Mangrove and Mangrove-Fringe Wetlands in Ostional, Nicaragua: Current Conditions and Pathways Forward

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About the Authors

Dr. Kai Coshow Rains is an ecologist, with a BS in Biochemistry/Biophysics, an MS in Botany, and a PhD in Ecology. She has more than 20 years' experience in natural resources, including more than 12 years' concentrated experience with wetland issues. She is currently a Research Assistant Professor at the University of South Florida and Vice President of Coshow Environmental, Inc. in Temple Terrace, Florida. Her primary research interests are in nutrient cycling and primary productivity, with a particular focus on nutrient uptake by plants through symbiotic relationships with mycorrhiza. However, she also has broad secondary research interests in applied botany and landscape ecology, including plant taxonomy and wetland delineation, functional assessment, and restoration and management. She is fluent in Spanish and enjoys travel and service-related work in Central and South America.

Dr. Mark Rains is an ecohydrologist with a B.A. in Ecology, Behavior, and Evolution, an M.S. in Forestry, and a Ph.D. in Hydrologic Sciences. He currently is an Associate Professor and the Chair of the School of Geosciences at the University of South Florida, the President of Coshow Environmental, Inc. in Temple Terrace, Florida, and the Associate Editor for Aquatic Ecology for the Journal of the American Water Resources Association. His research is focused on (a) local- and landscape-scale hydrological connectivity, (b) the roles that hydrological processes play in governing ecosystem structure and function, and (c) the roles that science plays in informing water-related law and policy. He has additional service-related interests in sustainable water-resources development in poor, rural communities in Latin America and the Caribbean Basin, and extensive experience in consensus building at the intersection of science and policy in wetland regulatory programs, including past and ongoing work related to providing the scientific justification underlying the federal definition of "waters of the US" subject to regulation under the Clean Water Act.

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EXECUTIVE SUMMARY

The mangrove and mangrove-fringe wetlands in Ostional, Nicaragua are a mix of intact forest and degraded agricultural lowlands. The intact forest is along the Ostional River, between the coastal road and the ocean, and totals 16.7 hectares; the degraded agricultural lowlands are to the south and are largely composed of ditched, drained, cleared, and, in many cases, abandoned or otherwise neglected fields, and total 23.1 hectares.

Impacts to both the intact forest and degraded agricultural lowlands include regional development, water use, waste and waste-water disposal, and invasion by non-native species. Impacts to the degraded agricultural lowlands also include ditching and draining, agriculture (including abandoned agricultural fields), and grazing. In spite of these impacts, wetland hydrology and hydric soils persist in much of the degraded agricultural lowlands, so this area represents an opportunity for restoration.

Restoration of the degraded agricultural lowland could increase the areal extent of the intact mangrove and mangrove-fringe ecosystem by up to 140%. Restoration activities could include acquiring land, filling ditches, planting native species, controlling non-native species, limiting the development of and guiding the use of the mangrove and mangrove-fringe wetlands, conserving water, and treating wastewater. Community engagement could be enhanced by clearly connecting the health of the mangrove and mangrove-fringe wetlands to community-based ecotourism and, thus, to jobs, such as through the development of interpretive trails and the training of local guides and docents (Bosire et al. 2008).

If restoration is undertaken, a monitoring program should be implemented to ensure that the full mangrove and mangrove-fringe ecosystem is trending toward reference standard conditions. Monitoring could be done with remote sensing data and modeling, or onsite data collection and comparison to reference conditions, be it through metric-by-metric comparisons, through an assessment model, or through opportunistic use of information gleaned from detailed studies. In any case, little baseline data exists, so any monitoring program would need to be committed to long-term monitoring and an adaptive management strategy that allows monitoring protocol, including reference standard benchmarks, to be changed as pre-project uncertainties become post-project outcomes.

This report is accompanied by a detailed geodatabase.

INTRODUCTION

Mangroves and mangrove-fringe wetlands cover ~240,000 km^2 of sheltered subtropical and tropical coasts between latitudes 24° N and S where mean annual temperatures are >20°C (Lugo 1990; Dawes 1998). They provide numerous ecological functions and goods and services. Mangroves support estuarine and near-shore marine productivity, in part by providing critical habitat for juvenile fish and through the export of nutrient-rich water (McKee 1995; Rivera-Monroy et al. 1998) or plant, algal, or animal biomass (Zetina-Rejón et al. 2003). Mangroves also protect coastal habitats against the destructive forces of hurricanes, typhoons, and tsunamis (e.g., Kandasamy and Narayanasamy 2005; Granek and Ruttenberg 2007; Alongi 2008).

Mangroves and mangrove-fringe wetlands can play vital roles in supporting regional and local economies, either directly through the goods and services they provide or indirectly through the tourism they can support. Therefore, sound management and conservation strategies are essential to ensure ecosystem function despite rapid development and rapidly shifting demographics (Valiela et al. 2001; Alongi 2002; Martinuzzi et al. 2009). This need is amplified in rapidly developing regions of impoverished countries, where the immediate and day-to-day needs of the people often take precedence over the sustainable use of the natural resources.

This report is centrally concerned with the past and potential future conditions of mangroves and mangrove-fringe landscapes in Ostional, Nicaragua. This region hosts a mix of intact but imperiled ecosystems and already degraded ecosystems on a coast that is undergoing rapid development. Unguided, these areas are likely to be further and irreparably degraded by this rapid development; guided, they could be restored and maintained, creating a sustainable resource that could be embedded in the ecology and economy of the region. This report is a first step toward that latter future. This report does not represent an end. Rather, this report represents a beginning. A great deal of thought, discussion, data collection and analysis, and decision-making remain. That all starts here.

SITE DESCRIPTION

Geography

The study site is located on the south-west coast of Nicaragua, adjacent to the town of Ostional (Figure 1). Ostional has ~130 households, all of whom rely upon groundwater derived from a shallow alluvial aquifer and all of whom discharge wastewater directly to the land surface and/or to septic systems of varying quality and functionality (Weeda 2011). The primary economic drivers are fishing and agriculture, though tourism is becoming increasingly important. Land cover/land use (LULC) in the region is predominantly forest (52 %), pasture (28%), and agriculture (20 %) (UNA 2003).

Regional and Local Geology

The region lies in the Pacific Coastal Plain geologic province, a narrow strip of land composed of Pliocene to Cretaceous deposits (McBirney and Williams 1965). Most of these deposits derived from submarine and coastal sediment deposition during sea-level regression-transgression, though some deposits originated from volcanic activity. Deposits are primarily sandstones, limestones, and shales along with volcanic breccias and tuffs (McBirney and Williams 1965; Swain 1966). The subduction of the Cocos Plate under the Caribbean Plate caused compression forces that resulted in the Rivas Anticline, a NW-SE trending feature characterized by small but steep-sloped coastal mountains with a fault and fracture system parallel to the ridge of the anticline (McBirney and Williams 1965; Swain 1966).

Figure 1. The study site is located on the south-west coast of Nicaragua.

The mangrove and mangrove-fringe ecosystem that is the focus of this study are located on a small delta and coastal plain created where the Ostional River flows into the Pacific Ocean (Figure 1). The hydrostratigraphy includes 1-5 m of clay-rich surface sediment, overlying 5-10 m of coarse-grained alluvium, overlying shale of unknown depth, as suggested from an analysis of six drill logs obtained along a short transect just south of the Ostional River (Calderon et al. 2014) and of one drill log at the primary water-supply well north of the Ostional River (Daniel Sanchez Personal Communication) (Figure 2).

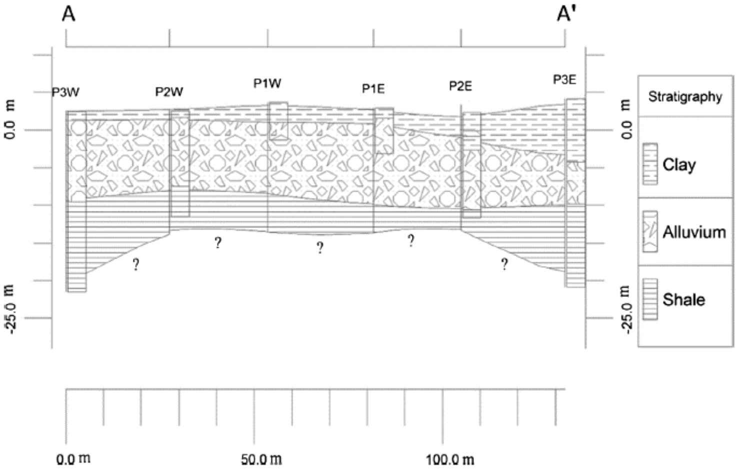


Figure 2. Hydrostratigraphic cross-section inferred from six drill logs along a short transect south of the Ostional River (Calderon et al. 2014). Data are consistent with the drill log from the primary water-supply well located north of the Ostional River (Daniel Sanchez Personal Communication).

Climate and Hydrology

According to the Koppen Climate Classification, the climate is Tropical Savannah Climate (Aw). Total annual precipitation is 1660 mm, approximately 93% of which falling during a pronounced rainy season during May-November (Figure 3; http://en.climate-data.org/location/431714/). In July-September, there is a pronounced decline in rainfall, which is known as the Midsummer Drought (Magaña et al. 1999). Discharge on the Ostional River is strongly seasonal, varying between <0.1 m^3s^{-1} in the dry season to >10 m^3s^{-1} in the wet season (CIRA 2008). The alluvial aquifer is relatively resilient, with hydraulic heads in monitoring wells in the alluvial aquifer being steady throughout the year with small increases in the peak wet season during a normal year (Calderon and Uhlenbrook 2014; Calderon et al. 2014) and hydraulic heads in the water-supply well only 2 m below normal in August 2015 after three years of lower-than-normal rainfall (Daniel Sanchez Personal Communication).

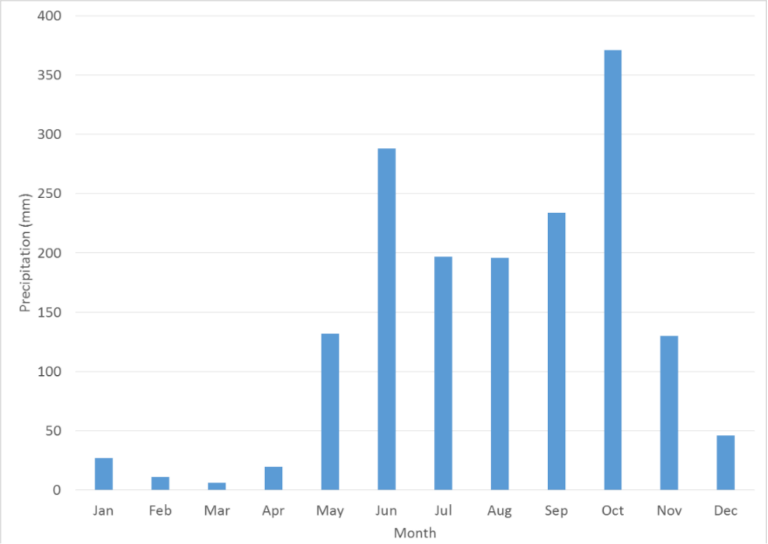


Figure 3. Mean monthly precipitation in Ostional, showing the pronounced wet and dry seasons.

METHODS

Defining the Study Units

The objectives of this project were to assess the current conditions of the mangrove and mangrove-fringe ecosystem and to determine if opportunities exist to restore degraded portions. Therefore, the general study site was initially divided into two study units: the mangrove and mangrove-fringe forest along the Ostional River south of Highway 224, hereafter called the intact forest, and the degraded mangrove and mangrove-fringe wetlands, hereafter called the agricultural lowland. The intact forest unit was subsequently divided into two subunits, the mangrove, delineated previously by Paso Pacifico, and the terrace forest, a mosaic of second growth forested wetlands and non-wetlands situated between the community of Ostional and the mangrove. These study units were defined and delineated through a pre-field review, a field survey, and interviews with key informants.

Pre-Field Review: Collect Existing Data and Data Products

The first step of this investigation was to review existing reports and acquire pertinent geospatial data and data products. Existing reports were identified through online databases, and included information on both regional and local geology and hydrogeology (e.g., McBirney and Williams 1965; Swain 1966; UNA 2003; CIRA 2008; Weeda 2011; Calderon et al. 2014; Calderon and Uhlenbrook 2014). Geospatial data products were obtained from Paso Pacifico, Google Earth, and ESRI/ArcGIS Online (Table 1).

The Mangrove Delineation layer (source: Paso Pacifico), a delineation of a portion of the intact forest was considered a master layer, i.e., no modifications were made to the borders of this layer and all adjacent polygon borders were constructed to abut this layer. The benefit of this approach is that the polygon areas can be summed across polygons without the errors that would be introduced if polygon areas overlapped or if there were gaps between adjacent polygons.

Upon review, it was determined the primary reference aerial imagery layer for this investigation would be the World Imagery composite layer available through ArcGIS online (Ikonos/ Geoeye March 28, 31, 2009; 1 meter resolution, 25.4 meter accuracy). Landsat/GLS and low-resolution Land Use/Land Cover layers were utilized as secondary information sources (Table M1). Detailed topographic data for the study site was not readily available.

Table 1. Source and imagery used in this study.

Source	Layer
Paso Pacifico	Mangrove Delineation
	Land Use/Land Cover 2009
	Aerial Imagery Orthomosaic
Google Earth	Aerial Imagery
ESRI/ArcGIS Online	Basemap: World Imagery (March 2009)
	LandsatGLS/HealthyVegetation
	LandsatGLS/FalseColor
	LandsatGLS/VegetationAnalysis

Field Work

Field work took place on August 2-7, 2015. Both authors were present throughout the entire field effort. Reconnaissance was conducted in all three study units, i.e., the contributing area, the intact forest, and the agricultural lowlands. Data collection, photographs, and observations were made in spatially explicit locations, with all locations being logged on a Garmin Rino 650 handheld GPS and later downloaded into ArcGIS 10.2.2 (Figure 4).

Water levels and flows were measured manually and/or modeled from field measurements. Field chemistry (i.e., temperature, pH, specific conductance, and salinity) of surface-water and groundwater samples were measured with a YSI 556 MPS (Figure 5). Soils were excavated using a hand auger and were described using terminology consistent with the US Department of Agriculture, Natural Resource Conservation Service protocol (Soil Survey Division Staff 1993) and the Munsell Color Chart System (Munesll Color 2000). Given existing time constraints, the authors gratefully relied on the botanical knowledge of Dr. Eric Olson for sight recognition of several vegetation species.

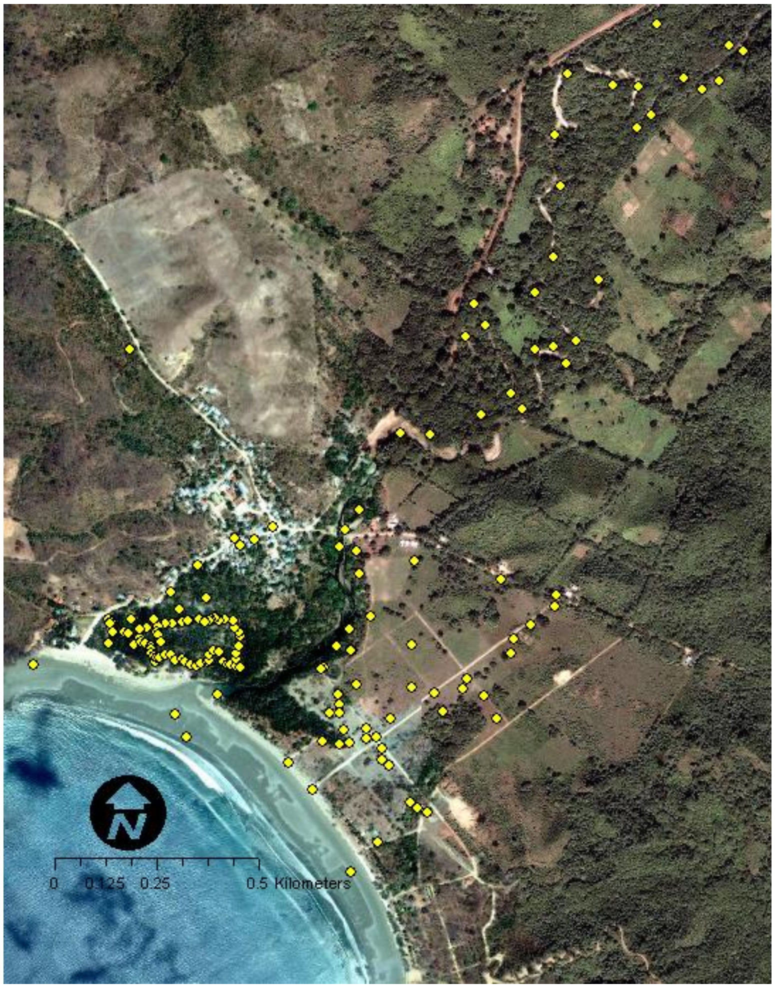


Figure 4. Locations where specific data were collected and/or observations were recorded.

Figure 5. Drs. Mark Rains and Eric Olson collect a groundwater sample from a shallow, hand-dug well in Ostional.

Additional Wetland Delineation

The agricultural lowland was delineated following the definition of a wetland provided by the United States Code of Federal Regulations, specifically 40 CFR 230.3(t) which states that wetlands are “those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions." By this definition, wetlands are delineated based upon three parameters: the presence of wetland hydrology, hydric soils, and hydrophytic vegetation. These parameters can be directly measured or inferred from evidence, such as sparsely-vegetated depressions or fiddler crab burrows (i.e., indicators of wetland hydrology), a soil matrix depleted of color (an indicator of hydric soils), and plant morphological adaptations to life in anaerobic soils (an indicator of hydrophytic vegetation). A key caveat is the term "normal circumstances," which means the conditions that would exist in the absence of any active and discretionary manipulation of hydrology, soils, and/or vegetation. This is a key caveat because it allows the delineation to extend into areas that do not current have all three parameters as long as there is sufficient evidence to suggest that such missing parameters are due to active and discretionary manipulations, such as ditching and draining, the placement of fill, and/or the clearing of natural vegetation (e.g., US ACOE 2011 Regional Supplement to Wetland Delineation: Caribbean Islands).

In the field, the data collection was conducted opportunistically by traversing the area, looking for both direct and indirect evidence of these three parameters. A handheld GPS unit was used to record key locations, including field data collection locations. These key locations were then transferred to ArcGIS where they could be viewed in association with available georeferenced ESRI base maps and other supporting layers (Table 1). The geographic extent of the intact and degraded portions of the mangrove and mangrove-fringe ecosystem were then manually digitized, known as heads-up digitizing, into a polygon feature classes.

Interviews of Key Informants

Interviews with key informants were conducted for background informational purposes only (Figure 6). There was no formal social data collection or analysis. One key interview was with Dr. Eric Olson, Senior Lecturer at The Heller School for Social Policy and Management at Brandeis University, who has worked in northwest Costa Rica and southwest Nicaragua for many years, and is currently developing an interpretive trail in the mangroves and mangrove-fringe wetlands of interest. Another key interview was with Daniel Sanchez, who administers the water-supply well and water-supply system for the community of Ostional. Still other interviews were conducted opportunistically with residents met in the field.

RESULTS AND DISCUSSION

Geographic Extent

The intact forest comprises 16.7 hectares, including 13.2 hectares of mangrove forest and 3.5 hectares of terrace forest (Figure 7). This area is situated along the Ostional River between the coastal highway and the ocean. The agricultural lowland is 23.1 hectares (Figure 7). This area also is between the coastal highway (Hwy 224) and the ocean, but is entirely southeast of the intact forest. Both are largely wetland areas, though inclusions of uplands occur. All are prone to flooding, with river flooding along the Ostional River and aerial flooding (i.e., inundation during intense rainfall due to poor drainage) elsewhere.

Figure 6. Dr. Mark Rains discussing the local geology and water-supply system with Dr. Eric Olson of Brandeis University and Daniel Sanchez of Ostional.

Figure 7. Delineation of the agricultural lowland (yellow line) and the intact forest, which is composed of the mangrove forest (red outline, Paso Pacifico delineation) and high terrace forest (purple line).

Existing Conditions

Geomorphology

The mangroves and mangrove-fringe wetlands are located on a small delta and coastal plain where the Ostional River flows into the Pacific Ocean. Flows on the Ostional River are variable, being very high during high-intensity rainfalls during wet periods and greatly reduced during dry periods (e.g., no water was observed in the channel above the zone near the Hwy 224 bridge during the field visit). Pronounced bank erosion and bed scouring, as well as the abundance of coarse-grained bed deposits, indicate that high flows are highly erosive and transport large volumes of fine-to-coarse-grained sediments (Figure 8).

Figure 8. The Ostional River above the study site has variable flows, but high flows are highly erosive, with evidence including eroded banks, scoured beds, and deposits or coarse-grained bed sediments and large woody debris. Plants have begun to colonize the dry riverbed during this prolonged drought. During our field visit, swarms of butterflies were observed on castor bean growing throughout the river channel.

When flows are high, the Ostional River flows into the ocean; when flows are low, waves and currents create a beach barrier ridge which blocks outflow and maintains surface water in the mangroves and mangrove-fringe wetlands (Figure 9). When the beach barrier ridge is present, the mangroves and mangrove-fringe wetlands function as an interior mangrove, with stable standing water and little Stream flow or tidal flow; when the beach barrier ridge is absent, the mangroves and mangrove-fringe wetlands function as a river-dominated mangrove characterized by unidirectional stream flow (Lugo and Snedaker 1974; Woodroffe 2002).

Hydrology

The mangroves and mangrove-fringe wetlands exist in a complex hydrogeologic setting. Hydrostratigraphy includes 1-5 m of clay-rich surface sediment, overlying 5-10 m of coarse-grained alluvium, overlying shale of unknown depth (Figure 2). The clay-rich surface sediment has low permeability, and perches surface water above on the ground surface and confines groundwater below in the coarse-grained alluvial aquifer (Calderon et al. 2014; Calderon and Uhlenbrook 2014). This can be easily observed, as there can be surface water in the mangroves and mangrove-fringe wetlands a few meters above the static water level in hand-dug wells in the underlying coarse-grained alluvial aquifer (Figures 10). This clay-rich layer is not entirely impermeable; therefore, flow between the surface environment and the underlying coarse-grained alluvial aquifer is slow but nevertheless a hydraulic connection exists (Calderon et al. 2014; Calderon and Uhlenbrook 2014).

As water passes through the coarse-grained alluvial aquifer, it flows beneath the mangroves and mangrove-fringe wetlands and encounters the beach barrier ridge and the ocean. The beach barrier ridge is comprised of mixed cobble, gravel, and sand, and is therefore highly permeable. The groundwater flows through these high-permeability deposits and discharges to the ocean. This groundwater discharge can be readily seen at low tide (Figure 11).

Field measurements indicate the surface water and groundwater are chemically similar to one another, with the salinity of surface water being 0.3±0.0 psu and the salinity of groundwater being 0.3±0.1 psu (Table 2; Figure 12). The region is in a deep and prolonged drought, with little rainfall and surface-water runoff. Most of the remnant surface water can be attributed to groundwater discharge, which was seen occurring in a variety of locations around the perimeter of the intact forest where contacts between different geologic units and abrupt changes in slope create conditions conducive to groundwater discharge. There is some seawater intrusion, as wave setup and tidal pulsing drive seawater into and through the beach barrier ridge, where it mixes with freshwater to form brackish surface water and groundwater in some locations right at the beach barrier ridge (Table 2; Figure 12). However, the general flow direction is from the mangroves and mangrove-fringe wetlands towards the ocean, and groundwater discharge is sufficient to freshen the sea water, lowering salinity from the typical seawater value of 35 psu to values of 25.3±2.5 psu (Table 2; Figure 12). This effect is localized to the area immediately in front of the beach barrier ridge; salinity of a single measurement in the ocean north of the mangrove and at the toe of the cliffs was 31.1 psu.

Figure 9. The integrity of the beach barrier ridge depends upon flows in the Ostional River, being (A) breached when flows in the Ostional River are high (Google Earth, February 2005) and (B) intact when flows in the Ostional River are low (Google Earth, November 2009). At times no surface water can be observed crossing the beach berm.

Soils

Soils in the intact forest and agricultural lowlands were predominantly hydric, particularly in concave microdepressions . Sample site soils are derived from the clay-rich surface sediments and, thus, also are clay-rich. Clay soils have low-permeability and are prone to saturation and ponding water, especially during high-intensity rainfall.

Three hydric soil indictors were frequently observed: 1) soil cracks accompanied by an accumulation of fine-grained surface soil, 2) redoximorphic features in a low chroma matrix, and 3) accumulations of organic matter.

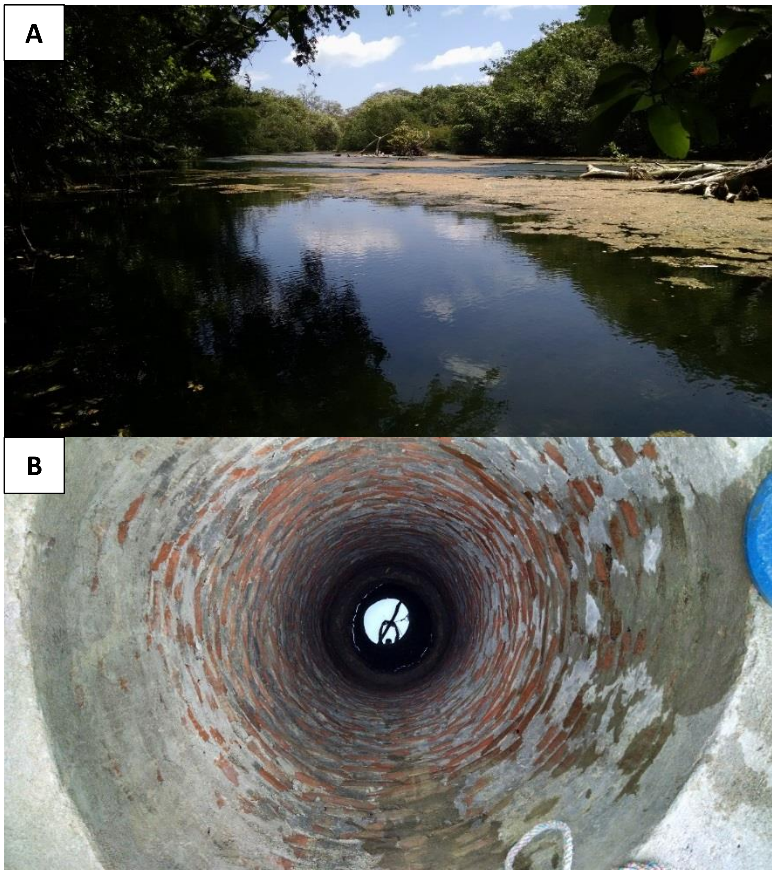


Figure 10. The clay-rich surface sediment perches surface water above and confines groundwater below, which is why there is (A) surface water in the mangroves and mangrove-fringe wetlands but (B) wells must be dug several meters to reach the underlying coarse-grained alluvial aquifer.

Clay soils swell and lose structure when they are inundated. During the dry season, evidence of seasonal ponding in concave landscape positions can be detected by surveying clay soil surfaces for a combination of soil cracks “frosted” with a layer of dried, structureless, fine-grained silt or clay. The surface soil cracks observed commonly in depressions in the agricultural lowlands are indicative of sequential inundation followed by drought (Figures 13 and 14).

Oxidized iron, like rust, is red-orange and is not easily washed away. It is this oxidized iron that provides the background reddish soil colors commonly observed in non-hydric (i.e., non-wetland) soils (Figure 15). When soils are saturated for prolonged periods, the redox potential drops and the oxidized iron typical of well-aerated soils is converted to reduced iron. Reduced iron is colorless and moves easily in water. This reduced iron can be transported away from saturated soils as moves through the soil. Evidence of iron reduction and movement, and, thus, of soil saturation, can be detected in dry soils as an uneven distribution of re-oxidized iron. The background (“matrix”) color is less bright red (“depleted”) and red-orange masses of re-oxidized iron (redoximorphic features) may be observed in soil locations where iron accumulated while it was reduced and mobile. These features commonly occur along roots, at transitions in soil texture, and the edges of seeps where reduced groundwater is newly exposed to oxygen (Figures 11 and 15).

Figure 11. Groundwater discharge from the coarse-grained alluvial aquifer through the beach barrier ridge can be seen at low tide as (A) the wide swatch of permanently wet sediments well above the tide line and (B) as distinct sand sapping and channelized flow at the upslope extent of the wide swath of permanently wet sediments well above the tide line. Note the orange stains where the sand sapping occurs, indicative of iron oxides precipitating where anaerobic groundwater first reaches the surface and reduced iron compounds are oxidized (i.e., “rusted”).

Table 2. Chemical characteristics of water samples for surface water (n = 8), groundwater (n = 4), surface water and groundwater at the beach barrier berm affected by seawater intrusion (n = 3), seawater in front of the mangrove (n = 2), and seawater north of the mangrove at the toe of the cliffs (n = 1). Though sample sizes are small, data are consistent with Calderon et al. (2014) and Calderon and Uhlenbrook (2014).

Water Type	T (°C)		pH		SC (mS/cm)		S (psu)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Surface Water[1]	30.2	2.3	7.9	0.2	627	50	0.3	0.0
Groundwater[1]	28.9	0.3	7.1	0.1	669	186	0.3	0.1
Water at the Beach Berm[2]	27.8	0.6	7.2	0.6	24,240	6,364	13.9	3.7
Seawater at Mangrove[3]	27.3	1.0	8.1	0.0	39,520	3,479	25.3	2.5
Seawater in Bay[4]	28.2	NA	8.2	NA	49,200	NA	31.1	NA

[1] Not including measurements taken at the beach barrier ridge where seawater intrusion occurs

[2] Surface water and groundwater from locations at the beach barrier ridge affected by seawater intrusion

[3] Measurements taken in swash zone in front of mangrove

[4] Measurement taken in swash zone north of mangrove at toe of cliffs

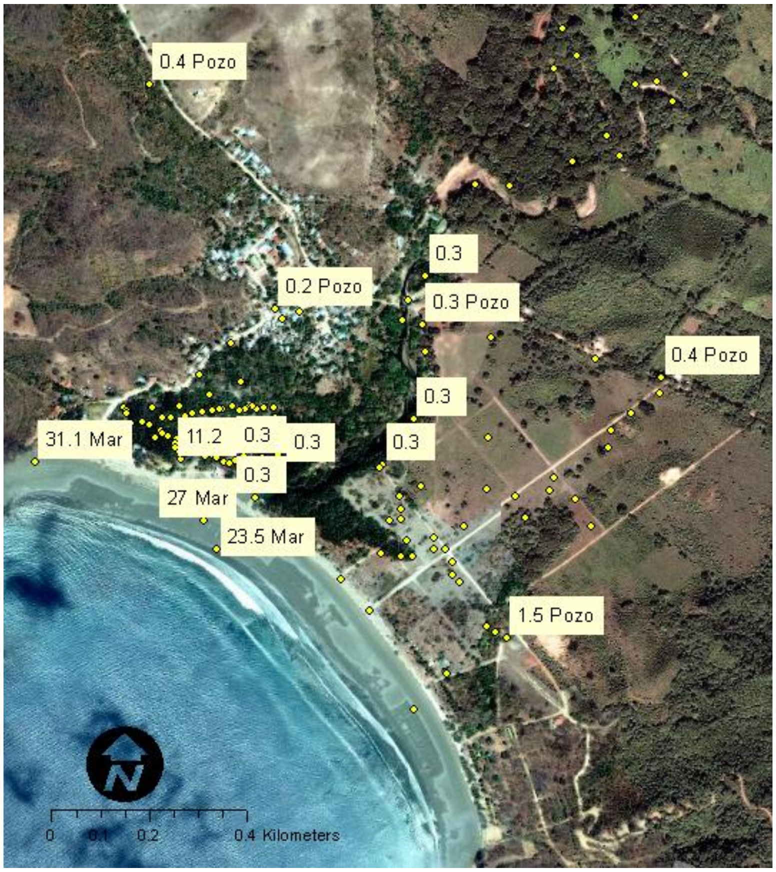
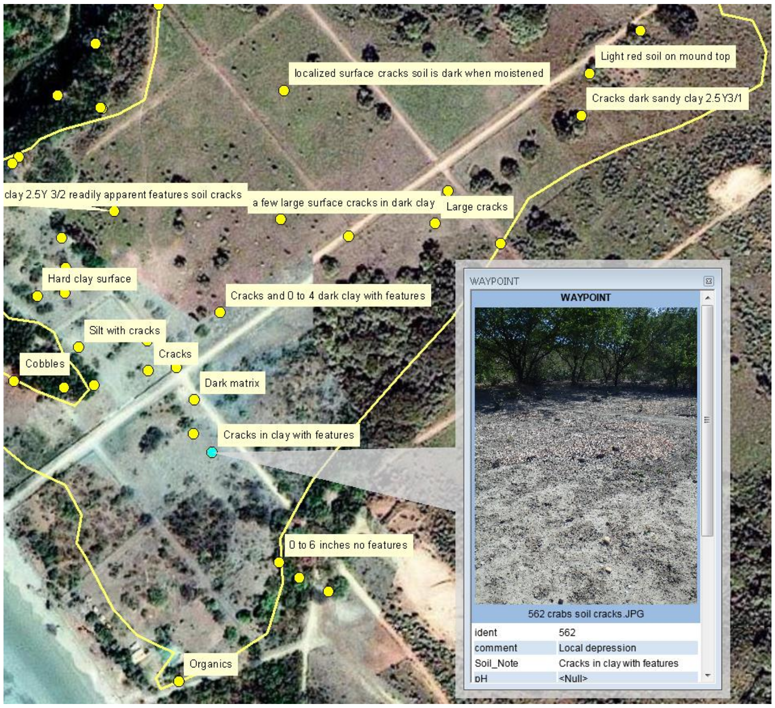


Figure 12. Surface water and groundwater are generally fresh, with salinities around 0.3 psu. Seawater intrudes through the beach barrier ridge, creating brackish surface water and groundwater in some locations directly behind the beach barrier ridge. However, the general direction of groundwater flow is from the mangrove and mangrove-fringe wetlands, through the beach barrier ridge, and into the ocean. These flows can be seen as the dark streaking on the beach above the tide, and they cause a freshening of the nearshore ocean in front of the beach barrier ridge.

Figure 13. Shrink-swell cracks covered with fine-grained silt or clay, characteristic of hydric clay soils.



ident 562
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Soil_Note Cracks in clay with features
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Figure 14 Field-derived evidence of hydric soils in the agricultural area (project geodatabase, map scale is 1:2500).

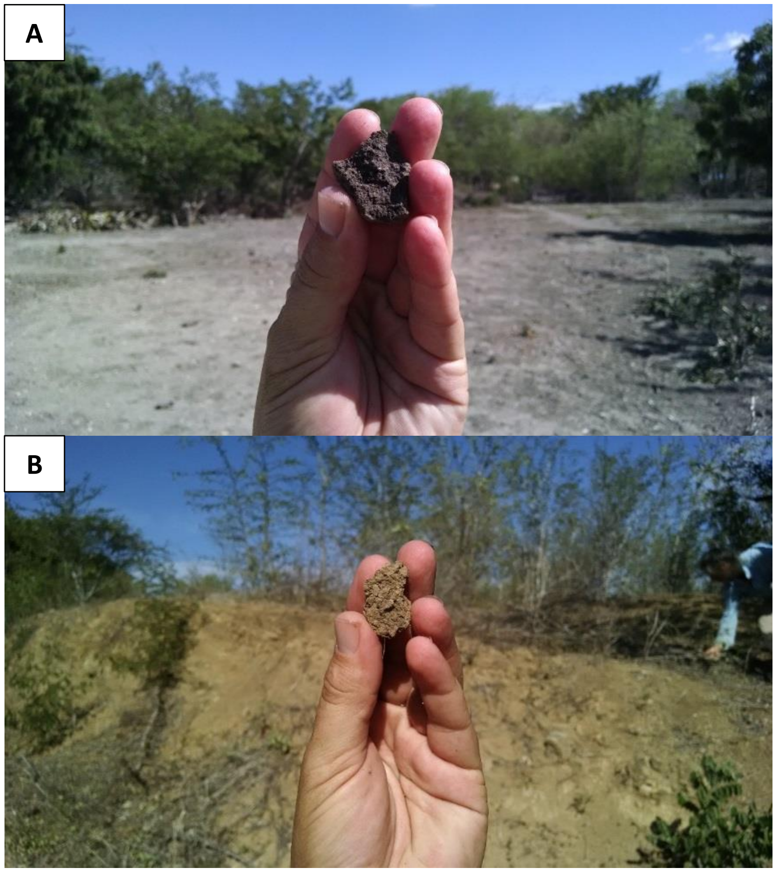

Figure 15. The intact forest and agricultural lowland have (A) hydric soils with inclusions of (B) non-hydric soils.

Vegetation

Vegetation varies greatly across the study site, both between the intact forest and agricultural lowland and over small distances within the intact forest and agricultural lowland (Figure 16). In general, the intact forest supports a diverse array of woody plant species including native trees of the genera *Laguncularia*, *Rhizophora*, *Acacia*, *Hippomane*, and *Pithocellobium*; the non-native and invasive tree species neem (*Azadirachta indica*); and other non-woody notables, such as cacti of the genus *Opuntia* (Figures 17 and 18). Species with dissimilar tolerances for prolonged inundation, e.g., trees of the genera *Rhizophora* and *Acacia*, are often located within meters of each other, with this fine-grained diversity likely correlated with equally fine-grained variability in microtopography (e.g., very small highs and lows) and soil texture (e.g., the ratio of sand to clay) (Figure 16). The herb and shrub layer is sparse allowing for easy passage over well-worn trails by people and by grazing animals (Figure 18). The woody species of the agricultural lowland is less diverse. Much of it has been cleared and apparently abandoned or otherwise neglected, at least during the drought, though some small forest patches remain. There was an abundance of dried herbaceous plants in the agricultural lowlands at the time of the visit (Figure 19).

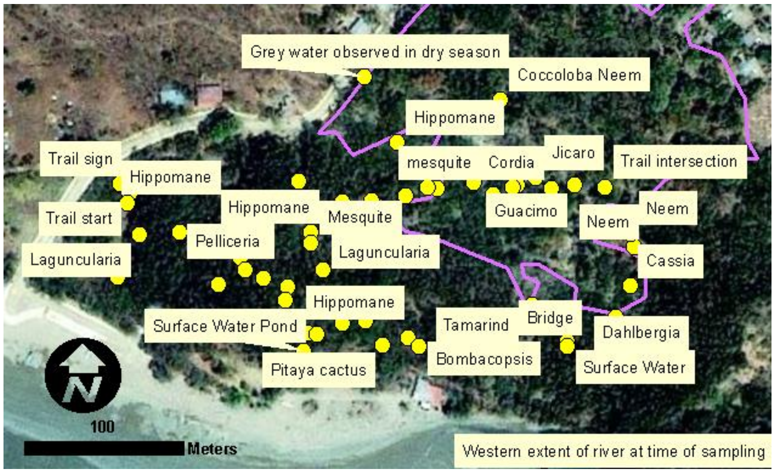

Figure 16. Georeferenced vegetation and hydrology notes provide supporting evidence that biotic and abiotic components of the intact forest can vary significantly over short distances. The purple outline separates the terrace forest from the mangrove (to the south) and from the community of Ostional (to the north).

Figure 17. Woody vegetation in the intact forest is diverse, but includes an abundance of mangrove, including mangrove of the genera *Rhizophora*.and *Laguncularia*

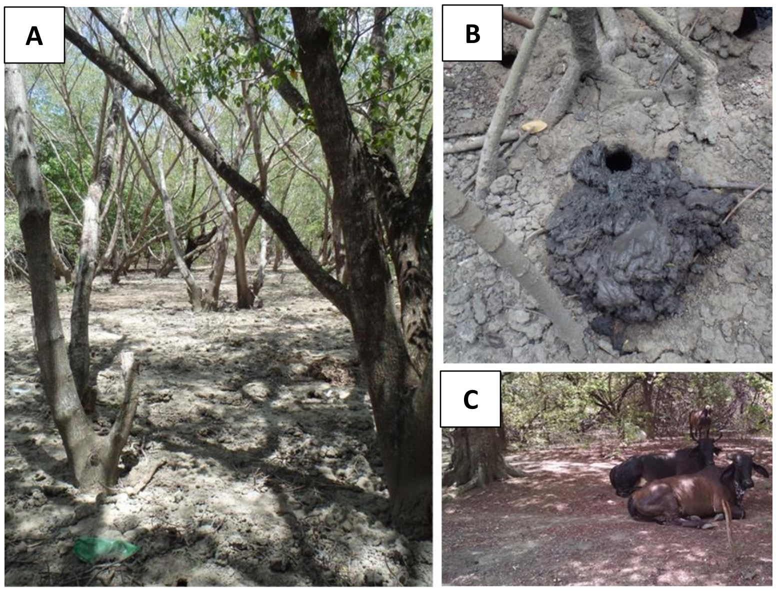

Figure 18. The intact forest (A) has little understory, permitting townspeople to easily travel along shaded trails to reach the beach, and has abundant animal use, including (B) crabs and (C) livestock .

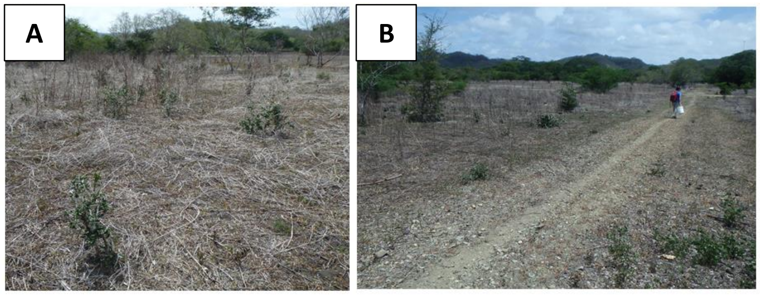

Figure 19. Woody vegetation in the agricultural lowland is less diverse than it is in the intact forest, being a mosaic of cleared land and second growth forest patches, including (A) regularly spaced Jicaro (*Crescentia*) growing among dead herbaceous material and (B) an abundance of dried herbaceous material.

Key Impacts

There are myriad impacts to the study site. Some impacts are to both the intact forest and agricultural lowland; other impacts are unique to the agricultural lowland.

The community has grown in recent years, increasing from ~50 to ~130 families (Daniel Sanchez Personal Communication). This near tripling of the size of the community, plus the addition of transient visitors associated with the growing tourism market, stress the natural environments in multiple ways, with both direct and indirect effects.

The municipal water supply is taken from the coarse-grained alluvial aquifer. Groundwater in this aquifer primarily flows beneath the mangrove and mangrove-fringe wetlands, but discharges in key locations around the perimeter providing a source of freshwater even during dry periods. Almost nothing is known about the safe yield of this aquifer, though increased demand by the growing community and three years of lower-than-normal rainfall have only lowered hydraulic heads in the water-supply well by 2 m (Daniel Sanchez Personal Communication).

More problematic is wastewater disposal, as there is no centralized wastewater treatment. Wastewater is discharged either directly to the land surface or to septic systems of varying quality and functionality (Weeda 2011). These wastewater discharges are high in nutrients, and flow into both the intact forest and agricultural lowlands (Figures 20 and 21), where they may be transformed by microbial activity or uptaken by vegetation (Calderon et al. 2014).

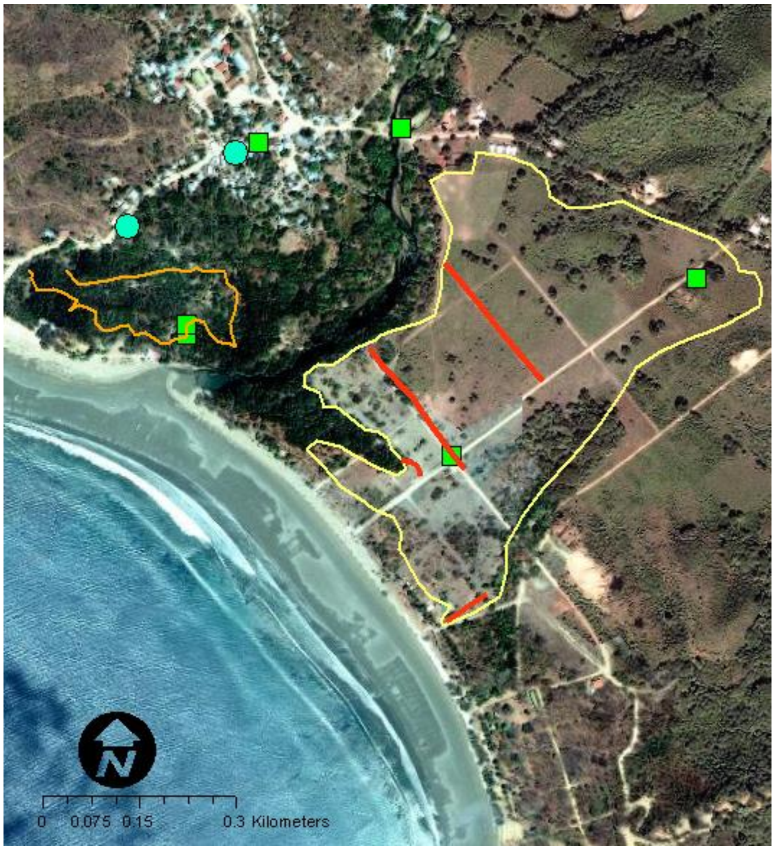

Figure 20. Constructed features to allow passage over water or to move water out of the community or off of the agricultural lowland. Blue circles are surface water runoff from the community observed in the dry season; green squares are bridges and culverts; red lines are ditches; and the orange line is a proposed trail which will include an improved bridge. The yellow line delineates the agricultural lowland and is provided for reference.

An excess of nutrients can cause water-quality problems. All organisms require nitrogen (N) and phosphorus (P): N is in the amino acids that compose all proteins, in nucleic acids that compose DNA, and in many other essential organic and inorganic compounds, while P is in the nucleic acids that compose DNA, in the ATP used to store energy harvested from sunlight or food, and in many other essential organic and inorganic compounds including bones and teeth. N and P are both essential nutrients; organisms cannot grow if one or the other is missing. Nutrient limitation is the condition where one essential nutrient is lacking. In aquatic ecosystems, the limiting nutrient is typically N or P (Elser et al. 2007). Therefore, primary productivity (e.g., growth by photosynthesis) can be spurred by the addition of N and/or P. This process is called eutrophication, and the primary beneficiaries are typically phytoplankton which can cause pronounced algal blooms. Algal blooms are typically green, but can also be yellow-brown or red, depending upon the species of algae (Figure 22). When phytoplankton die, dead biomass is consumed by microbes, which simultaneously consume oxygen. Decaying biomass during algal blooms can deplete oxygen to the extent that aquatic organisms such as fish can be suffocated.

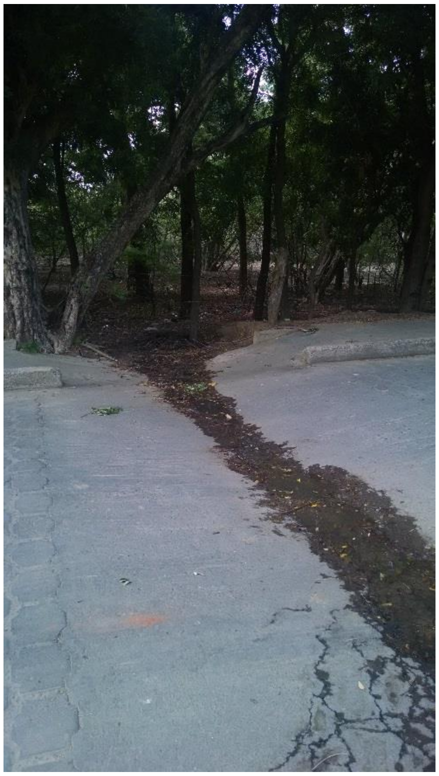

Figure 21. Untreated wastewater flows into the mangrove and mangrove-fringe wetlands in numerous locations, both through diffuse overland flows and focused channelized flows.

Figure 22. Algal bloom in the stagnant water on the Ostional River below the coastal road bridge.

More prominent are the combined direct and indirect effects of land clearing and agricultural activities in the agricultural lowlands. The most visible impact is the land clearing itself. However, there are other impacts associated with the land clearing that mean that may prevent abandoned or otherwise neglected fields from returning to pre-development conditions without some intercession. The most important of these other impacts are changes to drainage (Figure 20). Roads have been constructed throughout the agricultural lowland. Because the area is prone to aerial flooding, these roads are commonly slightly elevated, acting as levees that direct flow on a grid (Figure 23). Similarly, ditches have been constructed throughout the agricultural lowland. These ditches drain the agricultural lowland, reducing water levels and discharging sediment- and nutrient-rich water directly to the intact forest (Figure 23).

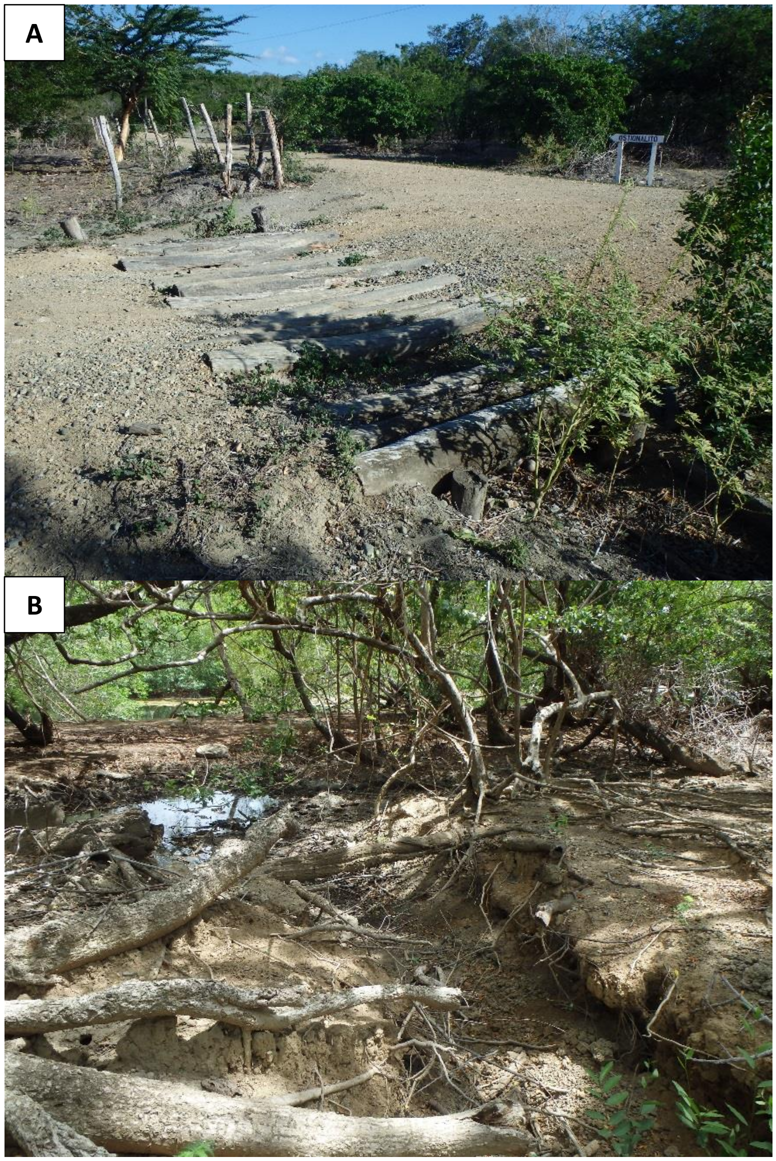

Figure 23. Drainage has been altered throughout the agricultural lowland, with (A) raised roads directing flows along a grid (note the primitive wooden bridge necessary because flows along one road have to be passed under the other) and (B) ditches concentrating and directing flows off of the agricultural lowlands, in this case into the intact forest (note the eroded bed and banks in the foreground and the Ostional River in the background).

A key indirect impact is invasion by non-native species. A common invasive, found throughout the intact forest and forested portions of the agricultural lowland, is the neem tree (*Azadirachta indica*). Neem is native to India, but is widely considered a weed species, having invaded habitats throughout the world (Csurhes 2008). Neem is located throughout the study site, occurring as all age classes from seedlings, to saplings, to mature adults (Figure 24). However, it is not particularly prevalent in the upper river channel, indicating the river channel is not a primary source of neem invasion during the dry season (Figure 25).

Figure 24. Neem is common component of the agricultural lowlands. At this location (Waypoint 442), neem occurs as a tree (foreground, silhouette), as a dense layer of seedlings near the tree (foreground, just beyond the shade), and as a sapling invading an otherwise sparsely vegetated depression with hydric soils (background, in the full light).

Restoration and Monitoring

The impacts to the mangrove and mangrove-fringe wetlands are relatively moderate, and true restoration, in which an environment is returned to a "former, normal, or unimpaired state of condition" (Lewis 1990), is possible. Some restoration of the intact forest is possible, with moderate changes in management. Further, and more profound, restoration of the agricultural lowlands also is possible. This would require more active measures, but restoration of this area could increase the total area of the intact forest by as much as 140%, if the entire agricultural lowland were to be restored.

The first step is to define the "former, normal, or unimpaired state of condition", which requires a reference site to guide the restoration of the impaired site (Brinson and Rheinhardt 1996). In this case, though it is slightly impacted, the intact forest nevertheless can serve as a reference site, as long as impacts due to water use, wastewater disposal, and invasion by non-native species are otherwise taken into consideration. The intact forest is a mix of wetland and non-wetland forest, with vegetation apparently responding to subtle differences in microtopography and soil texture. The agricultural lowland was likely very much like this prior to conversion, with evidence of this in the remnant wetland and non-wetland forest patches. The restoration of the both the intact forest and the agricultural lowlands would, in many ways, simply require the reversal of the impacts described in the previous section.

Restoration would begin by planning further development wisely, ensuring that development does not encroach on the key features of the mangrove and mangrove-fringe forest. This would include conducting aquifer performance tests to determine the safe yield of the aquifer (Figure 26). This also would include seeking to improve wastewater disposal through making improvements to septic systems and/or creating wastewater treatment systems, which may include constructed wetlands for wastewater treatment, around the perimeter of the mangrove and mangrove-fringe wetlands.

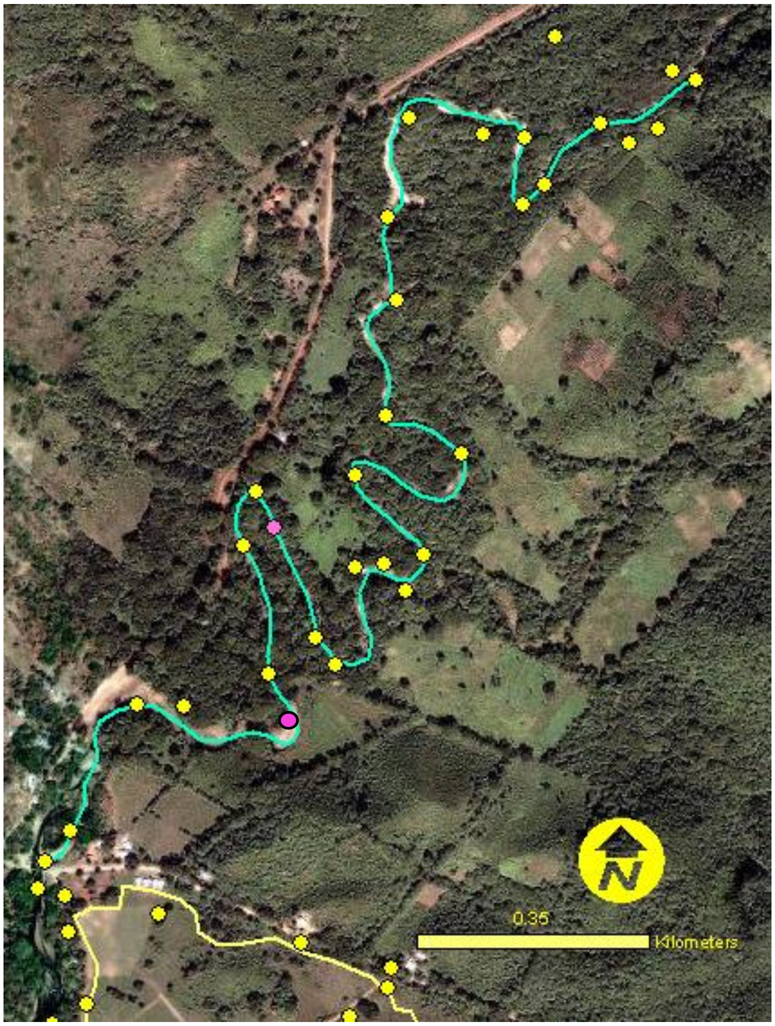

Figure 25. During the dry season, the Ostional River along the blue line is dry and colonized by pioneer species, and it may therefore provide a conduit for dispersal of invasive species into the intact forest. The invasive species *Ricinus communis* was observed throughout the dry riverbed but was not common in the intact forest. The invasives pecies neem, on the other hand, has invaded the intact forest, including portions of the mangrove, and the agricultural lowlands. Its distribution differed along the surveyed riverbed route (blue line): it was not observed within the channel between northern tip of the blue line and the location marked with the uppermost pink dot; it was uncommon between the uppermost and lowermost pink dots; and it was a common riverbed invader below the lowermost pink dot and the where water appeared in the channel (Hwy 224 bridge, i.e., the south tip of the blue line).

The more active measures on the agricultural lowland would begin with restoring appropriate hydrology. This would require the obliteration of some roads and the filling of some ditches, though more natural, meandering or deranged (i.e., erratically wandering) flow ways should be created to ensure that water continued to move off of the landscape and into the Ostional River, and thereafter out to the ocean. (Please note the important discussion of constraints in Next Steps, below.) Once the hydrology is restored, targeted planting of native species could be undertaken to begin the process of vegetation regeneration. This is particularly important for species that are poor dispersers and/or have short-lived seeds (Walker et al. 1986). In all cases, control of non-native and invasive species would require major startup efforts, and would likely require constant vigilance (see Monitoring, below) and minor continuing efforts to ensure that non-native and invasive species populations are maintained at manageable levels.

Figure 26. Conducting an aquifer performance test on a well in a rural community in Mexico.

Monitoring

Monitoring Strategy

The US Environmental Protection Agency (EPA) has adopted a three-tier framework for classifying assessment and monitoring efforts based upon the level of effort required: Level 1 assessment and monitoring efforts are rapid landscape-scale assessments meant to broadly characterize the condition of regional wetland resources using land-use/land-cover data; Level 2 assessment and monitoring efforts are rapid site-scale assessments meant to more specifically characterize the condition of specific wetland resources using simple indicators to rapidly identify stressors that might impair wetland function; and Level 3 assessment and monitoring efforts are intensive site-scale assessments meant to provide detailed information about the structure and/or function of specific wetland resources using detailed physical, chemical, and/or biological measurements (EPA 2002).

The level at which a monitoring effort is conducted and the specific ways in which it is conducted is a function both technical and institutional considerations (Stein et al. 2009). Technical considerations include the availability of reference sites and/or data sufficient to support a comparative study. What is a site supposed to look like? How is a site supposed to function? Neither question can be sufficiently answered in the absence of adequate reference sites and standards. Institutional considerations include the availability of sufficient financial and human capital. How much effort can be expended by monitoring personnel? And how much can be expected from monitoring personnel? Again, neither question can be sufficiently answered in the absence of adequate knowledge of the financial and human capital resources available for the term of the monitoring effort.

Fortunately, monitoring strategies do not need to be rigidly designed from the beginning. Rather, monitoring strategies should be flexibly designed to allow adaptation as pre-project uncertainties become post-project outcomes. This approach is called adaptive management, and it is useful in cases where natural resources are responsive to management and there are uncertainties about the impacts of management interventions (Walters and Holling 1990; Williams and Brown 2012), and is particularly useful in cases where recommendations may be made by one organization but implemented by another. Therefore, the following should be considered the starting point for a continued conversation, not final recommendations to be rigidly followed.

Level I

In Level I assessment and monitoring efforts, remote sensing data and products are used to calculate a performance index proportional to the level of functioning of the ecosystem being assessed or monitored. One example is the Landscape Development Intensity Index (LDI), which has been calibrated and validated for wetlands and rivers in Florida (Brown and Vivas 2005; Reiss and Brown 2007; Reiss et al. 2010). The LDI is based upon the idea that the condition of a landscape unit—a wetland, for example—is a function of the condition of the immediate contributing area. The condition of the contributing area is taken as a function of the LULC, specifically the amount of non-renewable energy required to create and sustain a given LULC. Therefore, low LDI values correspond to low-intensity LULCs (e.g., unmanaged forest), while high LDI values correspond to high-intensity LULCs (e.g., high-density residential).

Though originally calibrated to a specific location in Florida, the LDI is flexible and can be recalibrated to any landscape and any LULC data collection system (Rains et al. 2012; Rains et al. 2013). Therefore, an LDI could be easily adapted and applied to the monitoring of the mangrove and mangrove-fringe wetlands in Ostional. This would require the availability of remote sensing data and products and technical expertise that may not be readily available, and therefore might require the engagement of outside expertise, at least during the calibration and training periods. However, once the calibration and training periods were complete, an LDI could serve as a powerful tool to track how changes in LULC may be reflected in changes in functioning of the mangrove and mangrove-fringe wetlands.

Level II

In Level II assessment and monitoring efforts, easily collected data are either directly compared to reference data and/or used to calculate a performance index proportional to the level of functioning of the ecosystem being assessed or monitored. This is the level at which most monitoring is conducted when the objective is to evaluate the performance of restoration projects (EPA 2002).

Precipitation-Evapotranspiration

Precipitation and evapotranspiration are not performance metrics in and of themselves, but they can provide important context within which other performance metrics can be analyzed and synthesized. Precipitation (P) can be measured either with a rainfall collector manually operated onsite on a daily basis or with a tipping-bucket rain gage automatically operated and manually downloaded on a periodic basis (e.g., monthly, quarterly). Evapotranspiration (ET) cannot be directly measured, but can be calculated using easily obtainable meteorological measurements and one of many reference ET equations (Exner-Kittridge and Rains 2010). A simple baseline could be established using data available online (e.g., http://en.climate-data.org/location/431714/). Subsequent monitoring data could then be used to calculate the deviation of current P-ET from historically normal P-ET, which might then be helpful in explaining trends in other monitoring metrics.

Water Level

Surface-water stage is commonly measured at stage gages, while groundwater hydraulic head is commonly measured at monitoring wells (Figure 27). In both cases, measurements can be made manually during regular visits (e.g., monthly) and/or automatically using pressure transducers/dataloggers that are downloaded and reset periodically (e.g., monthly, quarterly). There are no existing stage gages on the site; however, there are numerous existing wells on and adjacent to the site, both monitoring wells located throughout the site as part of a recent study (Calderon and Uhlenbrook 2014; Calderon et al. 2014) and water-supply wells located throughout the community.

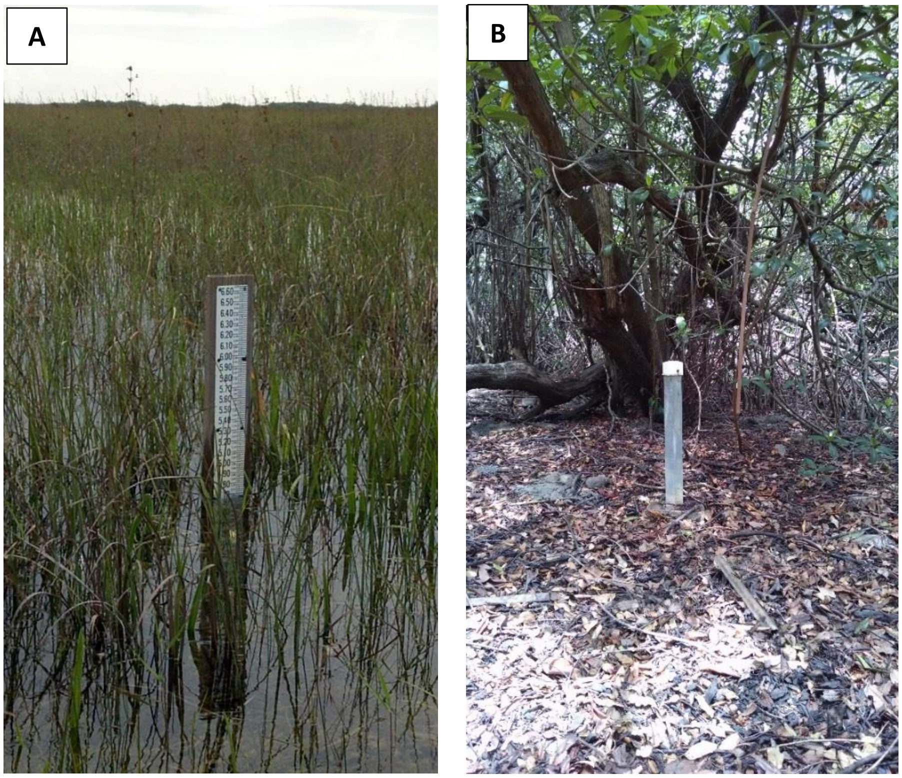

Figure 27. Surface-water stage can be measured with (A) stage gages, this one located in Everglades National Park, USA, and groundwater hydraulic head can be measured at (B) monitoring wells, this one located in the northwest corner of the intact forest. In both cases, water levels can be measured manually or automatically with pressure transdcuers/dataloggers.

Water Quality

One key water quality parameter is simply the amount of dissolved ions, which in this case is largely controlled by the relative proportions of fresh water and sea water. The amount of dissolved ions can be reported in numerous ways, but the two most common are specific conductance and salinity. Specific conductance is the electrical conductivity at 25°C, and is typically 100-2,000 μs/cm in fresh water and 55,000 μS/cm. Salinity is calculated by dividing the specific conductance of the sampled solution by the specific conductance of a reference solution. It is therefore unitless, though it is typically reported in practical salinity units (psu). Salinity is typically <0.5 psu in fresh water and 35 psu in sea water. Dissolved ions typically mix conservatively, meaning that both specific conductance and salinity can be used to infer the relative proportions of two end members in a solution composed of a mix of those two end members. For example, if fresh water has a salinity of 0.4 psu, sea water has a salinity of 35 psu, and a mix of the two in a mangrove has a salinity of 17.7 psu, then the mix of the two is precisely 50% fresh water and 50% sea water because [0.4 psu*0.50]+[35 psu *0.50]=17.7 psu.

Other key water quality parameters include nutrients (e.g., N and P) and enteric bacteria, such as *Escherichia coli*. Enteric bacteria are bacteria characteristic of animal digestive tracts. Many enteric bacteria are harmless. However, many others are pathogenic, commonly causing diarrhea. Enteric bacteria have long been used as a proxy for enteric viruses, which are harder to measure and quantify. Though commonly done, it must be emphasized that such relationships can be weak (Fong and Lipp 2005). Regardless, enteric bacteria can be used to infer if untreated or improperly treated wastewater from livestock or humans is entering into the system.

Soil Characteristics

Soil characteristics respond to numerous drivers, as described by the soil equation

$$S = f(cl, o, r, p, t, \ldots)$$

where S is soil, cl is climate, o is organic activity, r is relief, p is parent material, t is time, and … refers to the fact that one might imagine many more variables, depending upon specific conditions (Jenny 1994). Many of these drivers are beyond the control of the restoration effort. Furthermore, the time scale can be far in excess of any reasonable monitoring effort. Nevertheless, there are soil characteristics that respond quickly to restoration efforts and can therefore be used in monitoring efforts (Salmo et al. 2013, Dale et al. 2014). Soil moisture content can increase, through this is probably more easily assessed by using water level as a proxy for soil moisture and soil-water availability or indirectly through surveys of wetland biota dependent on elevated soil moisture, such as fiddler crabs. . Soil organic matter can rapidly accumulate, as restored plant communities increase litterfall rates and raised water tables slow decomposition. These changes may be detected through monitoring soil texture and/or soil color. As organic matter accumulates, soil nitrogen and soil phosphorous also can accumulate, as the ecosystem becomes more nutrient retentive and nutrient cycles become less leaky. Last, soil temperatures can decrease, as both soil moisture increases and plant canopies close, with the former moderating temperature fluctuations and the latter decreasing insolation.

Biota—Flora and Fauna

Vegetation monitoring metrics are commonly used in monitoring. Like soil characteristics, vegetation responds to numerous drivers; unlike soil characteristics, many of these drivers are well within the control of the restoration effort and occur on time scale well within reasonable monitoring efforts. There are many ways to characterize and quantify vegetation, far more than could possibly be summarized or synthesized herein (Mueller-Dombois and Ellenberg 1974). Still, a few metrics are commonly recommended for use in monitoring efforts because of their ease of use and sensitivity to change (Sellner et al. 2012; Salmo et al. 2013). Most focus on the occurrence and abundance of vegetation, such as species richness and diversity and percent cover of all species as well as height and density of shrub and tree species. It is common to calculate these metrics separately for both native and non-native species, especially when there are specific non-native, invasive species that are of concern, such as Neem, as is the case for the mangrove and mangrove-fringe wetlands of interest.

Faunal monitoring metrics are less frequently used in monitoring. Nevertheless, they can be powerful tools that help show that restored structure (e.g., restored habitats) are resulting in restored function (e.g., restored faunal communities related to those habitats). Many metrics are derived from simple species use surveys, such as surveys of invertebrates, including the Mangrove Tree Crab (*Aratus pisonii*); lizards and reptiles; fish; birds; and mammals, including bats (Figure 28; Sellner et al. 2012). Other surveys seek to quantify more than just casual use, such as surveys of crab burrows and bird nests (e.g., Li et al. 2015).

Figure 28. Bat caught in a mist net on the Ostional River at the coastal road as part of an ongoing monitoring program.

Assessment Models

Assessment models are expert systems that allow rapidly collected monitoring data and other field observations to be used to infer level of functioning in specific ecosystems. Many assessment models have been collected, some for coastal wetlands (see Bartoldus 1999; Fennessey 2007). Some are bioassessments, which seek to evaluate the degree to which an ecosystem might be able to sustain a community of organisms with the species composition, diversity, and functional organization of other, minimally disturbed ecosystems; others are functional assessments, which seek to evaluate the degree to which an ecosystem might perform functions relative to other, minimally disturbed ecosystems (EPA 1998). In both cases, models must be calibrated to regional conditions, especially the reference standard conditions at other, minimally disturbed ecosystems. Once complete, models can then be used to track performance over time, as assessed ecosystems remain stable or trend toward or away from the reference standard conditions.

Level III

Level III assessment and monitoring efforts are long-term studies, in which study design, data collection, and data analysis efforts are rigorous and focused on specific questions and/or hypotheses. Such studies are not commonly conducted as part of routine monitoring efforts, but can nevertheless augment routine monitoring efforts by providing a depth of understanding about specific components of the structure and function of the ecosystem in question. An excellent example of this includes a hydrogeology study used and referenced extensively in this study, in which the levels of effort and expertise exceed those needed in a monitoring effort, but from which much can be learned and applied to the monitoring effort (Calderon et al. 2014; Calderon and Uhlenbrook 2014).

Summary of Monitoring Options

This section details numerous potential monitoring metrics. This list is not comprehensive—many more monitoring metrics could be listed. However, as previously noted, monitoring metrics should be keyed specifically to monitoring objectives. There simply is no reason to monitor bird use, if the restoration of bird communities is not one of the restoration objectives. Therefore, this list is neither comprehensive not prescriptive; rather, this list represents a starting point for the discussion that should follow the setting of specific objectives for the restoration of the mangroves and mangrove-fringe wetlands of interest.

Next Steps

This effort has revealed opportunities. However, any restoration effort also has to identify and work within constraints because a complete restoration and monitoring plan can only emerge after a complete analysis of both opportunities and constraints. There are many potential constraints, including constraints that are physical, institutional, cultural, and financial. Two important constraints are related to human health and safety and land ownership.

One important constraint is how hydrologic restoration might affect human health and safety. The impacted area has been ditched, drained, and partially developed. Though some of the development has been abandoned or otherwise neglected, much of that development remains in use. There are some homes, including some new government-constructed homes along the coastal road. There also are some softer uses, such as unimproved roads, trails, and a ballfield. Interviews with key informants indicate that many of these areas are already prone to aerial flooding during intense rainfall; some types of hydrologic restoration, include the filling of ditches and rerouting of runoff, could exacerbate this aerial flooding in unintended ways if not properly planned. Hydrologic restoration should not be undertaken without additional hydrologic analyses, possibly including topographic surveys, field observations during a wet period, and some type of hydrologic modeling, be it conceptual, statistical, or numerical.

Another important constraint is land ownership. Land ownership is complicated. No land ownerships maps could be found, and interviews with key informants provided little additional information. Homes are built along the edges of the mangroves and mangrove-fringe wetlands. Ditching, clearing, fencing, and cultivating within the mangroves and mangrove-fringe wetlands were clearly performed at some cost, though much of this development appears to be abandoned or otherwise neglected at this time (Figure 29). Nevertheless, there are still indications that there are active land ownership claims and development plans (Figure 30). Therefore, a complete land ownership analysis must be conducted, and efforts must then be made to determine which parcels might be acquired and used in a restoration effort.

Once complete, the restoration and monitoring planning can truly commence, and objectives can be established, strategies for reaching those objectives can be developed, and specific monitoring protocol can be defined that can be used to measure progress towards those objectives.

Figure 29. Ditch and orchard, both apparently abandoned, directly adjacent to and south of the intact mangroves and mangrove-fringe wetlands.

Figure 30. Agricultural lowland field with a relatively new sign indicating the land is the property of Marbella SA.

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