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Hydrological dynamics of temporary wetlands in the southern Great Plains as a function of surrounding land use

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ABSTRACT

We used remote sensing imagery to characterize the hydrological dynamics of 8404 temporary freshwater wetlands (playas) in Texas (Landsat 5 TM WRS-2 P30/R36) from 2008 to 2011, comparing known wet and dry periods, and related these to land use within 100 m. Hydroperiods were highly variable, and peak water availability occurred in different seasons in different years, varying by as much as two orders of magnitude with date. Land use affected the likelihood and duration of inundation, with playas in urban settings being modified in such a way as to extend hydroperiod, and playas surrounded by cropland experiencing shorter hydroperiods: 3726 playa basins never contained standing water during the four-year period, and many of these were surrounded by cotton, corn, wheat, or sorghum. In contrast, 25 playas never dried, and most of these were surrounded by urban development. Median hydroperiod was 17–109 days, being longer during the relatively wet year of 2010 compared to exceptional drought in 2011. Remote sensing was useful in monitoring playa surface water fluctuations as a function of land use, providing an alternative source of data in the absence of ground-based hydrological records, and granting a temporal perspective that may otherwise not exist for seasonal or ephemeral wetlands.

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1. Introduction

Globally, seasonal and temporary freshwater wetlands are crucial habitats for supporting biodiversity (Griffiths, 1997; Williams, 1997). In arid and semi-arid regions of the world, these wetlands are the primary sites supporting biodiversity, owing to the absence of more permanent water sources. The conservation value of such wetlands is threatened by alterations to their structure and functioning, mainly through changes to the temporal availability of water. The hydrological dynamics of these wetlands is an inherent driver of biodiversity (Haukos and Smith, 1994; Williams, 2006), so changes to the hydrological regime have important implications on the ecology and management of these systems. However, the natural variability in seasonal and temporary wetlands poses significant challenges in detecting allochthonous changes to their hydrological dynamics due to phenomena such as climate change or land use/land cover change (Winter and Rosenberry, 1998). These challenges are often compounded by a lack of commensurate ground-level surveys, due to limited resources or to restricted land access. Given that wetlands are among the most important yet imperiled habitats on Earth (Brinson and Malverez, 2002), baseline data are lacking against which to compare projected effects.

Remote sensing (i.e., use of satellite-obtained data about the terrestrial surface) provides a way to overcome these challenges by allowing researchers to examine the long-term dynamics of wetlands rapidly and efficiently (Castañeda and Ducrot, 2009; De Roeck et al., 2008; Gómez-Rodriguez et al., 2010; McMenamin et al., 2008; Ozesmi and Bauer, 2002; Rover et al., 2011; Wright, 2010). This ability will be of increasing value to examine alterations to wetland hydroperiods being induced from climate change and from increasing water demands for a growing human population (Kernan et al., 2010). Satellite technology has mostly been used to map the locations and dynamics of wetlands in arid and semi-arid areas that otherwise lack ground surveys (e.g. De Roeck et al., 2008; Roshier and Rumbachs, 2004). Remote sensing does not provide a panacea for wetland examination because there is no methodological consensus as to which sensors, spectra, or resolutions to use for data acquisition; however, Landsat is a primary source due to its resolution, coverage, accuracy, and length of data record (see e.g. Baker et al., 2006; Beeri and Phillips, 2007; Castañeda et al., 2005; De Roeck et al., 2008; Gómez-Rodriguez et al., 2010; Wright and

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Gallant, 2007). Likewise, there is no standard regarding wetland classification method (Ozesmi and Bauer, 2002). Despite these factors, remote sensing has proven to be useful in wetland designation and monitoring of surface water fluctuations for conservation purposes, providing an alternative source of data in the absence of ground-based hydrological records, thus providing a temporal perspective that may otherwise not exist (De Roeck et al., 2008).

One such group of seasonal and temporary wetlands is the playa wetland system of the southern Great Plains of North America (Fig. 1). Broadly speaking, playas are ephemeral, runoff-fed wetlands that are thought to have generated by aeolian and dissolution processes. Because the name “playa” is of Spanish origin, the term is typically applied to depressional wetlands (both freshwater and saline) in Spanish-speaking portions of Europe and the Americas (see e.g. Castañeda and Herrero, 2005; Castañeda et al., 2005). In North America, the term is used to refer to seasonal and temporary wetlands of the southern Great Plains (Smith, 2003). These closed-basin wetlands have discrete hydric soil (clay) basins (Allen et al., 1972), are typically <3 m in depth, and range in size from <1 to >300 ha in surface area (Smith, 2003). There are >30,000 such wetlands in the southern Great Plains of the U.S. (encompassing portions of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas), with over three-quarters within Texas (Smith, 2003) (Fig. 2). Playas are the primary source of aboveground freshwater for wildlife in this region and are a source of recharge for the Ogallala Aquifer, which supports tillage agriculture in much of the central U.S. (Bolen et al., 1989). This region has been extensively converted from indigenous grassland to row-crop agriculture, with approximately 90% of playas in Texas occurring within cropland-dominated watersheds (Smith, 2003).

These wetlands are subject to effects induced by land-use change and climate change. Tillage has been shown to greatly increase sedimentation within playas surrounded by cropland relative to grassland (Luo et al., 1997; Tsai et al., 2007), and sedimentation is considered the primary disruption to playa hydroperiod (Smith et al., 2011). Playas within a tilled watershed typically experience a shorter hydroperiod relative to playas in untilled watersheds, although the mechanism is unclear, possibly resulting from reduction in basin volume as sediment depth increases, thereby inducing volume overflow and increased evaporative loss (Luo et al., 1997; Tsai et al., 2010), or from sediments keeping hydric soil cracks open and thereby facilitating infiltration (Ganesan, 2010). Moreover, the type of surrounding land cover also influences the rates of infiltration of runoff-fed wetlands, with tilled rows facilitating overland runoff but presence of continuous grass cover impeding it (Bartuszevige et al., 2012; Cariveau et al., 2011; Voldseth et al., 2007). In addition to land use/land cover effects, climate change is also predicted to affect wetlands of the Great Plains (Johnson et al., 2005, 2010), including playas (Johnson, 2011). Climate change models for the southern Great Plains generally show an increase in average air temperature, a decrease in annual precipitation amounts, a seasonal shift in precipitation, and fewer but heavier precipitation events (Rainwater et al., 2010). Such changes in the temperature and precipitation regimes will likely alter inflow and evapotranspiration, thus affecting hydroperiod (Karl et al., 2009).

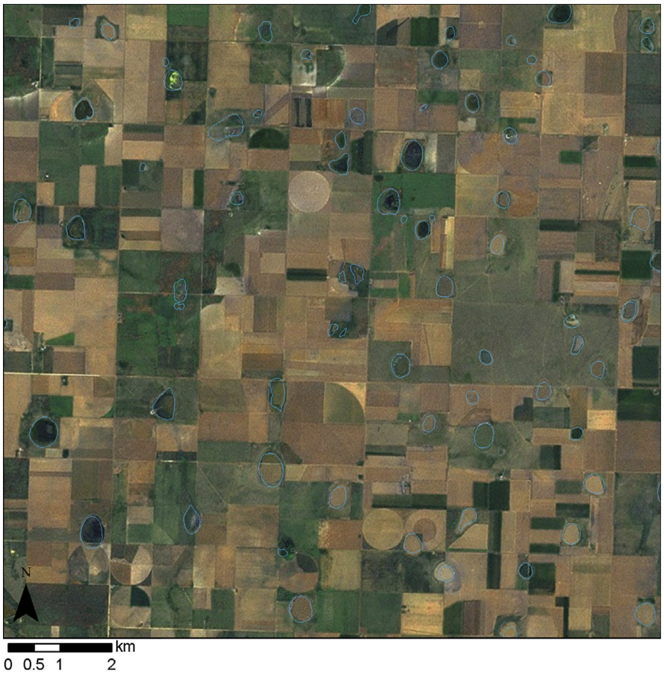

Fig. 1. Aerial image of playas from a portion of focal scene Landsat 5 TM WRS-2 P30/R36 (Swisher County, Texas). Image source: ESRI World Imagery via DigitalGlobe (http://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9). Playa basins are outlined in blue. Accessed: 13 January 2014. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In contrast to most other applications of remote sensing to the study of wetlands, the locations of playas in many parts of the southern Great Plains are already well-documented due to county soil surveys (Fish et al., 1998). The hydrological dynamics of playas, in contrast, are still largely unknown, owing in large part to the fact that >98% of playas in the U.S. occur on private property, meaning that the playa system is virtually inaccessible on the ground and thus understudied (Haukos and Smith, 2003). Most aspects of playa hydrology are still unknown, including the occurrence (frequency) of wet playas and the seasonal availability of open water. Some aspects of playa hydrology, such as hydroperiod and playa size, have been shown to be positively associated with amphibian richness (Venne et al., 2012) and bird richness and density (Tsai et al., 2012). These studies relied on a great deal of consistently performed field work, however, which is impractical for examining hydrological dynamics at a larger scale. The uncertainty surrounding how climate change-driven alterations to the regional precipitation regime will affect these dynamics, combined with potential positive feedbacks between sedimentation and climate change, creates complicated scenarios for planning sustainable management of natural resources. Given the importance of playas to regional biodiversity and for groundwater recharge, the extent of anthropogenic land conversion, and climate change projections for the region, knowledge is needed now to document the current hydrological regimes in these wetlands. Our objectives were to use time series of remote sensing imagery to characterize the hydrological dynamics of playas over a four-year period, comparing known wet and dry periods over a large spatial area as a function of surrounding land use.

2. Methods

2.1. Study site

Data from a single Landsat 5 Thematic Mapper (TM) scene (WRS-2 Path 30/Row 36) were analyzed from 2008 to 2011 (until sensor failure in mid-November 2011). This 185 × 185 km area (~34,225 km^2) includes the region with the highest density of playas in North America (Fig. 2) (Fish et al., 1998; Howard et al., 2003), where they occur at a density of 1/2.6 km^2 (Guthery et al., 1981). The focal region is classified as semi-arid (see next section

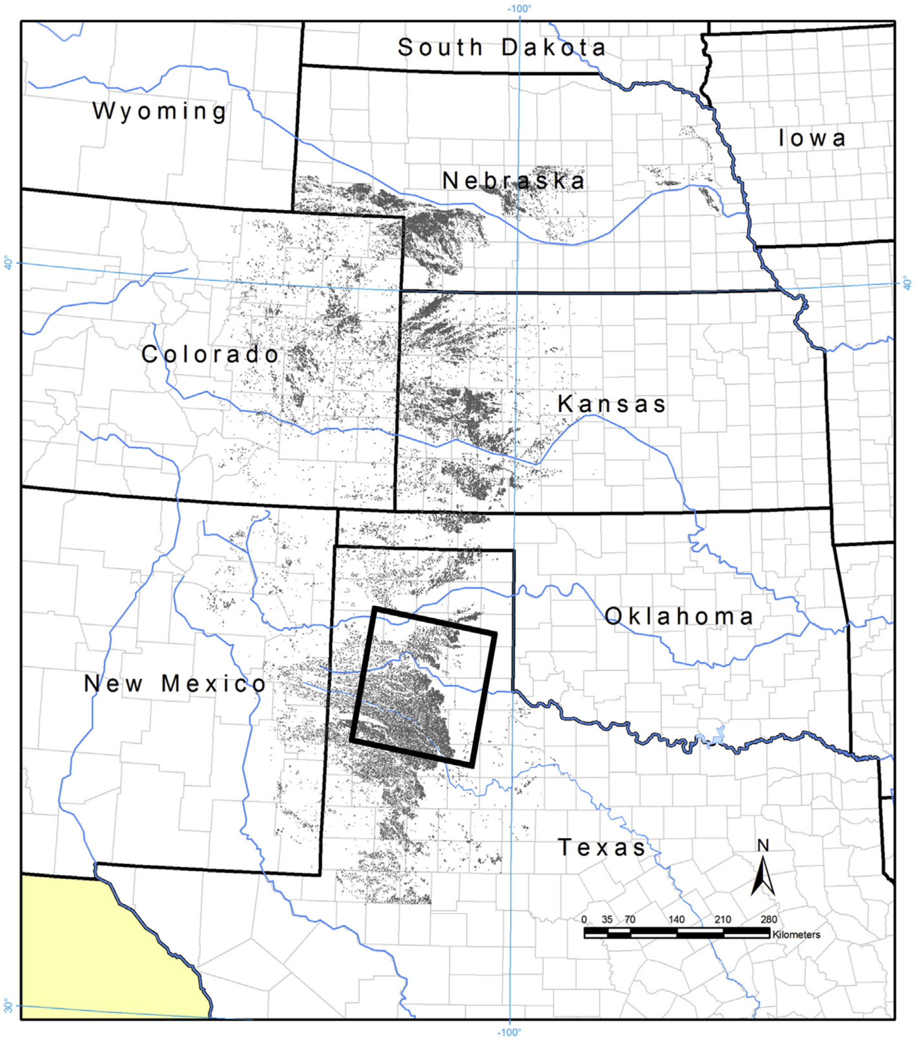

Fig. 2. Map of playas (shaded areas) of the Great Plains of North America, showing the location of the focal scene Landsat 5 TM WRS-2 P30/R36 within Texas (polygon). Digital data from the Playa Lakes Joint Venture (http://www.pljv.org/industry/playa-maps).

for information about precipitation amounts and patterns) and is part of a large plateau known as the Caprock Escarpment (Sabin and Holliday, 1995). Elevation declines gradually from west (~1500 m above sea level) to east (~750 m), with an abrupt decrease in elevation off the Caprock (Sabin and Holliday, 1995). Playas mainly occur on the Caprock, where they are hotspots of biodiversity (Bolen et al., 1989; Haukos and Smith, 1994). These freshwater, temporary wetlands are fed by runoff from seasonal precipitation; fewer than 50 wetlands in the southern Great Plains historically were associated with springs (Rosen et al., 2013). These spring-fed wetlands are considered saline lakes (also called salinas) distinct from playas due to the persistent presence of water and accumulation of minerals from groundwater, with a unique ecology and associated biota (Rosen et al., 2013).

2.2. Data acquisition and processing

Images from nearly cloudless (<10% cloud cover) dates were downloaded as GeoTIFF files from the USGS Landsat archive (http://glovis.usgs.gov). Images with <10% cloud cover but extensive coverage of popcorn clouds (isolated cumulus or stratocumulus) were also excluded. The digital (optical band) data were calibrated to top of atmosphere reflectance in ENVI 4.8 software. For each image date a rule-based wetland classification was applied in ENVI 4.8 (using the band math rule of band 5 [1.55–1.75 microns in the shortwave infrared, often used to distinguish wetlands; Ozesmi and Bauer, 2002] less than band 3 [0.63–0.69 microns in the red, part of the visible spectrum typically used to distinguish vegetation]), a technique that has also been used by Cariveau et al. (2011). The resulting binary image of water/nonwater was converted into a shapefile of wetland polygons in ArcGIS 10.0. Rule-based wetland classification like this has been deemed preferable to unsupervised classification methods (Sader et al., 1995) and is much more rapid than supervised classification.

This process was repeated for each date with <10% cloud cover and minimal popcorn clouds from 2008 to 2011 ($N = 35$; Table 1), which spans a period of wet, dry, and relatively normal years based on data from 1892 to 2011 from the National Weather Service for Amarillo, Texas, the largest metropolitan area contained within the scene, which we used as a surrogate for precipitation trends across the entire scene (http://www.srh.noaa.gov/ama/?n=yearly_precip). Within each year, these dates were concentrated within the period that receives the most precipitation in this region (72.59% of the annual precipitation falls from May through October, and 60% of our dates came from these months) but also included each season in each year (i.e., spanned each year) (Table 1). This four-year span contained two relatively normal years in terms of annual precipitation (2008, 2009), one year with a markedly

Table 1
List of dates analyzed (number of dates per year given in parentheses).

2008 (10)	2009 (7)	2010 (10)	2011 (8)
31 Mar	13 Jan	16 Jan	31 Jan
16 Apr	29 Jan	17 Feb	27 May
2 May	18 Mar	6 Apr	12 Jun
18 May	3 Apr	9 Jun	28 Jun
3 Jun	22 Jun	25 Jun	14 Jul
21 Jul	8 Jul	12 Aug	2 Oct
6 Aug	26 Sep	29 Sep	28 Oct
22 Aug		15 Oct	3 Nov
25 Oct		16 Nov	
12 Dec		2 Dec	

above-average amount of precipitation (2010), and one with a markedly below-average amount (2011) (average annual precipitation, 1892–2011: 51.38 cm). During the wet year of 2010, 67.41 cm of precipitation was recorded (131.20% of average, >1 standard deviation from the mean). Both 2008 (56.99 cm) and 2009 (53.67 cm) were near (slightly wetter than but within 1 standard deviation of) the long-term average. In contrast, 2011 (17.78 cm, 34.60% of average, more than two standard deviations from the mean) was the driest year on record in Amarillo and a year of “exceptional drought” over the entire state (U.S. Drought Monitor, http://droughtmonitor.unl.edu/).

Because of planetary and satellite wobble, which means that a given date's image does not align perfectly with the spatial extent covered in the previous date, we stacked the images and then defined a polygon that bounded the common study extent. This operation created a 31,935.10 km^2 polygon that was used to clip each classified image to a common spatial extent. Non-playa water features (e.g. streams) were then removed by overlaying a shapefile mask of playa locations ≥0.11 ha as defined by hydric soils (Fish et al., 1998).

Because not all portions of a playa basin may in fact be wet after a small precipitation event (due to the presence of small hillocks within the basin, for example), we could not assume that the presence of water at a given single point (such as the playa's centroid) could be used as a surrogate for the entire basin being filled or to assess total water surface area within the basin. Instead, we converted each date's classified and clipped shapefile to a raster file of square cells 30 m on a side (resolution of the original Landsat data). This process differs from that used by Howard et al. (2003) in that we included wet area as small as a single pixel (0.09 ha) whereas they only considered a playa wet if an area 0.36 ha (four pixels) was wet (using an unspecified classification scheme), which would underestimate both the frequency and the area of wet playas. We also converted the playa mask to a raster, with each cell associated with either a unique playa basin ID code or coded as “no data” (i.e., everything other than the playa basins). Overlaying these two raster files resulted in a binary output file with “1” in wet playa cells and “no data” elsewhere. Although ArcGIS's Zonal Statistics tool would be a more direct method to obtain this information, it was unable to handle such a large dataset as ours. We then converted each of those files to polygon files, which allowed us to calculate the number and size of wet playas by date. The attributes of the polygon files were spatially joined with the playa hydric soils mask file, creating an attributes table with columns for each date across each playa.

2.3. Estimation of hydroperiod

Because of a 16-d overpass frequency and occasional cloudy days, we were only able to assess wetland occurrence in irregular intervals (the shortest being 16 d). For this intermittent time series of data, we estimated minimum and maximum hydroperiod to bracket the range of plausible values. The minimum total hydroperiod for the scene was based on the assumption that the first wet date in the time series was the first day after enough precipitation had fallen to allow runoff to accumulate, and the last wet date was the last date before the playa dried (assumed to be the following day); these assumptions may have underestimated hydroperiod. The maximum total hydroperiod could be estimated in two ways. One method assumes that wet playas filled at the first available opportunity, i.e., the first day after the last dry scene date analyzed, and that they stayed wet until the day before the next dry scene date examined. This technique likely greatly overestimates hydroperiod, particularly for larger gaps in our 16-d time series (due to clouds). Therefore, we used an alternative method based on the assumption that a time series of two wet dates could be used to define a slope for predicting the date the playa dried up, if the last wet date had a smaller wet area than the preceding wet date, indicative of drying. This extrapolation technique shortened the maximum hydroperiod for 1865 playas compared to the first method (and thus also decreased the average and median hydroperiod values by 21 and 19 days, respectively). Due to the existence of wet playas on the first and last dates of analysis, both methods give estimates of maximum hydroperiod that are potentially less than the “true” maximum. For both the minimum and maximum estimation methods, during two consecutive wet scene dates, regardless of the number of days in between, the playa was assumed to have been wet for the entire time, which may overestimate hydroperiod.

2.4. Examination of land use

We examined hydroperiod lengths as a function of surrounding land use. We made use of all publicly accessible land-use data rather than proprietary information (cf. Bartuszevige et al., 2012; Cariveau et al., 2011), making our approach repeatable. Although previous studies have established that surrounding land use affects playa inundation and hydroperiod, these studies used a coarse approach with only two or three land-use types (typically cropland, rangeland [grassland, pasture], and Conservation Reserve Program [CRP]) (Bartuszevige et al., 2012; Cariveau et al., 2011; Tsai et al., 2007). The CRP is a USDA program designed to curb soil erosion, whereby cropland is taken out of production for multi-year leases and planted in a perennial cover type (typically grass) that is not grazed by domestic livestock; this program has provided habitat for wildlife and can reduce sedimentation in playas, but the vegetation can impede runoff from filling playas, reducing the occurrence and duration of standing water (Bartuszevige et al., 2012; Cariveau et al., 2011). Access to CRP data is restricted and was unavailable to us because of potential landowner privacy concerns. Instead, we reclassified the USDA National Agricultural Statistics Service Cropland Data Layer (NASS CDL) (http://nassgeodata.gmu.edu/CropScape/) annual digital (raster) data (>100 land-use categories, which differed by year based on crops grown) to a 12-category system (Table 2). Fallow land and fields that were double-cropped (i.e., multiple crops grown within a year) were treated as “all other crops.” This allowed us to examine cropland as a whole so as to be comparable to previous studies but also to examine individually the four predominant crops grown in this region (cotton, corn, wheat, sorghum). NASS data are only available in digital form for Texas since 2008, at a resolution of 56 m for 2008–2009 and 30 m for 2010–2011, which were resampled to 7.0 m and 7.5 m, respectively, to allow for land-use analyses to be conducted at relatively comparable scales. The proportion of each of the 12 land-use categories was calculated within an area comprised of each playa basin plus a 100-m buffer around each

Table 2
Our land-use classification scheme, based on >100 categories from the National Agricultural Statistics Service (NASS) (excluding background, undefined, no data, and perennial ice/snow categories).

NASS category	Our category
Pasture/grass (2 categories)	Pasture/grassland
Cotton	Cotton
Corn (multiple categories)	Corn
Wheat (multiple categories)	Wheat
Sorghum	Sorghum
Other crops (multiple categories)	All other crops
Shrubland	Shrubland
Forest (3 categories)	Forest
Developed (4 categories)	Developed
Wetlands (3 categories)	Wetlands
Open water	Open water
Barren	Barren

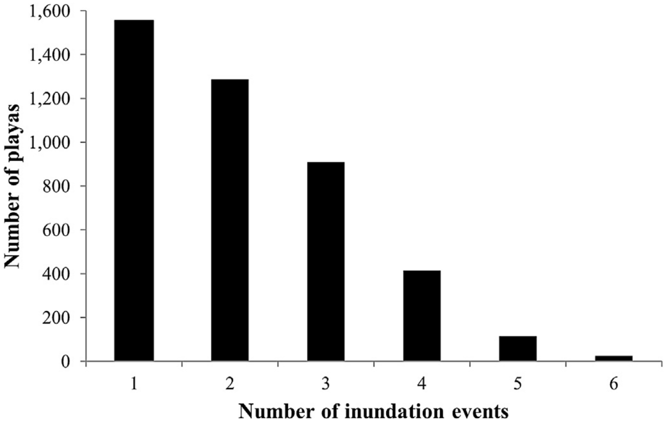

Fig. 3. Frequency of playa basins in Landsat 5 TM WRS-2 P30/R36 that were observed wet during 2008–2011.

playa (a buffer size also used by Cariveau et al. (2011) and Bartuszevige et al. (2012)). The buffers extended from each playa's fixed hydric soil basin rather than the wet area for each date so that buffer location would not vary over time with changes in precipitation, allowing for temporal comparisons unbiased by fluctuations in area. Playa basins and buffers that fell on the clipped study area boundary were included in their entirety. To calculate land use within each basin + buffer area, we used a protocol similar to how we designated wet areas within each playa: we created separate raster layers for each of the 12 land-use categories for each year (where each cell was associated with either that land use or coded as "no data") and joined these with a raster layer of the wet playa + buffer locations for each date (where each cell was associated with either a unique playa basin ID or coded as "no data"). A land-use category cell was counted if the majority of it overlapped with the playa + buffer raster.

We compared land use for playas that never held water from 2008 to 2011, those that never dried during that time, and those that held water at least once. For a coarse-scale analysis comparable to previous studies, we used a *t*-test to compare average proportion of pasture/grassland vs. cropland (all crop categories combined) between playa basins that never ponded water to those that held water at least once. For the more specific 12 land-use categories, we compared proportional composition among playas that were never wet, never dry, and those that held water at least once via chi-square analysis for each year, in SAS 9.3. The "barren" category was excluded because no barren land was found within 100 m of any playa. In addition, all of the playas that never dried were visually examined individually by aerial imagery (Google Earth).

3. Results

Of the 8404 playa basins (defined on the basis of hydric soils) that were within the clipped portion of the focal scene, only 4326 ever contained water at least once in the 2008–2011 period (2008: 2849 basins that were wet during at least one of our survey dates; 2009: 2459 wet basins; 2010: 3574 wet basins; 2011: 815 wet basins). The wet area within these playas ranged in size from 0.09 ha (smallest possible detection size with Landsat) to 126.09 ha (mean: 4.72 ha), which were smaller compared to the basin sizes overall in the scene, which ranged from 0.12 to 163.38 ha (mean: 9.01 ha).

The majority of playas experienced three or fewer inundation events during the 4-year period, with most filling only once (Fig. 3). The total area of water available in all wet playas on any given date (i.e., the sum of all wet playas by date) ranged from 357.75 to 12,514.05 ha (out of a maximum 75,442.41 ha possible based on the sum of the sizes of all of the hydric soil basins), in a highly variable and irregular pattern (Fig. 4). Peak water availability occurred in different seasons in different years.

Hydroperiod varied by year, being longest during the wettest year examined (2010: average 71.7 d using the minimum method, 160.8 d using the maximum method), shortest during the exceptional drought of 2011 (15.7–119.9 d), and intermediate during 2008 (51.9–126.6 d) and 2009 (60.5–158.3 d). Over the four-year span as a whole, the average minimum hydroperiod was 55.5 d (median: 17.0 d), and the average maximum was 141.2 d (median: 108.8 d). Twenty-five playas contained water on every date, with

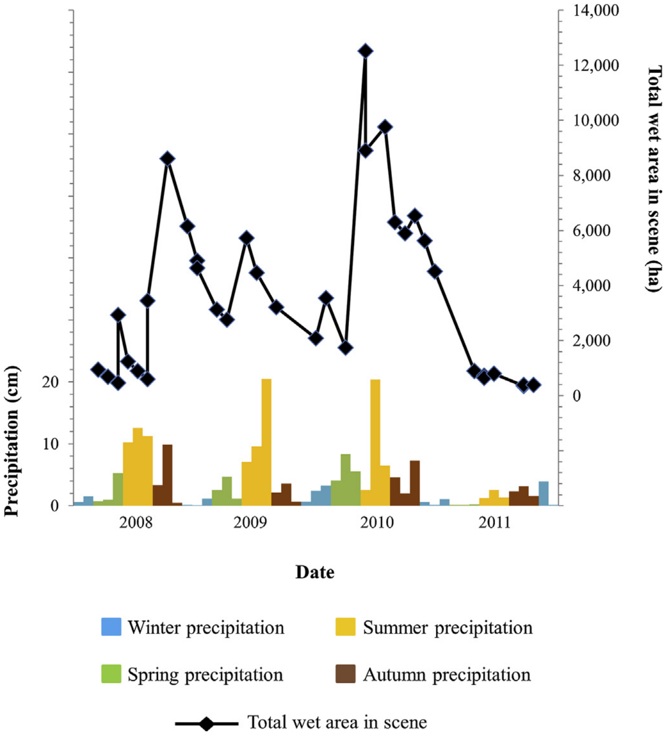

Fig. 4. The collective wet area in hectares (ha) in Landsat 5 TM WRS-2 P30/R36 (right-hand *Y*-axis) as a function of precipitation in centimeters (cm) (left-hand *Y*-axis) and season (colored bars: blue = winter, December–February; green = spring, March–May; yellow = summer, June–August; brown = autumn, September–November). Each black diamond represents a date that was analyzed, with the colored bar below it the precipitation (in cm) from that date. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

several dozen others containing water until the 2011 drought. The playas that were wet on every date were larger on average (26.78 ha; range: 1.89–118.13 ha) than the other playas that contained water at some point in the time span. Only one of these 25 playas had no obvious modifications; the remainder was highly modified in ways that would lead to artificially prolonged hydroperiod (as verified with aerial imagery). Specifically, nine were urban parks (primarily in the city of Amarillo, Texas), four had dugout pits (which are used for a variety of purposes, including irrigation and livestock watering), four were water treatment facilities, three were stormwater retention basins, one was a golf course water hazard, one was at a dairy, one was at a feedlot (concentrated animal feeding operation), and one was an industrial catchment basin. In contrast, 4078 playas never contained any standing water during the four-year span, mostly in agricultural settings (Fig. 5). These playas were in smaller basins than those that held water at least once (average: 4.19 ha; range: 0.12–113.80 ha) and were spread throughout the scene (Fig. 6).

Relatively small land-use changes were seen during 2008–2011 within our focal region (Table 3), attributed to changes in cropping between years as well as to inherent year-to-year variability and errors in the CDL. The predominant land-use types were pasture/grassland, followed by shrubland (primarily occurring off the Caprock escarpment to the east of the playa region; Fig. 2), cotton, and wheat. Land use affected the likelihood and duration of inundation (2008: $\chi^2 = 86.4$, $P < 0.0001$; 2009: $\chi^2 = 95.2$, $P < 0.0001$; 2010: $\chi^2 = 79.7$, $P < 0.0001$; 2011: $\chi^2 = 107.1$, $P < 0.0001$). Playas that held water at least once had a significantly higher percentage of pasture/grassland surrounding them ($\bar{x} = 54.0$, SD = 29.4) compared to playas that were always dry ($\bar{x} = 52.4$, SD = 37.9); $t_{8402} = -2.1$, $P = 0.03$). Similarly, playas that held water at least once had a significantly lower percentage of cropland surrounding them ($\bar{x} = 37.7$, SD = 29.6) compared to playas that were always dry ($\bar{x} = 41.1$, SD = 37.9); $t_{8402} = 4.6$, $P = 4.03 \times 10^{-06}$). Because pasture/grassland was the predominant form of land use within the scene (Fig. 7), it was the predominant form in the buffers of most playas except for those that never dried out, which were surrounded by more development. Cotton and wheat were especially associated with those playas that never held water.

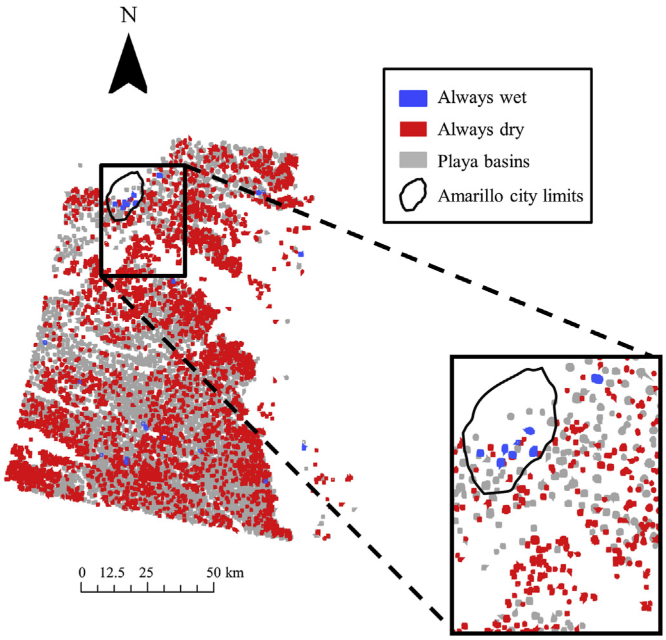

Fig. 6. Location of playa basins within Landsat 5 TM WRS-2 P30/R36 (see Fig. 2 for regional context) that always held water from 2008 to 2011 (blue), those that never held water (red), and those that were wet at least once (gray), with basin boundaries made bold (thus exaggerated in size) so as to differentiate the colors more clearly. The inset details an approximation of the 2011 Amarillo city limits. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Examples of (left) playas that never went dry due to urbanization (Amarillo, Texas) and (right) hydric soil basins that never held water during 2008–2011 (red outlines). Imagery from Google Earth. Accessed: 13 January 2014. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Percent reclassified NASS categories within the clipped Landsat 5 TM WRS-2 P30/R36 scene.

Land-use category	2008	2009	2010	2011
Pasture/grassland	41.9	38.3	39.5	36.4
Cotton	10.7	10.3	14.0	18.6
Corn	2.1	2.8	2.4	2.2
Wheat	9.5	10.6	11.5	8.0
Sorghum	1.6	3.2	1.1	1.3
All other crops	2.3	3.9	2.9	2.3
Shrubland	26.2	25.4	26.1	25.1
Forest	1.1	1.0	0.6	1.2
Developed	4.2	4.1	1.4	4.4
Wetlands	0.1	0.1	0.1	0.2
Open water	0.0	0.0	0.1	0.1
Barren	0.3	0.3	0.2	0.3

4. Conclusions

The area of open water in the playa wetland system in the Texas panhandle varied by as much as two orders of magnitude. The difference between the number of playas actually observed to contain surface water over the four-year period (4326) and the number of potential playa basins based on the presence of hydric soils (8404) was expected, given that many playas have been lost due to drainage and infill (Johnson, 2011). The magnitude of difference that we observed (51.5%) fell within the wide range of estimates of playa losses that exist, depending on how hydric soils are classified and region of the U.S. examined (17–85.7%; Johnson, 2011), and is indicative of a worrisome larger trend regarding playa vulnerability and loss.

Playa productivity is related to their inherent drying/re-wetting cycle (Haukos and Smith, 1994). The 4000+ playas that never held water thus no longer function ecologically as playas, and the 25 playas that permanently held water also no longer function ecologically as playas (are lakes instead). We found that occurrence of cropland (particularly cotton and wheat, the two dominant crops in our area) within 100 m of a playa was associated with decreased likelihood of a playa holding water, relative to other land-use types. Previous work has shown that playas are less likely to fill when surrounded by certain forms of land use compared to others (Bartuszevige et al., 2012; Cariveau et al., 2011), and land use is considered even more influential to playa hydroperiod than a simulated 5 °C temperature rise projected from climate change (Smith et al., 2011). However, previous work on playas (Bartuszevige et al., 2012; Cariveau et al., 2011) and other runoff-fed wetlands (e.g. prairie potholes; Voldseth et al., 2007, 2009) found that wetlands surrounded by cropland were inundated more often than those surrounded by grassland areas (particularly CRP and unmanaged grasslands of the tallgrass prairie, both cover types with taller vegetation that impedes runoff into wetlands). In contrast, our work found that wet playas in our focal region of Texas were more likely to be associated with pasture/grassland than

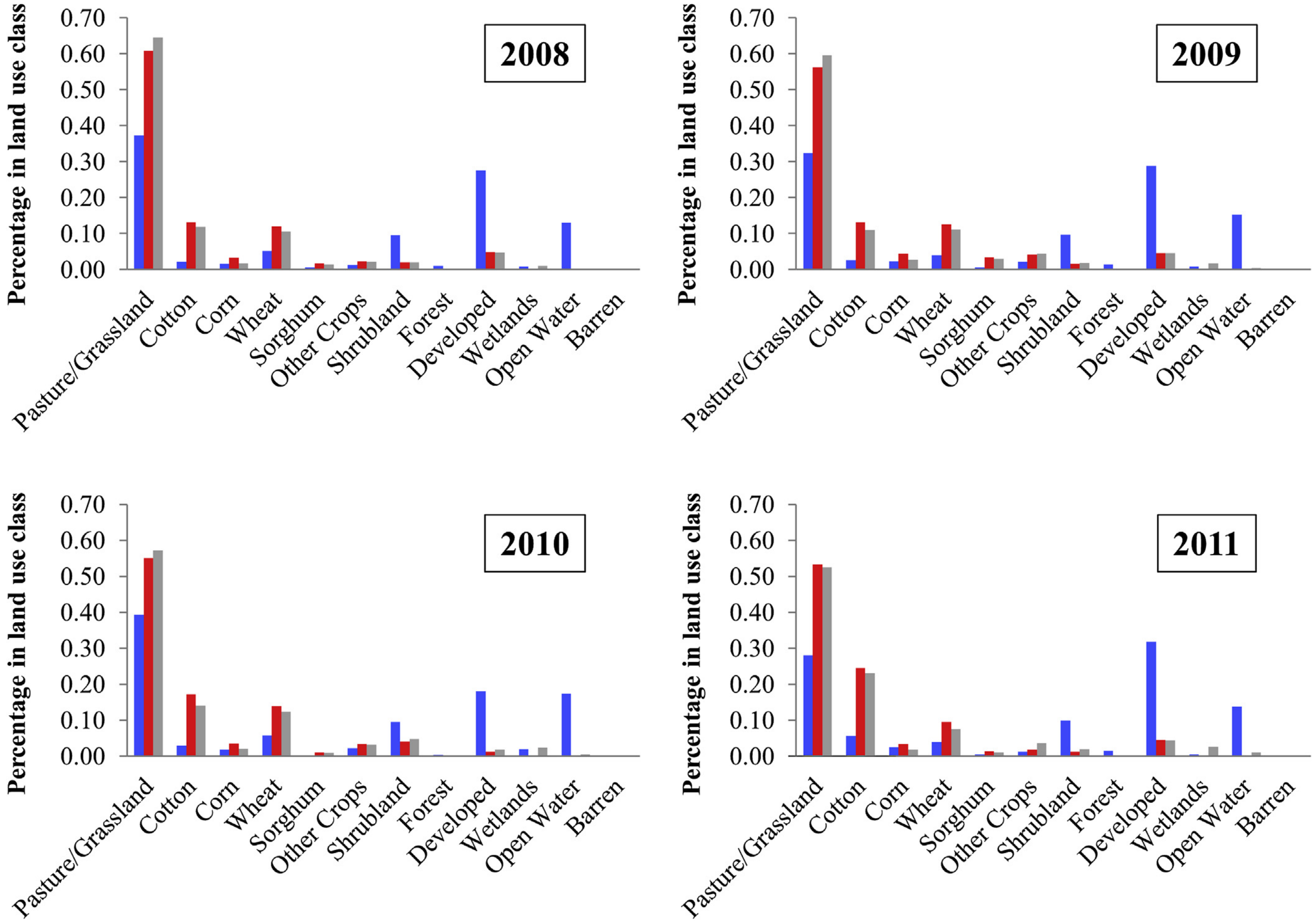

Fig. 7. Proportion of land use within 100 m of playas that were always wet (blue), always dry (red), and those that were wet at least once (gray) for 2008–2011. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

cropland. There are many possible reasons for this effect. For example, the higher water demand (evapotranspiration demand) from actively growing crops may have shortened hydroperiods relative to shortgrass prairie grasses. Furthermore, tillage can disrupt the clay basin's ability to hold water and can generate sediments that accumulate in runoff in cropland playas, diminishing hydroperiod (Johnson, 2011). So while cultivated rows may facilitate flow into a nearby wetland (and grassland vegetation may impede that flow) at a localized (individual playa) scale, cultivation was associated with fewer playas that held water at a regional scale: playas surrounded by crop fields tended to hold water for shorter periods of time than did playas surrounded by grass or pasture lands. Land-use practices thus may have reduced the habitat value of many of these wetlands.

Field studies of playas have observed hydroperiods ranging from 18 to 453 d, with hydroperiods in grassland playas lasting nearly twice as long as those in cropland watersheds (Tsai et al., 2007; Venne et al., 2012). We observed playa hydroperiods ranging from 16 to 1312 d (with 16 d being the minimum and 1312 d being the maximum possible over the time span we examined), although because we were necessarily sampling dates as 16-d intervals, it is possible that a playa could have gone from being dry to wet to dry within an interval. Mean hydroperiod measured in the field varied by year, with a regionally wet year (2004) averaging 231 d compared to 98 d in a drier year (2003) (Venne et al., 2012). Similarly, our results varied by dry and wet years, with minimum average ranges from 16 to ~72 days and maximum averages of ~120—~161 d. The high variability in hydroperiod (by season and by year) illustrates the irregular resource availability in this dynamic system.

A large number of playas were dry over our entire four-year span, even during very wet times. Extended dry periods are not uncommon in the playa system, and playa wildlife display various adaptations to desiccation, including ability to aestivate, drought-tolerant propagules, and rapid maturation. The upper limits of these abilities are relatively unknown, however. When playas do fill, different aquatic and amphibious species need different hydroperiod lengths to complete reproduction or maturation. For example, larval development times for playa amphibians range from ~21 d for spadefoot toads (*Spea* spp.) to over 70 d for tiger salamanders (*Ambystoma tigrinum*) (Venne et al., 2012), and waterfowl typically need hydroperiods of 80—110 d to complete rearing their young (Johnson et al., 2010). Our two methods to estimate hydroperiod gave us very different results, with differing conclusions about the ability of the playa wetland system in our focal area to permit development or reproduction.

The timing of hydroperiod (i.e., when the wetlands are wet) can be just as important biologically as duration. For example, whereas amphibians require playas to be wet during the summer (for reproduction), playas are important to waterfowl and shorebirds during winter. An examination of 221 playas during winter (January, during midwinter waterfowl aerial surveys) over a ten-year period (2001—2010) in our region estimated a playa to be filled in January only once every 11 years, with only a ~30% chance of a playa being wet more frequently (Johnson et al., 2011). In our study, 1342 playas out of 8404 basins were wet in at least one January date (a ~16% chance of being filled in January during the three years in which we had cloud-free January dates, 2009—2011; Table 1), which translates to a ~59% chance of being filled at least once in an 11-year span (to be directly comparable to Johnson et al., 2011). This figure is higher than that estimated by Johnson et al. (2011), with the difference possibly due to the larger number of playas that we examined, the method of examination (remote sensing vs. aerial survey), or the occurrence of the very wet year of 2010. Regardless of the estimate, what is not known is how frequently a wet year like 2010 needs to occur to deter regional biodiversity losses due to drought. For example, amphibian diversity should be significantly reduced in the Texas panhandle if playa hydroperiod were to consistently drop below 70 days (Venne et al., 2012).

Large permanent and semi-permanent wetlands are easier to detect and classify; smaller seasonal and temporary wetlands like playas pose more of a challenge yet are far more numerous in many areas and are of greater conservation concern but are often at greater risk due to land conversion and drought (Semlitsch and Bodie, 1998). Regularly repeated coverage is necessary for distinguishing between natural variability and directional changes due to climate change or land conversion, something that space-borne sensors can provide that airborne photography cannot (Winter and Rosenberry, 1998). However, monitoring large areas on a global scale at low cost must be paired with a straightforward method of measuring wetland hydroperiod. Our approach complements but does not replace field surveys because of the 16-d satellite interval that can be interrupted by clouds, but it allows for a broader extent of analysis as well as virtual access to playas far from roads and those that are inaccessible due to private land-ownership (cf. Bartuszevige et al., 2012; Cariveau et al., 2011). Our approach is one that will enable scientists and land-use planners to use satellite technology to evaluate land-use decisions, or to monitor mitigation efforts and restoration effectiveness.

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