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Vegetation dynamics in response to water inflow rates and fire in a brackish *Typha domingensis* Pers. marsh in the delta of the Colorado River, Mexico

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ABSTRACT

The Cienega de Santa Clara is a 5600 ha, anthropogenic wetland in the delta of the Colorado River in Mexico. It is the inadvertent creation of the disposal of brackish agricultural waste water from the U.S. into the intertidal zone of the river delta in Mexico, but has become an internationally important wetland for resident and migratory water birds. We used high resolution Quickbird and WorldView-2 images to produce seasonal vegetation maps of the Cienega before, during and after a test run of the Yuma Desalting Plant, which will remove water from the inflow stream and replace it with brine. We also used moderate resolution, 16-day composite NDVI imagery from the Moderate Resolution Imaging Spectrometer (MODIS) sensors on the Terra satellite to determine the main factors controlling green vegetation density over the years 2000–2011. The marsh is dominated by *Typha domingensis* Pers. with *Phragmites australis* (Cav.) Trin. Ex Steud. as a sub-dominant species in shallower marsh areas. The most important factor controlling vegetation density was fire. Spring fires in 2006 and 2011 were followed by much more rapid green-up of *T. domingensis* in late spring and 30% higher peak summer NDVI values compared to non-fire years ($P < 0.001$). Fires removed thatch and returned nutrients to the water, resulting in more vigorous vegetation growth compared to non-fire years. The second significant ($P < 0.01$) factor controlling NDVI was flow rate of agricultural drain water from the U.S. into the marsh. Reduced summer flows in 2001 due to canal repairs, and in 2010 during the YDP test run, produced the two lowest NDVI values of the time series from 2000 to 2011 ($P < 0.05$). Salinity is a further determinant of vegetation dynamics as determined by greenhouse experiments, but was nearly constant over the period 2000–2011, so it was not a significant variable in regression analyses. It is concluded that any reduction in inflow volumes will result in a linear decrease in green foliage density in the marsh.

1. Introduction

1.1. Importance of Cienega de Santa Clara as a remnant wetland in the Colorado River delta

The Colorado River delta in Mexico historically supported several hundred thousand hectares of wetland and riparian habitat (Glenn et al., 2001). Due to construction of upstream dams and the diversion of water for agriculture and urban uses in the U.S. and Mexico, river flows to the delta are much diminished (Nagler et al., 2009a,b). A bright spot in this picture is Cienega de Santa Clara, a large (ca. 5600 ha) emergent marsh in the eastern portion of the delta (Fig. 1) (Glenn et al., 1992; Zengel et al., 1995) This anthropogenic wetland was created starting in 1977 by the discharge of saline agricultural drain water from the Wellton-Mohawk Irrigtion District in the U.S. to the north end of the Santa Clara Slough in Mexico, an area of former mudflats in the intertidal zone of the river. The primary plant species in the Cienega is southern cattail (*Typha domingensis* Pers.), with common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) colonizing shallower areas within the *Typha* stands (Fig. 2) (Zengel et al., 1995). The Cienega is included in the core area of the Biosphere Reserve of the Upper Gulf of California and Delta of the Colorado River, and supports numerous species of resident and migratory water birds, as well as other wildlife (Zengel et al., 1995; Zengel and Glenn, 1996; Hinojosa-Huerta et al., 2001, 2002). It supports 80% of the remaining Yuma clapper rails, a listed endangered species in both the U.S. and Mexico (Hinojosa-Huerta et al., 2001, 2002).

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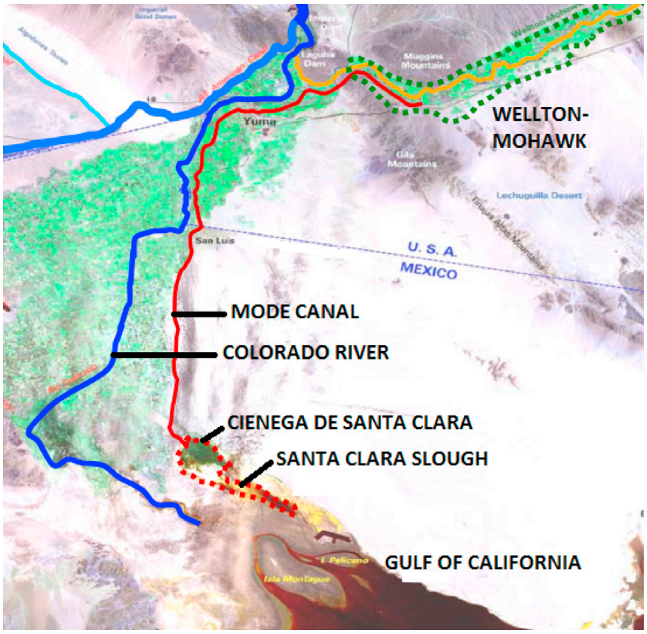

Fig. 1. Locator map showing Wellton-Mohawk Irrigation District, the origin of water flowing to Cienega de Santa Clara in the MODE canal.

1.2. Rationale for the study

Water flows to the Cienega are not guaranteed (Gabriel and Kelli, 2010); in fact, the Cienega was the inadvertent creation of the 1974 Colorado River Basin Salinity Control Act in the U.S. (Glenn et al., 1992). Before this act was passed, Wellton-Mohawk drain water was delivered to Mexico in the Colorado River as part of their allotment of Colorado River water. However, the brackish water caused salinity problems in Mexican agricultural fields, and the U.S. pledged to replace Wellton-Mohawk drainage with higher quality water, and to build the Yuma Desalting Plant (YDP) to ultimately desalinize the Wellton-Mohawk drainage water for delivery to Mexico. The Main Outlet Drain Extention (MODE) canal was built to convey drainage water to the intertidal zone of the Gulf of California while the plant was under construction, and ultimately to receive reverse-osmosis effluent brine from the YDP. However, due to delays and lack of funding, the YDP has only operated during brief test runs: at 33% capacity for 6 months in 1993; at 10% capacity for 3 months in 2007; and at 30% capacity for12 months in 2010–2011. Except during test runs of the YDP, flows to the Cienega have averaged about 4 m s^{-1} at a salinity of 2.8 g L^{-1} total dissolved solids since the MODE became operational (Garcia-Hernandez et al., 2000; Huckelbridge et al., 2010). As a result of these discharges, an internationally important wetland has been created.

Fig. 2. Aerial photograph taken by Francisco Zamora-Arroyo in January, 2010, showing green *Phragmites australis* amidst dormant *Typha domingensis* in the Ciénega de Santa Clara.

The present study was part of a monitoring program designed to detect effects of the YDP on the Cienega during the test run in 2010–2011. The objectives of this study were: (1) map vegetation in the Cienega before, during and after the test run of the YDP to determine effect of plant operation on the marsh vegetation; (2) determine longer term trends in vegetation dynamics in response to inflows, salinity and fire events; and (3) identify the main factors controlling vegetation extent and green foliage density in the Cienega. The overall goal was to contribute to the development of management tools for those agencies and stakeholders charged with maintaining the environmental values of the Cienega while meeting treaty obligations to provide water to Mexico. The research combined ground data with satellite imagery, including high resolution images for detailed vegetation mapping (Quickbird and WorldView-2) and high-frequency, moderate resolution images for detecting vegetation dynamics over time, using the Moderate Resolution Imaging Spectrometer (MODIS) sensors on the Terra satellite. Combining high-spatial-resolution imagery to create vegetation maps with high-temporal-resolution imagery to detect phenological changes in vegetation can be more powerful change-detection tools than either type of imagery alone (e.g., Lunetta et al., 2006).

1.3. Approach to vegetation mapping

Several approaches to vegetation mapping with satellite imagery have been developed (Muller, 1997; Jensen, 2000; Nagler et al., 2005; reviewed in Xie et al., 2008). For example, vegetation types can sometimes be differentiated based on spectral properties, using either supervised or unsupervised classification programs in which satellite bands are combined to produce unique signatures for each vegetation type. Another approach is for trained interpreters to divide the image into polygons representing different vegetation types based on expert opinion. In the present study, there were only two major vegetation types and their locations were stable, and our main interest was in detecting changes in green vegetation density over time. Therefore, we developed an approach based on the Normalized Difference Vegetation Index (NDVI) (Pettorelli et al., 2005). NDVI is calculated as:

$$\rho\text{NDVI} = \frac{\rho\text{NIR} - \rho\text{Red}}{\rho\text{NIR} + \rho\text{Red}} \quad (1)$$

where ρNIR and ρRed are reflectance values in red and near-infrared sensor bands. 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 (Jensen, 2000; Glenn et al., 2008).

NDVI of vegetation is strongly sensitive to chlorophyll absorption of Red and scattering and reflection of NIR by cell walls and stacked layers of cells in leaves, and provides a measure of canopy “greenness” (Glenn et al., 2008). Vegetation indices have been highly successful in assessing vegetation condition, foliage, cover, phenology, and processes such as evapotranspiration (ET) and