - \text{Untilled landscape}}{\text{Tilled landscape} + \text{Untilled landscape}} \quad (1)$$

(a) (b)

Figure 2. Floyd County, Texas. (a) Cropland Playa [inner polygon] and Associated Watershed [outer polygon] and (b) Grassland Playa [inner polygon] and Associated Watershed [outer polygon].

(a) (b)

Figure 3. Swisher County, Texas (a) cropland playa [inner polygon] and associated watershed [outer polygon] and (b) grassland playa [inner polygon] and associated watershed [outer polygon].

The tillage index of the three paired playas documented the playa watershed characteristics. Watersheds with a value of one indicate that the watershed was completely tilled whereas watersheds with a value of minus one indicate that none of the watershed was tilled. Data were analyzed using the Pearson correlation method

Within each playa wetland, up to 25 soil core samples were collected (Villarreal et al. 2012). One sample was collected at the center of each playa basin and others were collected at equal intervals proceeding outwards from the center towards the annulus within the sectors defined by the wheel-spoke transects described above. Soil core samples were collected using a 50 mm-diameter hydraulic probe (Concord Environmental, Wall, NJ) with a 39 kg hammer to refusal depth or 2 m, whichever came first. Soil cores were collected in plastic sleeves then capped and analyzed for soil color and texture in the laboratory. Not all planned 25 locations could be sampled due to location or disturbance problems. Sediment depth was derived from the analysis of soil physical and chemical properties following the criteria described by Luo (1994). Briefly, after the soil cores had been taken to the laboratory, soil from along the core was compared to a standard color chart (Melville and Atkinson 1985), clay and sediment layers identified, and the depth of the sediment layer to the underlying Randall clay noted. In most cases, the A horizon of the soil profile satisfied the definition of post-cultural sediments (See Villarreal et al. (2012) for specifics on how surface and sub-surface horizons, soil color, soil structure grade and kind were interpreted.). The sediment volume in each basin was estimated using the 3D Analyst extension in ArcGIS, and the average sediment depth calculated as the sediment volume divided by the estimated playa wetland area.

Table 1. Tilled and untilled areas for the watersheds, tillage index, maximum annulus slope, maximum watershed slope and mean sediment depth (Luo 1994, 1997) for the six U.S. Southern High Plains playa watersheds/wetlands used in this study.

Playa	Tilled, ha	Untilled, ha	Tillage index	Max annulus slope, %	Max outerbasin slope, %	Sediment depth, m
BC	250	56	0.63	5	6	0.12
BG	34	96	-0.48	4	7	0.11
FC	130	11	0.84	3.6	4.9	0.11
FG	38	140	-0.56	3	5	0.09
SC	49	13	0.58	12	4	0.19
SG	33	110	-0.54	3	6	0.12

Where BC indicates Briscoe County cropland, BG indicates Briscoe County grassland, FC indicates Floyd County cropland, FG indicates Floyd County grassland, SC indicates Swisher County cropland, and SG indicates Swisher County grassland. The tillage index was calculated using the formula of Tsai et al. (2007).

Shape is an obvious characteristic of the playa and watershed but is difficult to quantify (Ebdon 1977). Shape indices for playas and watersheds were calculated from georectified images using Adobe Photoshop CS5 (Adobe Systems Inc., San Jose, CA). The parameters measured for each feature were regional areas of playa wetland or playa watershed (A), length of longest axis (L), diameter (D), and radius (R_C) of the smallest circumscribing circle, radius of the largest inscribed circle (R_I), and the radius of a circle with the same area as the feature (R_A), as described by Ebdon (1977). Lengths were converted from pixel numbers to meters based on the map scale. The largest inscribed circle and smallest circumscribing circle were created using an empty circle that was scaled to the feature of interest by visual inspection of the images and converted to m^2, and the area inside each circle was calculated. The radius parameters; R_A, R_C, and R_I were calculated as $\sqrt{A/\pi}$. We used shape indices defined by Ebdon's (1977) methods S_2, S_3, S_4, and S_5 to characterize and compare the playa wetlands and the watersheds as follows:

$$S_2 = 4A/\pi L^2 \text{ where } \pi \text{ is } 3.14, \quad (2)$$

$$S_3 = 4A/\pi D^2, \quad (3)$$

$$S_4 = R_A/ R_C \text{ and}, \quad (4)$$

$$S_5 = R_I/ R_C. \quad (5)$$

Shape indices S_2, S_3, S_4, and S_5 would have values of one for a circle. Less circular or more irregular shapes are identified by shape index values that become smaller and deviate more from one. The Pearson correlation was used to evaluate the relationship between sediment volume and watershed to wetland ratio.

RESULTS AND DISCUSSION

Watershed management determines runoff and sediment transport to their closed-basin playa wetlands. Beasley (1972) and Tsai et al. (2007) stated that watershed slope and shape, infiltration and tillage/vegetative cover specifically influence watershed runoff and sediment movement into playa wetland basins. These playa watersheds/wetlands were selected to minimize watershed slope and shape and infiltration (soil texture) differences so that tillage/vegetation could be selectively evaluated. While all playas and watersheds had approximately 1% slope, cropland playas had greater sediment depth accumulations than their paired grassland sites (Table 1). There were, however, differences in maximum slopes for the 16 slope transects per playa (Table 1). The maximum slope for the annulus to wetland center was *positively* correlated to sediment depth accumulation (0.959), while the maximum slope for the outer edge of the watershed to wetland center was *negatively* correlated to sediment depth accumulation (-0.541). This suggests that the annular area surround the playa wetland is responsible for sediment accumulation. Steeper slopes tend to be more easily eroded because greater energy is imparted to flowing water over a given distance along the soil surface.

Watershed management can be characterized using a tillage index in which tilled watersheds have positive tillage index values and grassland watersheds have negative values (Table 1). Average tillage index for the cropped watersheds was 0.69 compared to the average tillage index of -0.53 for the grassland watersheds. Cropland watershed tilled indices ranged from 0.58 to 0.84 and indicated that 58-84% of the watersheds were tilled. The grassland watersheds had tillage indices of -0.47 to -0.56 which indicates that 48-56% of the watersheds were untilled. These values indicate that even though the areas immediately surrounding the grassland playa wetlands were in perennial grass vegetation, large areas within the watershed were tilled. The presence of tilled areas within the watersheds reflects the intensive cultivation of the Texas Southern High Plains region; though an effort was made to identify watersheds devoid of row cropping very few could be located. The correlation between tillage index and sediment was 0.45. The low correlation is attributed to the relatively large sediment accumulation in the Swisher County cropland playa. Using regression for sediment as a function of tillage index gives a positive slope as follows:

$$SA = 0.023*TI + 0.12 \quad (r^2 = 0.2) \quad (6)$$

where, SA is average sediment accumulation (meters, Table 1), and TI is tillage index. Therefore, cropping the watersheds increases the amount of sediments that enter the playa wetlands.

The second method used to quantify sediment transport employs shape indices to characterize the watersheds and wetlands (Ebdon 1977). The measured length and diameter of the playa wetlands are presented in Table 2. The computed shape indices are presented in Table 3. Ebdon shape indices were similar between the four indices for each location and watershed/wetland area (Table 3). These minor differences were due to the differing formula in computing the indices. Only the Briscoe County, Texas cropland playa S2 index was 1.0 indicating the most compact, circular shape by Ebdon's terminology. All of the remaining areas (playa wetlands and watersheds) had Ebdon shape indices less than one, indicating more irregular shapes. While the values for S2, S3, S4, and S5 differ in formula to quantify shape indices, average S value for the wetlands was 0.741 compared to 0.574 for the watersheds. These differences indicate that, in general, the playa wetlands were more circular than the surrounding playa watersheds. These indices show that the watersheds were not compact (Figures 1-3) and that most of the watersheds (excepting the Floyd and Swisher County grassland watersheds) were elongated and rectangular in shape. For each watershed or wetland, all of the S values were consistently higher or lower for all shape indices. Shape index (S2) was negatively correlated with sediment accumulation in playa wetlands having a Pearson's correlation coefficient of $r = -0.818$. This relationship was similar for both the cropland ($r = -0.884$) and the grassland ($r = -0.899$) watersheds. Regression analysis for all playas had the following equation:

$$SA = -0.337*S2 + 0.321 \quad (r^2 = 0.67) \qquad (7)$$

where, SA is sediment accumulation, meters and SI is shape index S2. The R^2 value was 0.669 with $\alpha = 0.0467$. Recall that the index (S2) used here is a measure of how much the longest axis of a shape deviates from that of a circle of equal area. Since the measurement is unity for a circle and decreases as a shape either becomes more elongated or exhibits a more convoluted edge, this index is also called "roundness" in some image analysis programs such as ImageJ (Schneider et al. 2012). The rounder, or more compact, the playa watershed, the less sediment is transported and subsequently accumulates.

A third factor that influences wetland sediment accumulation was ratio of playa watershed to wetland areas. Large watershed area to wetland area ratio (WWR) might suggest larger quantities of runoff and greater sediment accumulation in wetlands. As a topologically closed watershed reaches the point of runoff during a precipitation event all of the runoff must be directed to the lowest point, in this case a playa basin. A larger watershed will have a proportionally greater amount of runoff directed towards a focus. With larger watersheds considerably greater flow volumes, velocities, and erosion might be observed especially as the runoff is directed nearer to the playa. Vegetation may also interact with WWR so that vegetated areas minimize runoff while row-cropped areas enhance runoff and sediment. There was no statistically significant relationship ($R^2 = 0.15$, $\alpha = 0.43$) between WWR and sediment accumulation (Figure 4). Figure 4 visually indicates that there was more sediment accumulation at low WWR for the cultivated watersheds whereas there was less sediment at low WWR in the grassland watersheds. Correlation between sediment accumulation and WWR was -0.65 for cropped watersheds and 0.69 for grassland watersheds.

Table 2. Measured length parameters for the playa wetlands and their watersheds for six playas in the U.S Southern High Plains.

	County					
	Briscoe		Floyd		Swisher	
	Land use					
Factor	Cropland	Grassland	Cropland	Grassland	Cropland	Grassland
	Playa wetland					
L, m	721	542	448	563	367	357
D, m	805	545	463	569	372	365
Rc, m	402	272	232	285	186	183
RI, m	325	140	167	182	162	113
RA, m	365	196	201	218	171	147
	Playa watershed					
L, m	2570	1810	1730	1860	1390	1820
D, m	2580	1810	1740	1870	1400	1820
Rc, m	1290	906	872	936	700	909
RI, m	727	437	498	676	319	521
RA, m	196	673	662	774	473	686

Where L is the length of the longest axis, D is the diameter of the smallest circumscribing circle, R_C is the radius of the smallest circumscribing circle, R_I is the radius of the largest inscribed circle, and R_A is the radius of a circle with the same area as the feature, as described by Ebdon (1977).

Table 3. Shape indices for the playa wetlands and their watershed for six playas in the U.S Southern High Plains.

	County					
	Briscoe		Floyd		Swisher	
	Land use					
Factor	Cropland	Grassland	Cropland	Grassland	Cropland	Grassland
	Playa wetland					
S2	1.00	0.522	0.803	0.600	0.869	0.774
S3	0.822	0.517	0.751	0.587	0.847	0.645
S4	0.907	0.719	0.866	0.766	0.921	0.802
S5	0.808	0.514	0.721	0.639	0.871	0.619
	Playa watershed					
S2	0.666	0.552	0.590	0.691	0.459	0.570
S3	0.659	0.553	0.577	0.685	0.456	0.570
S4	0.811	0.744	0.759	0.827	0.675	0.755
S5	0.564	0.482	0.571	0.722	0.456	0.573

Where $S_2 = 4A/\pi L^2$, $S_3 = 4A/\pi D^2$, $S_4 = R_A/ R_C$ and $S_5 = R_I/ R_C$ as defined by Ebdon (1977).

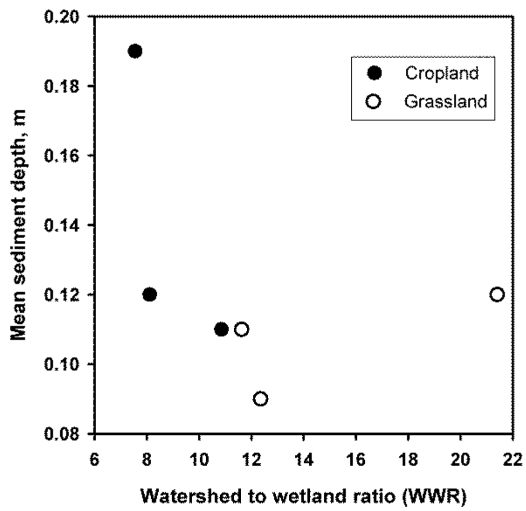

Figure 4. Mean Accumulated Sediment Depth (m) as a Function of Watershed to Wetland Area Ratio for Two Watershed Cropping Systems.

CONCLUSIONS

As shown in other studies, cropped watersheds increase sediment transport to playa wetlands compared to grassland watersheds on the Texas Southern High Plains. This study reconfirms those findings in that sediment accumulated in the cropped wetlands exceeded that for the grassland wetlands for each of the paired playa watershed evaluated. This study indicates that the slope of the annular area surrounding the playa wetland is more important for sediment transport than the slope of the complete watershed. Tillage indices for the watersheds indicated increased wetland sedimentation in tilled as compared to predominately grassland watersheds. Playas embedded in more compact, or "rounder", watersheds exhibited less sediment accumulation in both cropland and grassland. Neither the wetland shape indices nor the watershed-to-wetland ratios were significantly associated with playa sediment accumulation.

The Texas Southern High Plains is an intensively cultivated region. Little grassland remains, and what does remain is under fairly constant grazing pressure, hence it does not exhibit characteristics of what was once "native grassland". It should also be borne in mind that watersheds considered grassland can have a considerable cultivated land component. For such reasons, the increased erosion from row cropped land, and the distribution of row cropped lands within watersheds, better management practices will need to be implemented to lessen sediment movement into the wetlands.

ACKNOWLEDGMENTS

The authors appreciate the research support provided by the Ogallala Aquifer Program. Paper No. T-4-655 College of Agricultural Sciences and Natural Resources, Texas Tech University.

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