Sabana Wetlands in Quintana Roo, Mexico: What We Know and What We Don't

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ABSTRACT

Locally called "sabanas" are a group of herbaceous karst wetlands in the Yucatan Peninsula (Mexico) that form in exokarstic solution depressions. They are groundwater-dependent ecosystems ranging from permanently to seasonally flooded and dominated by plants from the family Cyperaceae. In this paper, we briefly summarize most of the knowledge regarding these wetlands, highlighting some recent findings obtained from our study of a sabana wetland - La Esperanza in Quintana Roo, Mexico. We also identify areas that require attention in order to generate the basic knowledge necessary to properly evaluate their ecosystem services.

RESUMEN

Los humedales conocidos como "sabanas" en la Península de Yucatán (México), son un grupo de humedales herbáceos kársticos que se forman en depresiones exokársticas. Son ecosistemas dependientes del agua subterránea de inundación permanente hasta inundación estacional, y están dominados por plantas de la familia Cyperaceae. En este artículo, reunimos brevemente la mayor parte del conocimiento sobre estos humedales, destacando algunos hallazgos obtenidos recientemente de un sitio de estudio llamado La Esperanza en Quintana Roo, México. Finalmente, identificamos áreas que requieren atención para generar el conocimiento básico necesario para evaluar adecuadamente sus servicios ecosistémicos.

INTRODUCTION

In southeast Mexico, sabana is a local term mostly given to herb-dominated wetlands found in karst landscapes. They are typically tropical karst marshes established in solution depressions associated to geological faults and fractures (McKay et al. 2020). Sabana wetlands have been studied mainly from the floristic point of view, so our knowledge of most of them is limited. In this paper, we attempt to summarize most of the available published literature regarding sabana wetlands from the State of Quintana Roo, Mexico (Figure 1). Starting in 2017, we began research at sites in common lands (ejido) of several localities from the northern part of the State of Quintana Roo, Mexico. Herein, we also present an overview of the advancements of knowledge in these little-known tropical wetlands.

WHAT WE DO KNOW?

Sabana wetlands are established in the bottom of solution depressions carved in carbonates rocks. These depressions are commonly slender, elongated valleys, U or V-shaped, where the boundaries are terraced rock outcrops (Figures 1 and 2). These wetlands contain fine-grained, carbonate-rich silts and clays – products of weathered limestone (Scott et al. 2004). Most of them (81% of the depressions; Fragoso et al. 2014) are found below 50 meters above sea level (masl).

Microrelief and Hydroperiod

Sabana wetlands have a very distinctive cross-sectional pattern. As true for many other wetlands, tropical karst marshes are established in depressions or in lowland areas. As one approaches the center of the wetland, the ground surface of the sabana typically slopes gradually to the center of the depression. Annual fluctuations of water lead to high water level 90 cm above the ground surface in the central portion (Cejudo et al. 2021). However, during extreme hydrometeorological events such as the hurricanes Wilma (2005), Delta, and Zeta (2021), the water level can reach up to three meters above ground level (Figure 3), even spilling over the paved road that dissects the wetland. Permanent and temporal flood regimes are the most common in sabana wetlands from Quintana Roo.

Geomorphology and Soil

The three most important geomorphological features in this area are exokarstic closed depressions: sinkholes, uvalas and poljes (Fragoso et al. 2014). Sinkholes are funnel-shape depressions caused by dissolution and collapse of carbonate rock, which area oscillates from few meters to not larger than one kilometer. Uvalas are multi-coned depressions, frequently formed by the enlargement of smaller depressions. Lastly, a polje is a large, flat-floored depression that can span of several kilometers (USEPA 2002).

Palacio-Aponte et al. (2002) highlight that these wetlands are not restricted to cumulative plains established on Gleysols, they can be found along a terrestrial-aquatic continuum linked to adjacent ecosystems, regardless of their geoform, by water. These landscapes function as atypical endorheic basins, where infiltration and dissolution occur. Large parts of the terrestrial ecosystems in the Yucatan Peninsula are dominated by Leptosols, which are generally thin soils with an elevated content of calcium as a result of the parent material. Inside the wetlands, at a micro-scale, we found other types of soil. Rather than organic or gleyic soils associated with many wetlands, the dominant soil unit in some wetlands is Calcisol (Solleiro-Rebolledo et al. 2011). Apparently, a fair share of this soil was biogenically created

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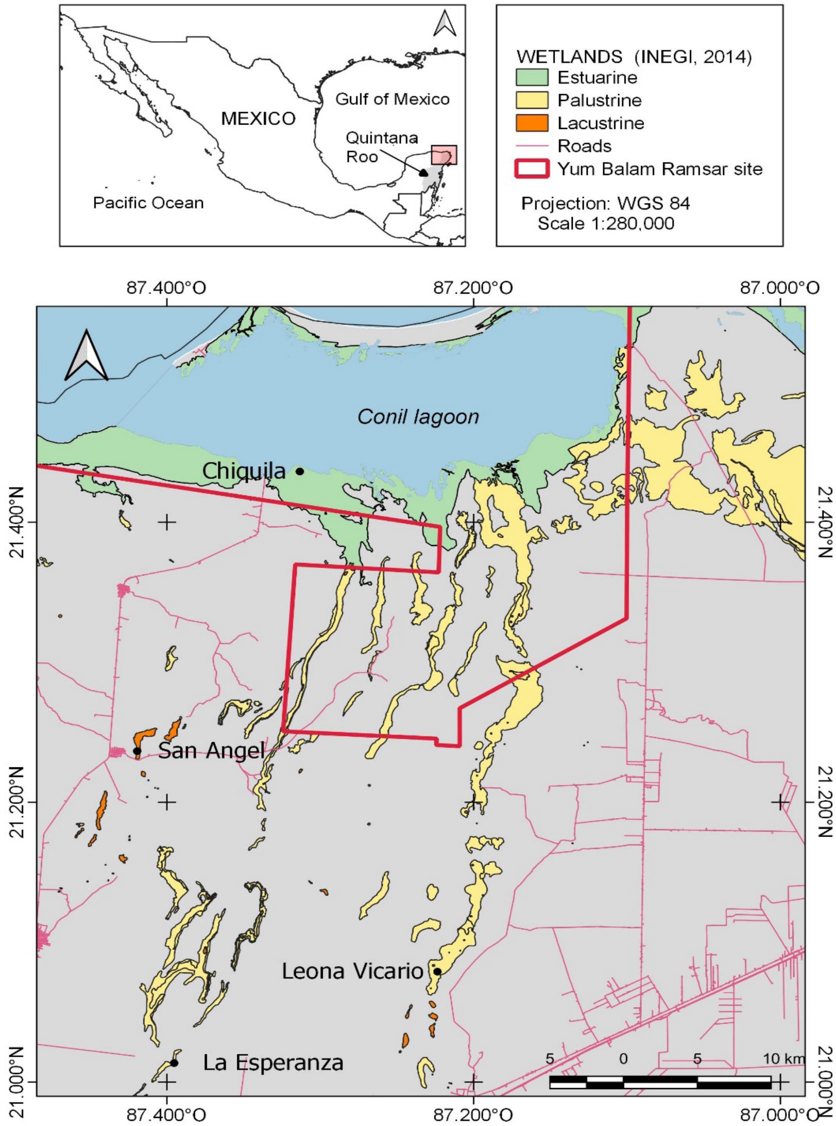

Figure 1. General location map (above) and more detailed map showing sabana wetlands from the State of Quintana Roo, Mexico where research has been done. Wetlands classification (estuarine, palustrine, lacustrine) according to the Mexican wetlands inventory. (Compiled from INEGI 2014)

Figure 2. Terraced rock outcrops mark the outer limits of sabana wetlands (Photo by Eduardo Cejudo).

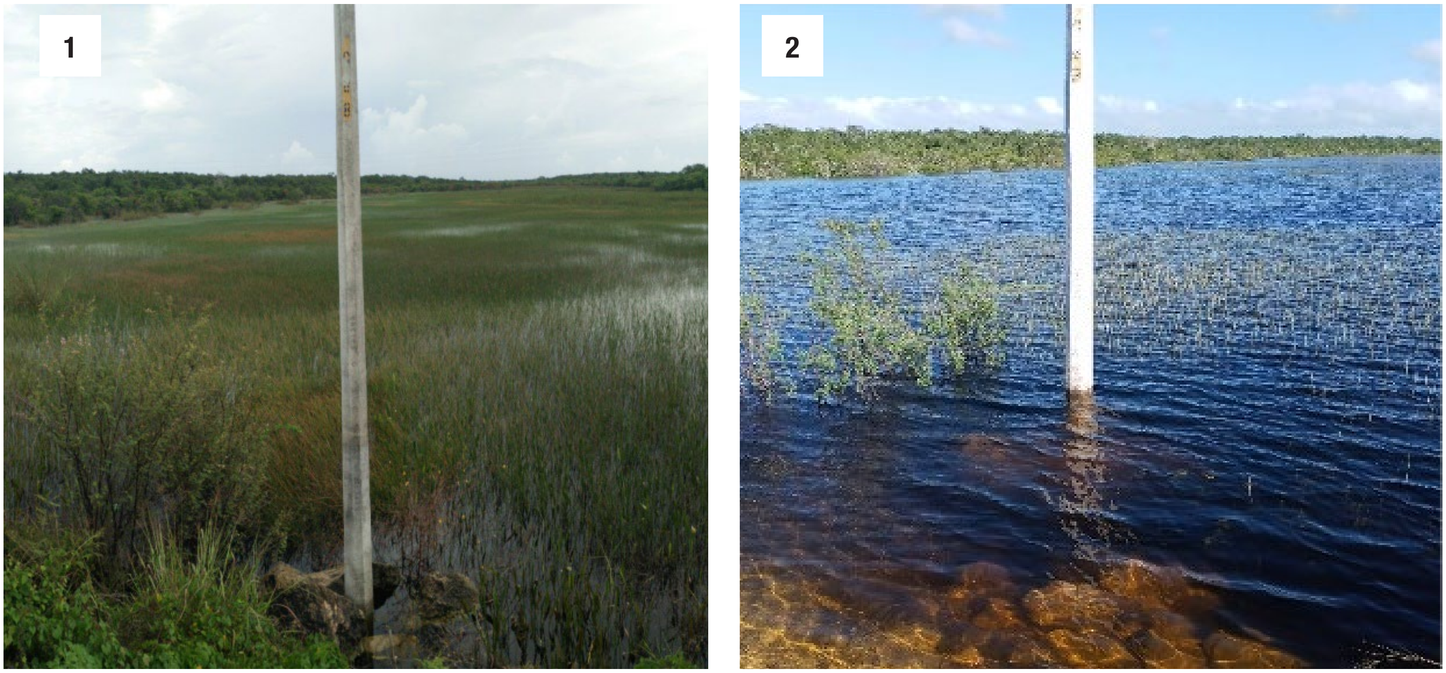

Figure 3. Variation in flood intensity in Lazaro Cárdenas, Quintana Roo, Mexico: 1) typical condition — saturated soil with shallow water (left) and 2) flooding after Hurricanes Delta and Zeta in 2021 (right). (Photos by Pedro Zapotecas).

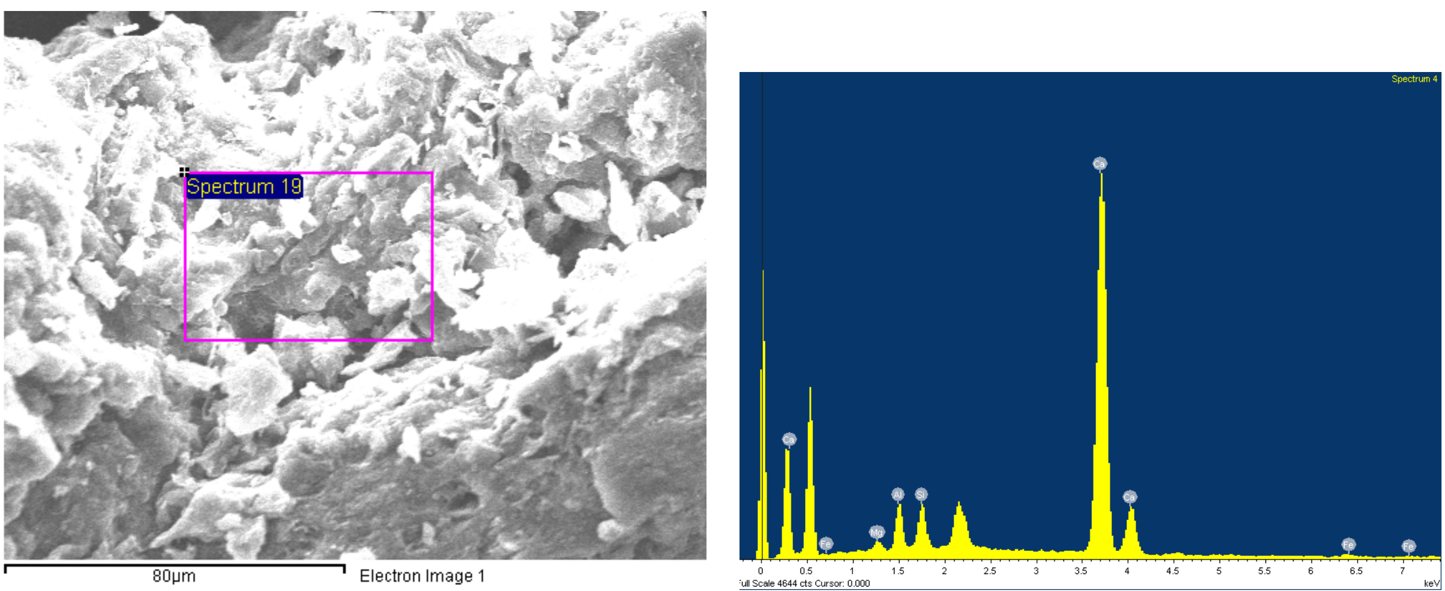

Figure 4. Microscopic view of porosity of a sabana soil. Left: Image taken on a JEOL JSM6360LV Scanning Electron Microscope, 20 kV at 300X. Right: Spectrum with energy dispersive X-ray spectroscopy (EDS) of the sample in the left. This spectrum shows the most abundant elements; calcium, magnesium, silicon, iron, aluminium, chloride. (Photo by Silvia Beatriz Andrade Canto)

by algae subject to periodic flooding from rising groundwater with elevated carbonates. One of the most interesting findings is the sequence of horizons alternatively enriched with organic material or with carbonates, indicative of the duration of flooding and alternating wet and dry conditions.

As hydromorphic soils, bulk density is low, from 0.14 to 0.25 g/cm3, and they can hold anywhere from 2 to 7 grams of water per gram of soil. As a result, these soils have very high porosity (84 to 92%, Figure 4). While the soil in these wetlands is chemically dominated by calcium due to the parental rock (calcite), other elements are also important components, such as magnesium, aluminum, silicon, sulfur and small portions of iron, potassium and chloride (Cejudo et al. 2021).

Based on our observations, soil pH is slightly alkaline (7 to 8) and not very variable among dry and wet seasons (unpublished results). Electrical conductivity has been measured from 400 to 800 µs/cm, with an increase in values during the dry season, likely due to the absence of surface water (i.e., most dissolved substances precipitate and increase the amount of ions in the soil). However, these values still indicate low salinity and optimal value for nutrient availability. We also examined cationic exchange capacity (CEC) and ferrous iron. The former parameter is above 200 meq/100 g soil that are very high yet reasonable due to the soil organic matter content (Kaiser et al. 2008). These high values can be mainly attributed to the organic matter content present in the wetland soil (≈ 8%), which provides great retention capacity. The ferrous iron test (Fe^{2+}) is a diagnosis test for redox soil conditions, which provides information regarding probable electron acceptor and microbial metabolism (Bird et al. 2011). As with electrical conductivity, Fe^{2+} concentration changes between seasons, decreasing during the dry season in the absence of water when anaerobic conditions cease and Fe^{2+} becomes oxidized into Fe^{3+}.

Groundwater Flow

McKay and others (2020) used strontium isotopes and ion geochemistry to demonstrate that water effectively flows north within the fracture system where sabana wetlands are located. They suggest the existence of at least two flow paths, one eastward and one westward and reported differences in water chemistry in each of the flow paths with greater Mg contribution in the eastern boundary (a finding that we confirmed later, Zapotecas-Tetla 2022). As most of us dealing with the hydrogeology of this area, identifying watershed divides is challenging in karst landscapes. Hydrologically, they provided evidence that the fracture zone encompasses areas beyond the visible sabanas, providing the ecological flow for these wetlands.

Hydrogeochemistry

Sabana wetlands are dominated by calcium bicarbonate

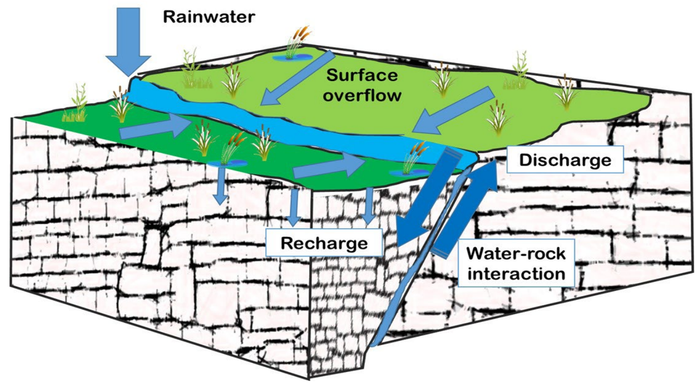

Figure 5. Diagram of water movement in a cross section of the sabana wetlands "La Esperanza", Quintana Roo, México.

water as a result of carbonate rock dissolution. They are phreatotrophic wetlands, primarily fed by groundwater (Cejudo et al. 2021), but also receive rainwater. When the soil is saturated and the phreatic table is above the ground, rainwater stays on top of the wetland and then gradually mixes with pore water and eventually infiltrates into the saturated zone. Thus, sabana wetlands serve as both groundwater recharge and discharge areas (Figure 5).

Vegetation

Sabana wetlands are floodable lowlands (Palacio-Aponte et al. 2002). While botanical inventories have been conducted, those studies are scarce and isolated, lacking phytogeographic and conservational approaches. The earliest description we found regarding karstic wetland in the Peninsula was in the chapter "Wetlands of Mexico" by Olmsted (1983). Due to the lack of a classification system, Olmsted used the US wetland classification system to give some order, but also referred to local names which rooted in specialized literature. She described the Peninsula as a large plain with elevation no higher than 300m above sea level with no surface flow due to high permeable sedimentary rock. Seagrasses were barely mentioned; mangroves were better described. Herbaceous wetlands were brackish and freshwater marshes, designated in a patchy organization, occurring on marl with a thin organic layer, adjacent to mangroves and/or buttonwood. The dominant species of marshes are Typha, Phragmites, Cladium, Eleocharis, and Rhynchospora. Another important contribution about herbaceous wetlands came from Rejmankova et al. (1996). Their work studied several marshes, from mesohaline to completely freshwater, in different water types from sulfate-chloride water to calcic-carbonate water. They described these wetlands generally with low nutrient levels but high N accumulation in sediments. One of the most important outcomes from their research was that biomass production and decomposition are functions of individual plant growth and environmental conditions. The decomposition of *Typha domingensis* and *Eleocharis cellulosa* is relatively fast (200 days) while *Cladium jamaicensis* has

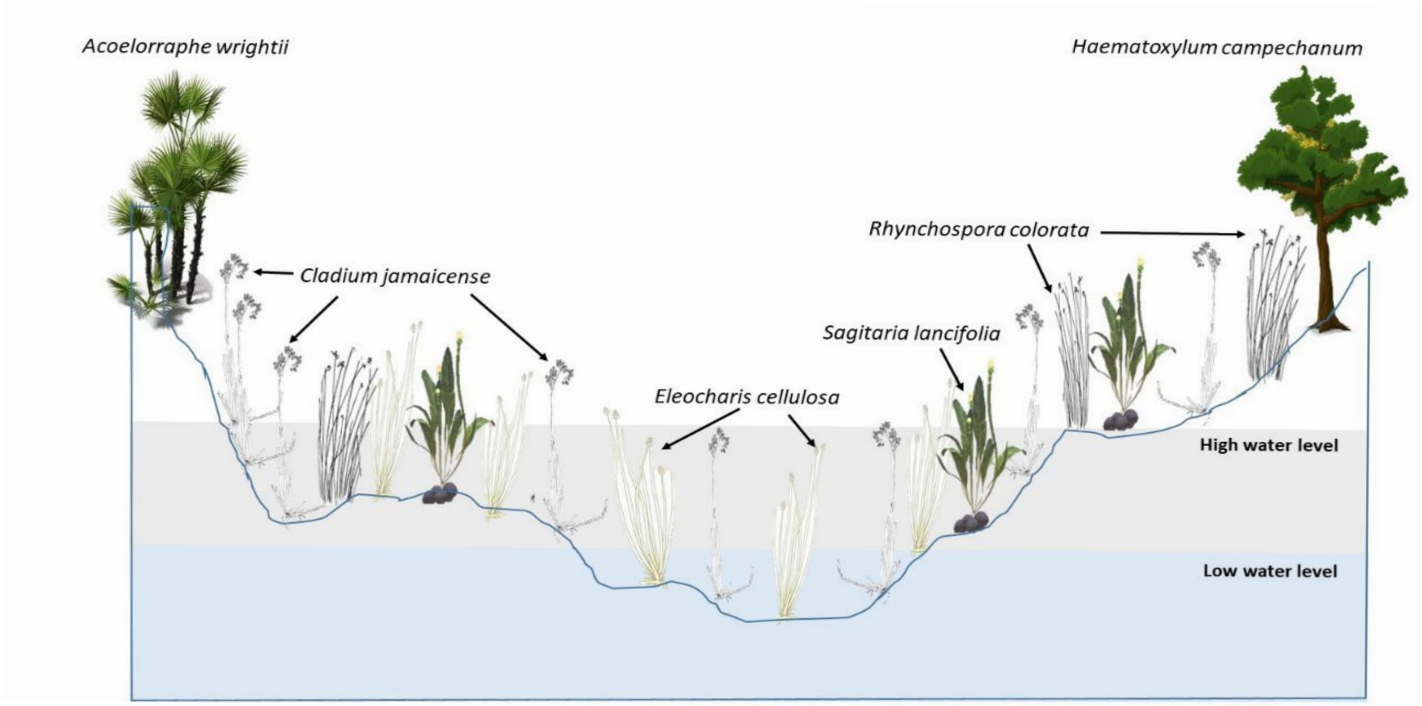

Figure 6. Cross section of La Esperanza sabana wetlands with dominant vegetal elements.

a slow decomposition, with half of the tissue decomposed around 600 days. The formation of the peat layer was enhanced after the establishment of herbaceous species. There has been also reported preferences on substrate, with some plants establishing in peaty clays, and others with clayey soils or alluvial sands. For instance, the work by Bridgewater et al. (2002) in the frontier between Mexico and Belize, reported that sabanas are part of an ecotone — areas of ecological succession, not necessarily considered as stable communities. After a detailed vegetation description, they concluded that sabanas are frequently in poor conservation status, impacted by human economic activities.

In La Esperanza wetland, we found 11 species, *Eleocharis cellulosa* and *Cladium jamaicense* dominates in both saturated and unsaturated soil (Figure 6). Both can thrive in flooded conditions. On saturated soil with shorter flood periods, we found *Sagittaria lancifolia, Rhynchospora colorata*, and *Ludwigia bonaerensis*. On the outer border of the wetland, where surface water seldom reaches and the soil is almost unsaturated, we observed *Persicaria segetum* and *Lippia graveolens*. Dominant trees are *Acoelorraphe wrightii, Haematoxylum campechanum*, and *Crescentia cujete*.

Regarding plant biomass, since 2018, we have focused on the dominant sabana species: *Cladium jamaicense*, *Eleocharis cellulosa*, and *Sagittaria lancifolia*. Our sampling comprised of small blocks of soil, plants and root to determine the biomass per surface area and root biomass per volume. These samples are obtained from a 20 x 20 cm (0.04 m2) area, delimited with a PVC frame. Then, with a straight shovel, a cut was made in the soil to a depth of 20 to 25 cm to extract plants, soil and roots coexisting in the soil block (Figure 7). After drying, we obtained dry soil weight and dry biomass (either aerial, subterranean or both). To calculate the biomass per surface area, the proper dimensional adjustments were made to express the result in kg biomass (dry weight)/m2 and kg roots (dry weight)/cm3 in the topsoil (the upper 25 cm of the soil). What we have learned so far indicate that *Eleocharis cellulosa* produce more subterranean biomass (roots) than *Cladium jamaicense*. Unfortunately, we do not have consistent information (roots and shoots biomass) for Cladium and Sagittaria.

Table 1. Aerial and subterranean biomass of the two dominant species *Eleocharis cellulosa* and *Cladium jamaicense* in La Esperanza Sabana wetland.

Species	Aerial	Root (surface)	Root (topsoil)
Cladium jamaicense	n.a.	0.430 kg/m2 (0.148 – 1.54)	0.001 g/cm3
Eleocharis cellulosa	2.63 kg/m2 (1.25 – 4.5)	3.65 kg/m2 (1.09 – 9.01)	0.018 g/cm3 (0.005 – 0.045)

Macronutrients: N and P

To assess the role of wetlands in nutrient retention we have taken steps towards generating a baseline about the quantity and mass of the nutrient's nitrogen (N) and phosphorus (P). To achieve this, we have tried to identify how these two nutrients are distributed in these ecosystems – in the water, in plants, and in the soil.

N in water. During our research, we have noticed certain trends in sabana wetlands: 1) elevated ammonium

Figure 7. Plant, soil, and roots sampling in sabana wetlands. Left: PVC frame for delimit a 0.04 m2 area. Right: Soil block

(from 0.5 to 1.5 mg $N\text{-}NH_4^+/L$), 2) nitrite ranging from not detected (>0.01 mg $N\text{-}NO_2^-/L$) to 0.2 mg $N\text{-}NO_2^-/L$) and 3) nitrate levels from 0.2 to 1 mg $N\text{-}NO_3^-/L$, occasionally values as high as 1.5 mg$N\text{-}NO_3^-/L$. These trends can be interpreted as enhanced generation or recent production of ammonium due to organic matter mineralization or decaying tissue. Sometimes we were able to "catch" the nitrite increase before being further reduced or oxidized, which then might incorporate into biomass or be moved into facultative or anaerobic zones and be denitrified. The organic nitrogen fraction (Norg, obtained from the difference between total nitrogen and dissolved inorganic nitrogen) has shown to be very important since it represents between 10 and 40 % of the total nitrogen (TN). This fraction is likely comprised by soil organic matter together with cells, either alive or dead, debris, and can be influenced by the clay content, dominant plant species, and the water table (Bai et al. 2005). Unfortunately, we do not have information about the gaseous phase of this cycle and cannot confirm paths, rates and fluxes of N into and from these wetlands. The $\delta^{15}N\text{-}NO_3^-$ is currently being explored, but these results are not conclusive, either because we have not observed a typical denitrification trend (Chen et al. 2009), or our results suggest nitrate may be derived from fertilizers and from atmospheric sources. It is worth to explore both of the latter possibilities: the first one might represent regional water flow from areas with use of synthetic fertilizers, and upward via groundwater discharge. The second alternative implies that wet and dry nitrate deposition plays an important role (Poor et al. 2001). Further research is required for having information of the actual N processes and sources.

P in water. Soluble reactive phosphorus is regularly low, from 0.05 to 0.2 mg $P\text{-}PO_4^{3-}/L$. The largest share of P in wetlands is organic, as high as 90%; similar to Norg, likely derived from cells and organic debris. We think that this measured concentration is controlled by the geological and edaphic characteristics of karst landscapes, where calcite precipitates phosphorus in mineral complexes, forming Ca-Fe/Al-P minerals (Shenker et al. 2005; Gao et al. 2019). So, most of the P is not dissolved but precipitated and stored in sediments and soils, as well as in plant tissue (see below P in plants).

N and P in plants. Presently, we only have information about the N and P concentration and stock in roots of one of the dominant species in sabana wetlands - Cladium jamaicense (Sawgrass). TN in roots of C. jamaicense oscillates between 6 and 12 g N kg^{-1} roots and TP from 24 to 52 mg P kg^{-1}, separated by three orders of magnitude, with a N:P ratio from 50 to more than 2000. This is higher than the average N:P ratio of terrestrial plants (50; Elser et al. 2000); such high values have not been previously reported (Wassen et al. 1995). Results of N and P experimental enrichment showed that N:P ratios are indicative of the relative availability or deficiency of either nutrient (Güsewell et al. 2004). Thus, elevated N:P ratios can be interpreted as current P deficiency, so that this community can respond to P fertilization (i.e. external inputs). These values can also be interpreted in light of all the ecological processes such as carbon assimilation, nutrients uptake, allocation, biomass turnover and reproduction, among the most important (Güsewell 2004). We have research in progress regarding Eleocharis cellulosa.

N and P in soil. Studies on nitrogen fixation report annual nitrogen fixation rate of periphyton mats around 9 g N m^{-2} $year^{-1}$, likely in the high end for cyanobacteria when compared with other tropical karst environments (Vargas and Novelo 2007). The concentration of TN and TP in the soil of sabana wetlands are separated by three orders of magnitude, TN from 3 to 15 g N kg^{-1} and from 4 to 10 mg P kg^{-1}, where the N:P ratio gets as high as 50,000. So, we think that the little available P in soil might be associated to adsorption or precipitation with hydroxides, iron, manganese or sequestered by ion exchange with clays (Ponnamperuma 1972). Also, in calcareous soils, P is associated to minerals such as hydroxyapatite or vivianite (Audette et al. 2020). The TN in soil agrees with values reported in floodplain marshes (Bai et al 2004). At global scale, the N:P molar ratio in soils goes from 1 to 77 (Cleveland and Liptzin 2007). This review unfortunately does not included N:P ratios in wetlands, but Bedford and others (1999) mentioned that elevated N:P ratios in soil are common in soils with high OM content. The scarce information regarding molar or mass N:P ratios in tropical wetlands, invites us to further explore this topic, especially in light of climate change and changes in species composition and richness associated with cultural eutrophication.

WHAT WE DO NOT KNOW

As you can tell by the brevity and content of the prior discussion, there is so much that we do not know. To conclude this article, we have identified some areas that we consider priorities for research.

Hydrogeology

Although we have some knowledge of the regional groundwater flow (Bauer- Gottwein et al. 2011), we still need to know more precisely the local groundwater flows, such a groundwater divides (the boundary between groundwater basins), recharge and discharge zones and water budgets, among the most important topics.

Carbon Cycle and Greenhouse Gases

Given climate change, there is great need of the estimation of carbon stocks and budget, and quantification of greenhouse gases emitted from herbaceous wetlands. Some information is available for forested wetlands, particularly mangroves (Adame et al. 2021; Cinco-Castro et al. 2023) and seagrasses (Herrera-Silveira et al. 2020), but not for other wetlands.

Biodiversity Beyond Plants

While we have some studies of vegetation, they are no exhaustive. Furthermore, we need a better understanding of the biodiversity of sabana wetlands derived from broad-based ecological studies. A good number of such studies has been completed at the Natural Reserve El Eden that is the first ecological reserve in Mexico located on private property. For example, there is information on the biodiversity of algae, epiphytes, fungi, birds, diatoms, nematodes, insects, gastropods, and mammals. There are also studies on restoration, carbon and nitrogen cycling. This information is posted on the Reserve's website (https://www.reservaeleden.mx/t-tulo) and serves as a good example of what can be produced for sabana wetlands.

Macronutrients and Micronutrients

Although we have some information about the nitrogen and phosphorus in the water, soil and plant roots of sabana wetlands, we do not have information for the gaseous part of the N cycle. We still need to complete information of fluxes, incorporation efficiency, point or diffuse sources, among others. We are in the process of generating knowledge about the distribution of macroelements, microelements, trace elements and heavy metals in a herbaceous sabana wetland, including its water, soil, plants, and snails. Our ongoing research considers heavy metals because of the existence of a road dividing the wetland, presumably a source of contaminants from urban dust. Additionally, two of the most important pending assignments in sabanas are C and Si stocks and balances.

Management and Conservation

Sabana wetlands have not been severely altered, except for road construction. In most of the locations with sabana wetlands in this area of Mexico, local habitants do not have an immediate plan for these lands. One of the key informers in La Esperanza mention that "people are not interested in having an (economic) project on it, and we want to preserve it. But if there is someone with an aquiculture project, we will be willing to listen. But we do not have the money for starting a business". It would be desirable to have a management plan, a living and acting document that aims to conserve biodiversity, maintain sabana ecosystems, and improve the quality of life of the local inhabitants. Such initiative must consider the environment and the society together, with the involvement and participation of several actors acknowledging and willing to adopt this commitment.

CONCLUSION

Our work has just begun and we have a long road ahead. In order to help fill the gaps, we are currently conducting research relative to the elemental composition of sabana wetlands, focusing on macronutrients, micronutrients, trace elements and heavy metals. Some other research topics to consider include carbon, nitrogen, phosphorus, and silicon fluxes and balances. There is also the need of more ecohydrological knowledge about wetlands in general, and we would welcome others to work with us and share information about sabana wetlands. Our work provides a baseline to begin to understand the hydric dynamics or the interaction with the shallow aquifer and the surrounding highlands. It is a starting point. While we have what we believe to be some of the building blocks to establish the current status of some sabana wetlands, we aim to produce more information that can be used to predict ecosystem services for these wetlands. Ultimately, we hope that all of our activities yield supporting information to promote environmental legislation that supports reserves, preserve, protects and restores wetlands and waters that feed them, and to carry out actions and processes to rehabilitate or restore wetlands.

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