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Long-term sustainability of the hydrology and vegetation of Cienega de Santa Clara, an anthropogenic wetland created by disposal of agricultural drain water in the delta of the Colorado River, Mexico

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ABSTRACT

The Ciénega of Santa Clara is a valuable coastal wetland sustained almost entirely by discharge of brackish agricultural drain water from the U.S. and Mexico. In other locations, agricultural drain water has been problematic in supporting wetlands due to problems of salinity buildup, toxic substances and undesirable plant succession processes. We studied the development of the Cienega de Santa Clara from its creation in 1977 to the present to determine if it is on a sustainable trajectory in terms of vegetation, hydrology and habitat value. We used Landsat NDVI imagery from 1975 to 2011 to determine the area and intensity of vegetation and to estimate evapotranspiration (ET) to construct a water balance. Remote sensing data were combined with hydrological data, site surveys and other sources of information on the Cienega. The vegetated area increased from 1978 to 1995 and has been constant at about 4200 ha since then. The dominant vegetation type is *Typha domingensis* (southern cattail), and peak summer NDVI since 1995 has been stable at 0.379 (SD = 0.016), about half of $NDVI_{Max}$. Flows into the marsh have been stable both month-to-month and year-to-year, with a mean annual value of 4.74 $m^3\ s^{-1}$ (SD = 1.03). Salinity has been stable with a mean value of 2.09 $g\ L^{-1}$ TDS (SD = 0.13). About 37% of the inflow water is consumed in ET, with the remainder exiting the Cienega as outflow water, mainly during winter months when *T. domingensis* is dormant. The sustainability of the Cienega is attributed to: stable inflow rates; salinities within the tolerance limit of the dominant vegetation; and tidal flushing which maintains the wetland as an open system.

1. Introduction

1.1. Use of agricultural wastewater to support created wetlands

Created wetlands can increase the amount of aquatic habitat available for wildlife and provide replacement habitat when natural wetlands are lost (Mitsch, 1992). An attractive water source for artificial wetlands is subsurface drain water from agricultural fields, which is generated in very large quantities in arid-zone irrigation districts around the world (Gregoire et al., 2009). Often this water is discharged into rivers, reservoirs or the ocean; prior use of the water to support wetlands not only creates wildlife habitat but can reduce pesticide and nutrient levels entering receiving water bodies (Gregoire et al., 2009).

However, agricultural drain water is saline and can contain a wide variety of potentially toxic chemicals (Lemly et al., 1993; Lemly, 1994). Some large-scale failures have occurred when agricultural drain water has been used to create aquatic habitats. For example, the Kesterson National Wildlife Refuge, created by disposal of drain water from the San Joaquin Valley irrigation districts, produced wildlife deformities due to excess selenium in the inflow water, and the wetland was ultimately capped and closed (Wu, 2004). This was not an isolated incident, as subsequent investigations showed that selenium hazards were present in over half of western U.S. wildlife refuges receiving agricultural drain water, and that elevated salinities and other toxicity problems were also present in these wetlands (Lemly, 1994).

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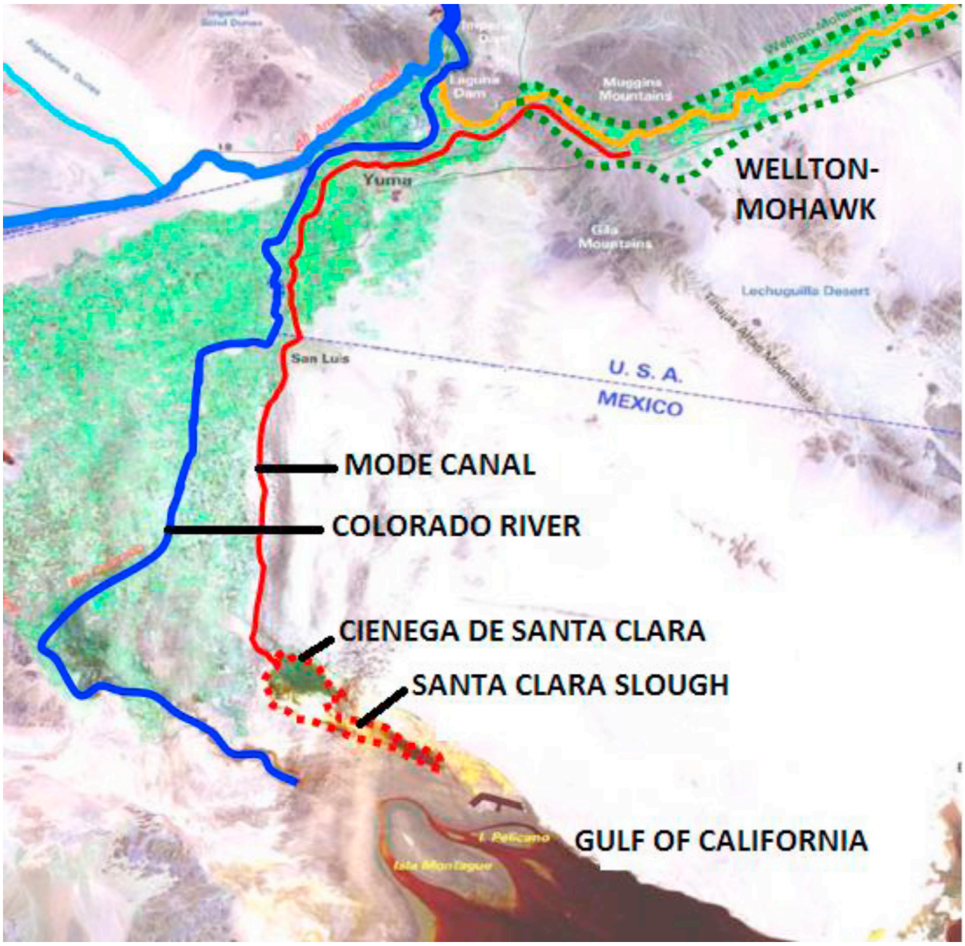

Fig. 1. Locator map for Cienega de Santa Clara and the MODE canal water sources.

Other created aquatic habitats have problems of sustainability over time; for example, the Salton Sea, created by disposal of drain water from the Imperial Valley Irrigation District, provides important avian habitat but has become hypersaline and is experiencing an ecosystem turnover that threatens avian populations (Cohen et al., 1999). Smaller-scale evaporation ponds sometimes provide good wildlife habitat when they are new but they too eventually become hypersaline and can become "ecological traps" (Battin, 2004) that attract wildlife yet are either toxic or do not provide essential habitat requirements (Tanner et al., 1999). In reviewing the effects of irrigation drainage on wetlands, Lemly (1994) advised caution in using these water supplies, noting the negative effects of salinity and elemental toxicity that have occurred throughout the western U.S.

Even well-designed created wetlands that are hydraulically sustainable can experience plant species successions, such that desired species for maintaining wildlife are replaced by less desirable, invasive species over time (Garde et al., 2004; Lin et al., 2010; Kaplan, 2012). A review of the performance of mitigation wetlands that were designed to provide specific habitat types for wildlife showed that they frequently do not follow the intended trajectory of vegetation development (Zedler and Callaway, 1999). An alternative approach is to follow the principle of "self-design", allowing a natural succession of plant species to develop in a constructed wetland (Mitsch, 1992; Mitsch and Wilson, 1996; Mitsch et al., 2005). However, the final ecosystem might not fulfill the original goals set for the restoration project (Moreno-Mateos and Comin, 2010).

1.2. Development of Cienega de Santa Clara in Mexico

This study examines the long-term stability of Cienega de Santa Clara, an anthropogenic marsh in the delta of the Colorado River in Mexico (Glenn et al., 1992; Greenberg and Schlatter, 2012). This paper treats sustainability in terms of hydrology and vegetation; two other papers treat sustainability in terms of contaminants in the water, sediments and food chain (Garcia-Hernandez and Flessa, in press) and habitat value for birds (Hinojosa-Huerta et al., in press), and those results are summarized briefly in the Discussion. The Cienega was formed on the principle of self-design (Mitsch and Wilson, 1996). It was the inadvertent creation of disposal of agricultural drain water from the Wellton-Mohawk Irrigation District in the U.S., which is discharged onto the mudflats of the Santa Clara Slough in the intertidal zone of the Colorado River (Fig. 1). Since 1978 water has entered the Cienega in the Main Outlet Drain Extension (MODE) canal at a rate of approximately 4–5 $m^3\,s^{-1}$ at a salinity of 2–3 $g\,L^{-1}$ TDS (Glenn et al., 1992, 1996; Zengel et al., 1995). The discharge point was originally a small (50 ha) marsh supported by local agricultural drain water from the Mexicali Valley Irrigation District. It has developed into a 5635 ha marsh dominated by *Typha domengensis* (southern cattail), with smaller patches of *Phragmites australis* (common reed), *Schoenoplectus americanus* (three-square bulrush) and 21 other hydrophytes and with 13% open water lagoons within the marsh (Mexicano et al., 2012). It is a major wintering and stopover site for waterbirds on the Pacific Flyway (Hinojosa-Huerta et al., 2008a,b), and supports the largest remaining breeding population of the endangered Yuma clapper rail on the Lower Colorado River (Hinojosa-Huerta et al., 2001, 2002). Note that estimates of the size of the Cienega vary depending on how the perimeter is defined (Glenn et al., 2012).

The only regular maintenance activity is periodic dredging, which has taken place since creation of the marsh to keep the entry point for water from being block by silt. Although the source water from agricultural wells in the Wellton-Mohawk valley is relatively free of silt, the MODE canal passes beside the Gran Desierto de Altar on its way to the Cienega, and this unstabilized dune field adds sand to the canal, which is then deposited at the mouth of the Cienega. So far the discharge point has been extended 500 m from the original end of the canal into the marsh area by dredging (authors' personal observations). The Cienega also experiences fires that burn over most of the vegetation at irregular intervals (Glenn et al., 2012; Mexicano et al., 2012). Fires occur in winter or spring when the dominant vegetation is dormant and flammable. Fires are either deliberately set by local residents to improve access, or by lightning strikes. Other than this, the Cienega has been left to develop without intervention.

1.3. Goals and objectives of this study

A common problem in evaluating the performance of created wetlands is lack of long-term monitoring. In many cases after construction and an initial short period of evaluation, created wetlands are not subjected to further monitoring, yet plant succession and toxicity processes can take many years to play out. In the present study, we evaluated the stability of the Cienega de Santa Clara over its 35 year lifetime. We combined satellite imagery with flow volume and salinity data to compile a record of vegetation density, evapotranspiration (ET) and marsh area from the creation of the Cienega in 1978–2011. We reviewed the literature on selenium, trace metal and pesticide levels in the Cienega over time and surveys of clapper rail populations from 1989 to the present. The overall goal was to track the long term development of the Cienega and to determine if it has reached a sustainable equilibrium state in terms of size, vegetation, habitat quality and water balance parameters. The factors contributing to the stability of the marsh are discussed in comparison to other created aquatic ecosystems that receive agricultural return flows in arid environments. Implications for future management of the Cienega are also discussed.

2. Materials and methods

2.1. Landsat satellite imagery

Landsat represents the world's longest continuously acquired collection of space-based moderate-resolution land remote sensing data. We acquired a July or August image for each year from 1978 to 2011 (Table 1). 1978–1983 images were Landsat 2–4; subsequent images were Landsat 5, except for 1990 when a Landsat 4 image was used. Images were acquired from the USGS Earth Explorer website (http://earthexplorer.usgs.gov/). Level 1T images for cloud-free scenes with a quality score of 9 were selected for analysis; these images are systematically corrected for radiometric and geometric accuracy by the U.S.G.S. EROS data center (Sioux Falls, North Dakota). No atmospheric correction of DN values was attempted.

Green vegetation density was quantified by the Normalized Difference Vegetation Index (NDVI) (Baugh and Groeneveld, 2006):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}} \tag{1}$$

Using Red and Near Infrared (NIR) band values from the Landsat images. NDVI reduces the image to a single layer with NDVI values from −1.0 to +1.0, with water having strongly negative values, soils slightly negative to slightly positive, and vegetation having positive values.

Table 1
List of Landsat images used in this study.

3-August-78	Landsat-2	26-July-95	Landsat-5
11-July-79	Landsat-2	16-July-96	Landsat-5
5-July-80	Landsat-2	15-July-97	Landsat-5
18-July-81	Landsat-2	18-July-98	Landsat-5
4-July-82	Landsat-3	21-July-99	Landsat-5
17-July-83	Landsat-4	7-July-00	Landsat-5
27-July-84	Landsat-5	10-July-01	Landsat-5
30-July-85	Landsat-5	29-July-02	Landsat-5
1-July-86	Landsat-5	16-July-03	Landsat-5
4-July-87	Landsat-5	2-July-04	Landsat-5
22-July-88	Landsat-5	5-July-05	Landsat-5
25-July-89	Landsat-5	8-July-06	Landsat-5
20-July-90	Landsat-4	11-July-07	Landsat-5
15-July-91	Landsat-5	13-July-08	Landsat-5
1-July-92	Landsat-5	30-June-09	Landsat-5
4-July-93	Landsat-5	3-July-10	Landsat-5
7-July-94	Landsat-5	22-July-11	Landsat-5

For each image, an area of interest (AOI) file was created, encompassing the flood area of the Cienega. NDVI ranges for soil, water and vegetation were determined based on training sites determined on high-resolution Quickbird images (Mexicano et al., 2012) and by sampling pixels of each cover class on each image. Pixels in the AOI file were classified as vegetated if the NDVI value was 0.10 or greater.

2.2. Evapotranspiration (ET) estimation by Landsat imagery

Annual estimates of ET from the vegetated portion of the Cienega were determined from Landsat images using methods described in Baugh and Groeneveld (2006), Groeneveld and Baugh (2007) and Groeneveld et al. (2007). NDVI values were scaled (NDVI*) between bare soil ($\mathrm{NDVI_{Soil}}$) and maximum vegetation response ($\mathrm{NDVI_{Max}}$) on each image using the relationship:

$$\mathrm{NDVI}* = 1 - \left(\frac{\mathrm{NDVI}_{Max} - \mathrm{NDVI}}{\mathrm{NDVI}_{Max} - \mathrm{NDVI}_{\mathrm{Soil}}}\right) \tag{2}$$

where $\mathrm{NDVI_{Max}}$ represents fully transpiring vegetation and $\mathrm{NDVI_{Soil}}$ is the NDVI of bare soil where ET is assumed to be zero. $\mathrm{NDVI_{Max}}$ was selected from histograms of Cienega NDVI values in 1994, 2006 and 2011 when vegetation was at maximal greenness due to fires that removed that during the dormant season ($\mathrm{NDVI_{Max}} = 0.720$ over these years). $\mathrm{NDVI_{Soil}}$ was set at 0.078, the mean value of bare soil from dune areas adjacent to the Cienega.

Following Groeneveld et al. (2007), ET was calculated as:

$$\mathrm{ET} = \mathrm{NDVI} * (\mathrm{ET_o}) \tag{3}$$

where $\mathrm{ET_o}$ is potential ET from a fully transpiring plant canopy determined from meteorological data. While this method of estimating ET is only an approximation, Groeneveld et al. (2007) reported an r^2 of 0.94 for ET determined from single summer Landsat images and annual ET measured at 15 moisture flux tower sites set in western U.S. plant communities.

$\mathrm{ET_o}$ was calculated by the Blaney-Criddle formula (Brouwer and Heibloem, 1986).

$$\mathrm{ET_o} = p(0.46T_{\mathrm{mean}} + 8) \tag{4}$$

where p is day light hours determined from Table 4 in Brouwer and Heibloem (1986) by month and latitude and T_{mean} is mean monthly air temperature, obtained from the Yuma, Arizona AZMET station (AZMET, 2012). Evaporation from the open water portion of the marsh was assumed to be equal to $\mathrm{ET_o}$. ET estimates for 2009–2011

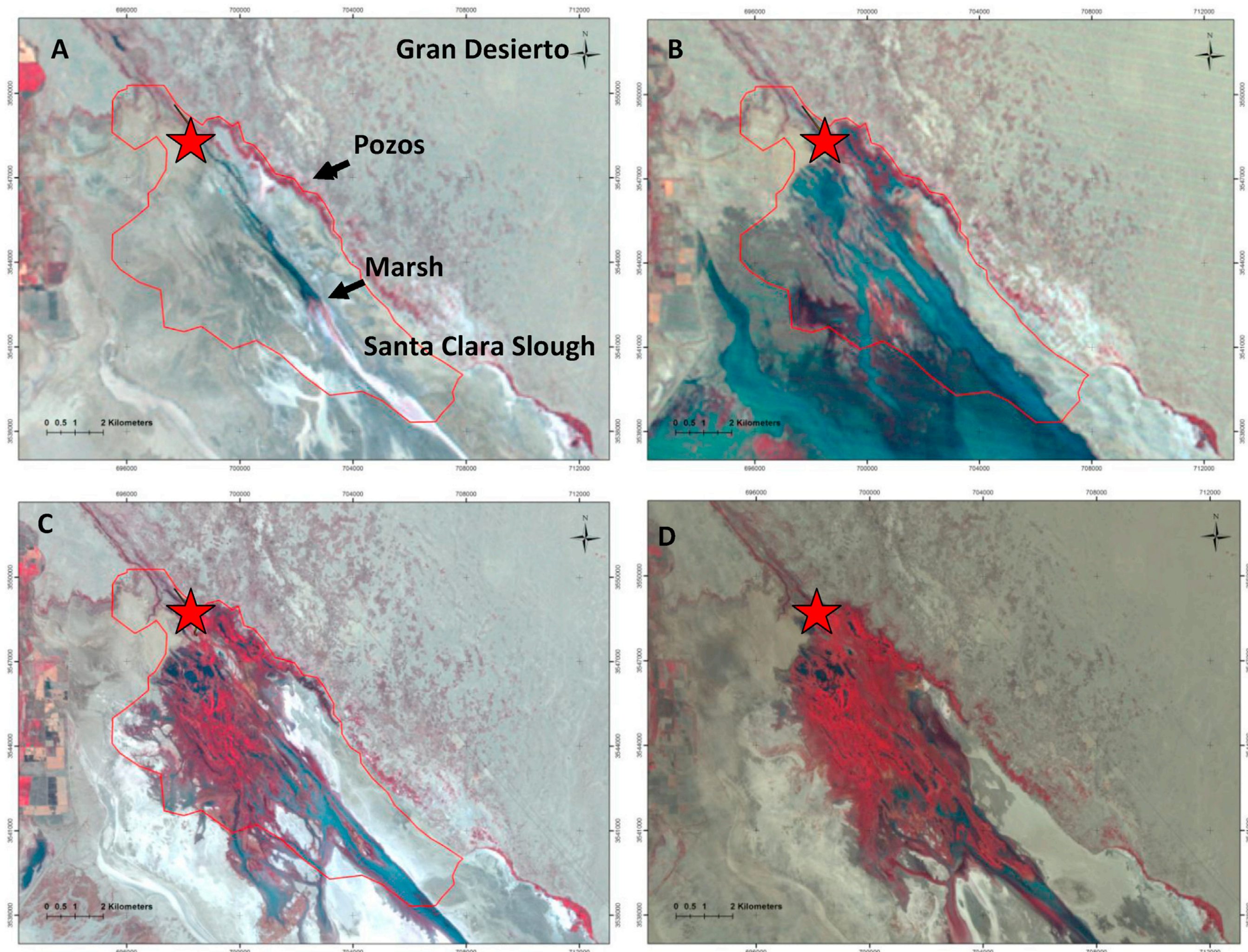

Fig. 2. Development of the Cienega de Santa Clara showing Landsat images for the years 1975 (A), 1985 (B), 1990 (C) and 1995 (D). Red star shows the entry point for MODE canal water. Vegetation is shown as false-color red for reflectance by the NIR band. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

were validated by comparison to ET determined by a salt and water balance approach for those years (Glenn et al., 2012).

2.3. Other data sources

Daily flow rates of the Wellton-Mohawk Bypass Drain water were determined from the International Boundary and Water Commission (IBWC) gauging station at the Southerly International Boundary (http://www.ibwc.state.gov/wad/DDQWMSIB.HTM). Monthly salinity values of MODE water were obtained on request from the IBWC U.S. Section (El Paso, TX).

3. Results

3.1. Time course of marsh development

Figs. 2 and 3 illustrate the time course of marsh development from 1975 to 2011 at approximately five year intervals, based on Landsat imagery. In 1975 the MODE canal had not yet been constructed and the future discharge point was a mudflat at the north end of the Santa Clara Slough in the intertidal zone of the Colorado River (Fig. 2A). The point at which the El Indiviso line enters the Gulf of California (Nelson et al., 2013) is visible as a low area partially filled with local agricultural drain water from the Riito canal (Glenn et al., 2012). Also visible is a fringe of natural vegetation supported by artesian springs along the escarpment between the tidal zone and the Gran Desierto dunes on the eastern edge of the future Cienega. By 1980 discharge of MODE water had created a large brackish pool of water in the northern part of the Santa Clara Slough, with marsh vegetation starting to develop at the entry point of the MODE canal and in high spots within the flooded area (Fig. 2B). Marsh vegetation occupied more area than open water by 1985 (Fig. 2C) and continued to expand through 1995 (Figs. 2D and 3A), by which time the final vegetated footprint of the Cienega was established. See Mexicano et al. (2012) for a detailed description of the composition of the wetland based on high-resolution Quickbird imagery.

A series of permanent, open-water lagoons also developed at apparent deeper-water locations in the Cienega (compare locations of open water lagoons in Fig. 3A with initial pattern of flooding, Fig. 2B). The overall area of the Cienega and the vegetation footprint were stable between 1995 and 2011 (Fig. 3A–D). The 2011 image (Fig. 3D) shows the effect that a spring fire had on the vegetation; the fire cleared out accumulated thatch and resulted in a flush of new vegetative growth over much of the marsh by July 2011 (see also Section 3.3).

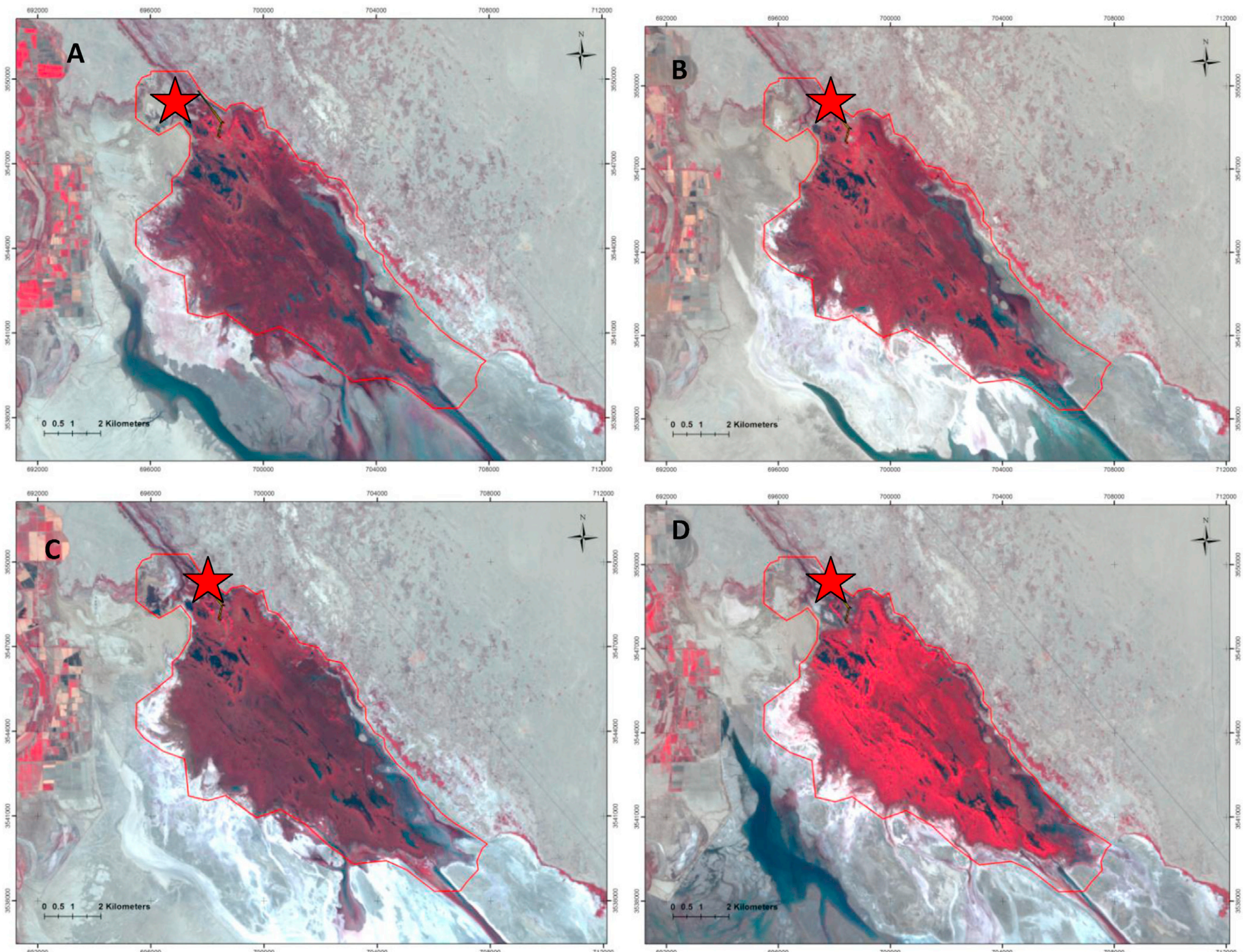

Fig. 3. Development of the Cienega de Santa Clara showing Landsat images for the years 2000 (A), 2005 (B), 2010 (C) and 2011 (D). Red star shows the entry point for MODE canal water. Vegetation is shown as false-color red for reflectance by the NIR band. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The main plant species in the Cienega is *T. domengensis*(dominant and subdominant species are in Table 2) (Zengel et al., 1995). However, colonies of *P. australis* have developed near the entry point for water, growing in shallower areas created by silt deposited by inflow water (Fig. 4). These patches of *P. australis* have been stable in size and location from 1995 to the present.

3.2. *Stability of vegetated area, vegetation vigor, ET and inflow and outflow volumes and salinities*

The vegetated area of the marsh and vegetation vigor were determined by NDVI values on Landsat imagery. Although images were not corrected for atmospheric effects, the minimum, maximum and mean NDVI values were stable over images (Fig. 5). The small dip in maximum and mean NDVI noted in 1983 and 1984 were due to flooding of the image area due to high flows in the Colorado River (Nelson et al., 2013), which reduced mean values as NDVI of water is negative, and reduced maximum values as the agricultural fields in the image area which normally produced the highest NDVI value were fallowed due to lack of access. Open water areas within the Cienega had higher (less negative) NDVI values than ocean values because the Cienega water was shallow and the underlying soil was visible (see Mexicano et al., 2012).

Table 2
Dominant and subdominant plant species in the Cienega de Santa Clara.

Species	Notes
Typha domingensis (southern cattail)	Dominant emergent species; present throughout marsh
Shoenoplectus americanus, *S. maritimus* (three square, alkali bulrush)	Subdominant species present throughout marsh
Phragmites australis (common reed)	Forms dense monocultures on silt mounds near MODE entry point
Najas marinas (spiney niad)	Most common submerged aquatic species, dominant in open-water lagoons
Distichlis spicata, *D. palmeri* (salt grass, Palmer's salt grass)	Saltgrasses in shallow water around periphery of marsh
Allenrolfia occidentalis, *Tamarix ramosissima* (iodine bush, saltcedar)	Halophyte shrubs found on high ground within marsh
Juncus cooperi (Spiney rush)	Emergent species in shallow water near MODE entry point
Ruppia maritima (widgeon grass)	Submerged aquatic species found in saline outflow at south end of marsh

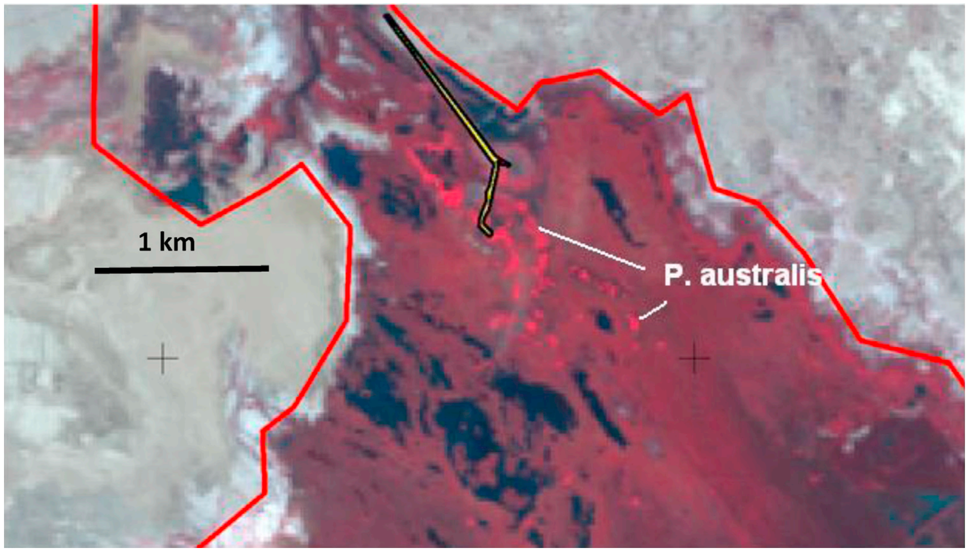

Fig. 4. Close-up 1995 image of the Cienega de Santa Clara at the entry point for MODE canal water (yellow line), showing the development of *Phragmites australis* (brighter red spots) on silt mounds around the mouth of the canal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The vegetated area of marsh increased up to 1995, when it stabilized at about 4200 ha (Fig. 6A). Flows in the MODE canal decreased from an initial value of about 7 $m^3 s^{-1}$ in 1978 to 4–5 $m^3 s^{-1}$ by 1995–1997, and remained in that range through 2010 (Fig. 6B). A notable reduction in flows took place in 1993 due to floods on the Gila River in the Wellton-Mohawk Irrigation District, which required the canal to be closed for repairs for an extended period. Salinity decreased slightly from 3.5 $g L^{-1}$ in 1978 to 2–3 $g L^{-1}$ from 1995 to 2011, with dips recorded in 1983, 1993 and 1997 when flood waters were conveyed to the Cienega in the MODE canal. Mean NDVI values of the vegetated portion of the marsh rose from 1978 to 1984 but have been remarkably stable since then (Fig. 6C). Flows have been relatively stable on a monthly basis as well, ranging from a low of 3.5 $m^3 s^{-1}$ in August to 5.2 $m^3 s^{-1}$ in November (Fig. 7).

ET was estimated from summer NDVI values by assuming a fixed relationship between NDVI and ET_o. Although only an approximation of actual ET, these estimates allow a calculation of the annual water balance in the Cienega. ET losses by vegetation in the Cienega have been steady at about 1000 mm $year^{-1}$ since the 1980s, about half of ET_o (Fig. 8A). Total ET was 23% higher when

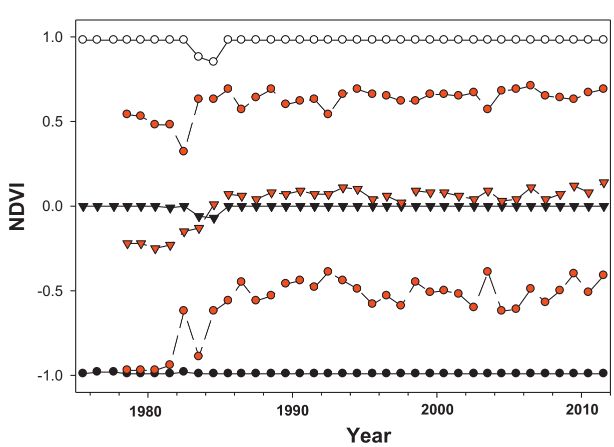

Fig. 5. Minimum (closed circles), mean (black triangles) and maximum (open circles) NDVI values for whole Landsat images, 1975–2011, and for values within the footprint area of the Cienega de Santa Clara (red symbols). A separate area of interest file was prepared for the Cienega each year as it increased in area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

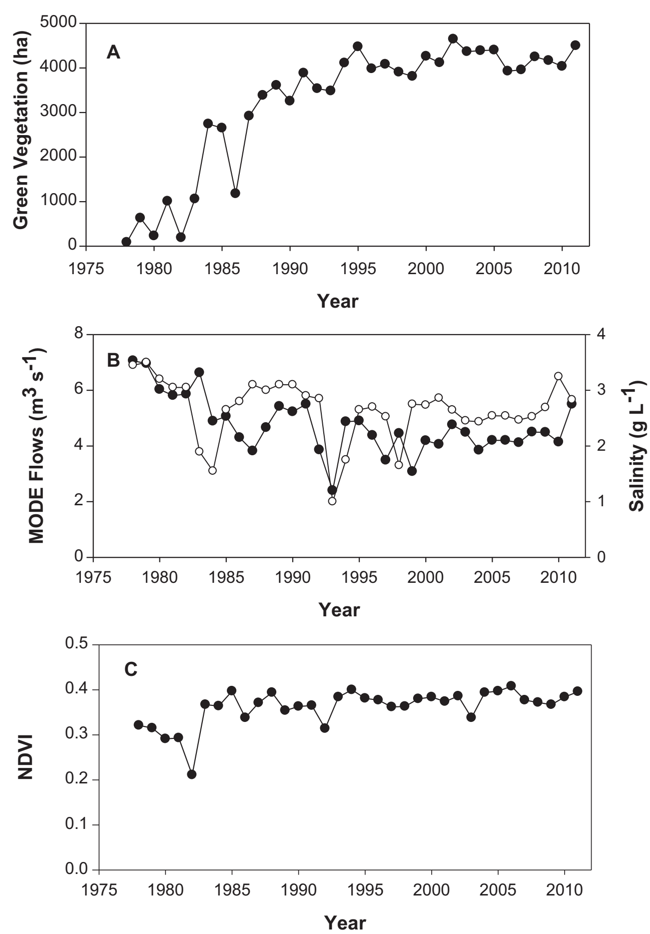

Fig. 6. (A) Vegetation development; (B) MODE inflow rates (closed circles) and salinities (open circles) and (C) mean NDVI for the Cienega de Santa Clara, 1978–2011.

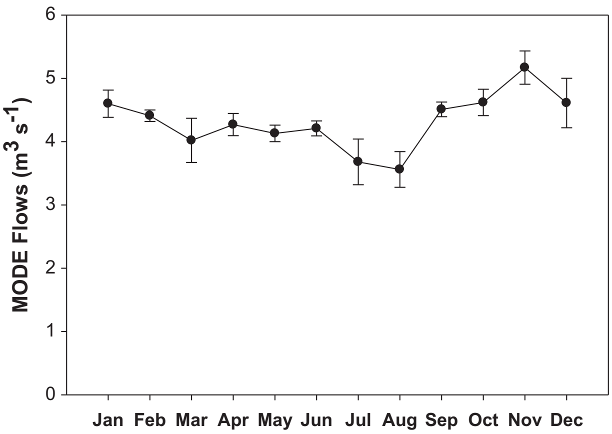

Fig. 7. Mean monthly inflow rates of MODE water, 1978–2011. Error bars are standard errors of means.

open water evaporation is added in. Landsat total ET estimates for the period 2009–2011 were 1263 mm year^{-1} (SE = 34), very close to the value of 1270 mm year^{-1} estimated by a salt and water mass balance approach (Glenn et al., 2012). However, both methods are subject to errors on the order of 20% (Glenn et al., 2012).

Total vegetation water use was calculated by multiplying the annual vegetation ET rate by the area of vegetation. Vegetation water use increased up to 1995 as the marsh grew but since then has consumed about 30% of annual inflows (Fig. 8B), with the rest

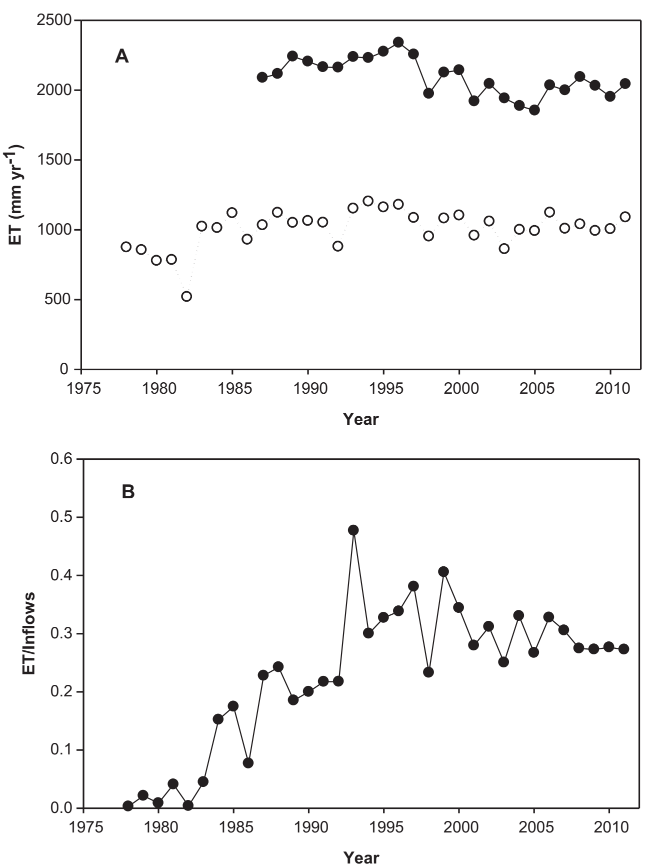

Fig. 8. (A) Potential ET (closed circles) and ET by vegetation in Cienega de Santa Clara, 1978–2011 and (B) fraction of inflow water consumed by vegetation in transpiration.

lost as open water evaporation (7%) within the marsh and as outflows into the Santa Clara Slough to the south (73%).

3.3. Effects of salinity and fire on NDVI

Mean annual NDVI was significantly correlated with salinity ($P < 0.05$), although the correlation coefficient was low ($r = 0.37$). The correlation was mainly due to the reduction in salinity and increase in NDVI during the period 1978–1995. At least three major winter or spring fires have been documented in the Cienega, with over 50% of all vegetation burned over in 1994, 2006 and 2011. Histograms of NDVI values for summer Landsat scenes in the year before a fire and in the year of the fire shows a marked upward shift in peak NDVI (Fig. 9). Fires burned out accumulated thatch, allowing more light to penetrate into the canopy to stimulate new shoot growth from rhizomes.

4. Discussion

4.1. Stability of inflows and vegetation over time

Although there have been several brief interruptions in water delivery, inflow volumes and salinities have been remarkably stable over the 35 year life of the Cienega. The salinity is beyond the optimal salinity for growth of *Typha domingensis* (Glenn et al., 1995; Baeza et al., 2013) the dominant species in the marsh. However, 2–3 g L^{-1} TDS is sufficiently low to maintain vigorous stands of this species in the Cienega as also reported for California coastal wetlands (Beare and Zedler, 1987). Only 30% of the inflow water is actually consumed in transpiration by the vegetation. Most of the outflow occurs during the dormant period for *T. domingensis* (November to March), due to low ET_o, and shading of the water surface by the dormant vegetation (see monthly estimates of ET in Glenn et al., 2012). Outflows fall to near-zero during summer when ET is at its maximum.

Stable open water lagoons support near-monocultures of the submerged aquatic plant, *Najas marinas* (Zengel et al., 1995), which is considered an excellent food source for waterfowl and other aquatic birds (Tarver et al., 1986). As a consequence of the steady inflows, the Cienega is flushed about five times per year, and has avoided a gradual increase in salinity as has occurred in other wetlands that tend to receive flushes of agricultural drain water on a seasonal basis, followed by dry periods (Lemly, 1994). During the period 2009–2011, mean salinity in the marsh was 3.73 g L^{-1} TDS, well within the tolerance range of *T. domingensis* for vigorous growth and reproduction (Beare and Zedler, 1987; Glenn et al., 1995; Baeza et al., 2013).

4.2. Selenium, pesticides and other toxicity issues

Although not the topic of this study, selenium, trace metals and pesticides have been periodically monitored in water, sediments and biota in the Cienega (García-Hernández et al., 2000, 2001, 2006). Pesticide levels are low, as is typical of subsurface drain water from agricultural areas after the water passes through the soil profile (Lemly, 1994). However, selenium and trace metals can be major problems in wetlands receiving agricultural drainage water (Lemly et al., 1993; Lemly, 1994). Selenium was identified as a possible chemical of concern in 2000 (García-Hernández et al., 2000), but has not bioaccumulated to levels of concern in sediments, fish or birds in the marsh (García-Hernández et al., 2001, 2006). Levels in 2012 were similar to levels measured in 2000 (Garcia-Hernandez and Flessa, in press), suggesting the levels have reached a non-toxic equilibrium level due to the flushing action of the inflows.

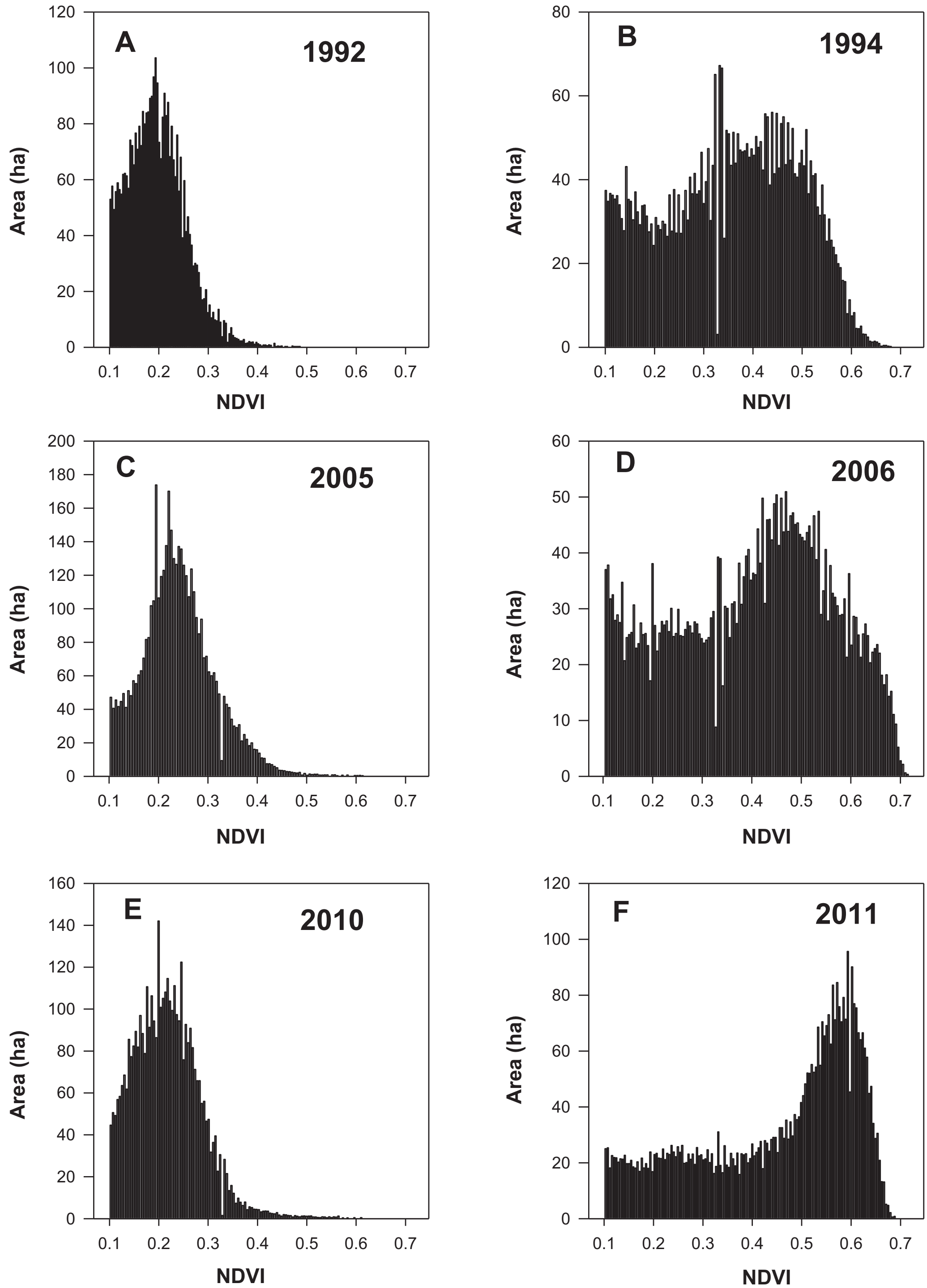

Fig. 9. Effect of fire on the distribution of summer NDVI values in Cienega de Santa Clara, comparing non-fire years (A, C and E) with years in which winter/spring fires removed thatch (B, D and F).

4.3. Habitat value of the Cienega

The Cienega was first noted as a valuable aquatic ecosystem in 1989 (Eddleman, 1989), during a brief study of the food chain organisms including invertebrates, fish and birds. It was subsequently found to provide nesting and wintering habitat to a diversity of waterbirds, especially for the largest remaining population of the endangered Yuma clapper rail (Abarca et al., 1993; Piest and Campoy, 1998; Hinojosa-Huerta et al., 2001, 2002), with an estimated abundance of 8600 individuals during 2011 (Hinojosa-Huerta et al., in press). Periodic monitoring of the Yuma clapper rail from 1998 to 2012 showed no overall change in the population over time (Hinojosa-Huerta et al., 2001, 2008a,b).

The Cienega also provides important breeding habitat for other marshbirds, including California Black Rail (*Laterallus jamaicensis coturniculus*, listed as endangered in Mexico), Virginia Rail (*Rallus* *limicola*, listed as species with special protection in Mexico), and Least Bittern (*Ixobrychus exilis*) (Hinojosa-Huerta et al., in press). The three are considered priorities species within the Lower Colorado River Multi-Species Conservation Plan (LCR-MSCP, 2004).

Due to the extent and quality of habitat, the Cienega is a critical stopover and wintering site for migratory waterbirds in the Pacific Flyway. This wetland provides habitat for 54 species of migratory shorebirds and waterfowl in winter, with concentrations ranging from 150,000 to 300,000 individuals feeding in the lagoons within the northern vegetated portion and in the Santa Clara Slough to the south of the Cienega (Gomez-Sapiens et al., in press).

The Cienega also supports the endangered pupfish (*Cyprinodon macularius*) in shallow areas on the periphery of the marsh (Zengel and Glenn, 1996). Overall, the Cienega is a key part of the Colorado River complex of habitats, which support equal or greater numbers and diversity of wildlife as the Salton Sea and other critical habitat areas on the Pacific Flyway (Getches, 2003).

4.4. Factors contributing to the stability and habitat value of the Cienega

The Cienega appears to be an exception to the generalization that agricultural drain water degrades the quality of wetlands, leads to toxicity effects and cannot support high quality wildlife habitat in the long run (Lemly et al., 1993; Lemly, 1994; Letey, 2000). Several factors appear to be responsible for its stability over time. The MODE water inflow rates and salinities are remarkably stable over seasonal cycles and over years. The Wellton-Mohawk Irrigation District has a permanently high perched aquifer, recharged by surface flows and underflows from the Gila River, and from application of Colorado River water to the fields (Leitz and Ewoldsen, 1977). From about 1995 to the present the flows have been remarkably steady at 4–5 $m^3 s^{-1}$ and 2–3 $g L^{-1}$ TDS, with flows varying by less than 25% from month to month (International Boundary and Water Commission, 2012), and with salinities remaining within the tolerance limit of the dominant vegetation at all times (Glenn et al., 2012).

The winter flows might be especially important in preventing the accumulation of salts and chemicals of concern, as they flush the Cienega several times during the dormant period of the vegetation in winter. Furthermore, the Santa Clara Slough, which receives the outlflow water, is flushed by tides on an approximately monthly basis (Nelson et al., 2013). Hence, key factors contributing to the stability of the Cienega are its stable hydroperiod, flushing flows, and perhaps most important, the fact that it is an open system connected to the Gulf of California.

The stability of the main vegetation units is due to the fact that *T. domingensis*, *N. marinas* and *P. australis* frequently form climax communities in marshes. In fact all three are considered invasive species in some wetland systems (Kaplan, 2012). In the Cienega they are distributed according to depth of water. *P. australis* requires shallow water and aerated soils (Hellings and Gallagher, 1992; Wijt and Gallagher, 2006), which occurs on silt deposits near the MODE entry point and along the periphery of the marsh. *T. domingensis* grows under anaerobic conditions in water up to 1.15 m deep (Grace, 1989), while *N. marinas* dominates the open lagoon areas where water is apparently too deep for *T. domingensis*. The combination of dense *T. domingensis* stands and open water lagoons with submerged aquatic vegetation has created valuable habitat for a wide variety of marshbirds, shorebirds, and other waterfowl (Abarca et al., 1993). Vegetation vigor and marshbird habitat value are also markedly stimulated by occasional fires, which release nutrients back to the water column and remove thatch, improving the habitat value for nesting rails (Conway et al., 2010).

While the Cienega has reached a stable condition over the first 35 years, some longer term processes can impact the future development of the marsh. The continual entry of silt can eventually lead to more shallow water areas, favoring the growth of *P. australis* over *T. domingensis*, with a reduction in marshbird habitat (Kaplan, 2012). Eventually some of the marsh could fill in enough to support the growth of *Tamarix* spp. and other halophyte shrubs, changing portions of the marsh to shrublands. Siltation can be controlled through **co**ntinued dredging and silt removal near the entry point of the MODE canal. However, excessive dredging can release soluble forms of selenium from the sediments into the water column, increasing the selenium hazard (García-Hernández et al., 2000, 2001, 2006), and more research on the siltation problem is needed. Finally, a continued flow of water from the Wellton-Mohawk Irrigation District is not guaranteed, and if farming practices in the district become more water-efficient, flows to the Cienega would be diminished. Operation of the Yuma Desalting Plant would also reduce inflow volumes and increase salinities (Leitz and Ewoldsen, 1977).

4.5. Implications for management

The example of the Cienega de Santa Clara shows that under a proper set of conditions, agricultural drainage water can be used to support valuable wetland habitat. An outlet to the ocean and flushing flows are important elements in creating a flow-through system in which salts and contaminants do not accumulate. The extreme tidal amplitude in the northern Gulf of California contributes to flushing and mixing the outflows from the Cienega into the sea. Not only agricultural brines, but effluents from desalination plants could conceivably be used to support expanded wetlands in the delta of the Colorado River. For example, a collector drain has been proposed to carry desalination plant brine from reverse osmosis plants in southern Arizona for disposal in the vicinity of the Cienega (U.S. Department of Interior, 2004). This water would have salinities similar to MODE water (2–3 $g L^{-1}$ TDS) and, based on the 35 year record of the Cienega, could result in enhanced and sustainable coastal wetland systems that contribute to restoration of wetlands lost through water diversions in the U.S. and Mexico (Glenn et al., 1996). However, increasing the salinity of the Cienega would be harmful to the ecosystem.

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