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Main Article

Costa Rican wetlands vulnerability index

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Abstract
Costa Rica comprises approximately 6% of the world's biodiversity. Among these lush ecosystems, wetlands are represented in mangrove forests near the sea, along river lowlands, sedimentary and volcanic mountains, and highland páramo landscapes. In 2018, the Ministry of Environment and Energy (MINAE), through the National System of Conservation Areas (SINAC), the United Nations Development Program (UNDP), and the Global Environment Facility (GEF) carried out the new National Wetlands Inventory (NWI) which identified 10,699 wetland polygons. This assessment collected key information such as location, characteristics of the wetland, land use in the vicinity, threats, and other generalities. Based on these valuable results, we propose a wetland Vulnerability Index composed of a Condition Index and a Hazard Index to determine the different vulnerability conditions of each wetland unit. Our findings provide a better comprehension of the status of wetlands in Costa Rica with an environmental geography perspective. Located in a climate change hotspot, Costa Rica's conservation policies and actions should consider how to manage the most vulnerable wetlands at different scales. This methodology can improve and generate regional and national wetlands inventories as a basis for evidence-based decision making in other latitudes.

Keywords
Wetlands, environmental degradation, environmental management, environmental conservation, ecology, biogeography

1 Introduction

Wetlands are considered one of the most productive ecosystems worldwide. They support thousands of communities' fundamental services related to water quality, floods, biodiversity, and wildlife habitat (Costanza, 2006; Shaw and Fredine, 1956; Strassburg et al., 2020). The main drivers of change

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in natural wetlands are climate change, sedimentation, erosion, sea level changes, eutrophication, glaciation, and water table level oscillations (Jackson et al., 2014; Reis et al., 2017). Moreover, changes in wetlands because of human impacts have considerably expanded during the last decades (Mitsch et al., 2010). Land-use intensification can enhance ecosystem services provisioning, but it also pushes changes in ecosystem performance and biodiversity loss, which finally compromise human wellbeing (Felipe-Lucia et al., 2020). Globally, roughly 50% of the global wetland area was depleted in the last century (Hu et al., 2017; Zedler and Kercher, 2005).

Wetland restoration and conservation policies might include comprehensive learning of wetland extent and conditions changes (Patino and Estupinan-Suarez, 2016). There is a clear information gap at national and international scales to account and examine changes in wetlands for large scales using efficient but economic tools (Li et al., 2015). Several national assessments have taken place, for example, in Canada (Mahdianpari et al., 2020), China (Meng et al., 2017), Colombia (Patino and Estupinan-Suarez, 2016; Ricaurte et al., 2017), Ethiopia (Mengistu, 2018), India (Bassi et al., 2014), and Saudi Arabia (Al-Obaid et al., 2017). The first and only National Wetlands Inventory (NWI) made in Costa Rica was published more than 20 years ago (Córdoba et al., 1998). The new NWI (2018) was not just an update but a source of new data such as detailed layers at a small scale, databases with information of each wetland, photographs, and descriptions for most Costa Rican wetland ecosystems. All of them were inputs that motivated us to calculate and generate different analyses such as the ones presented in this paper.

Wetlands worldwide are affected by continuous impacts produced by anthropic activities (Ellison, 2004; Mitsch and Hernández, 2013). The main objective of the NWI was to identify, delimit, and characterize the terrestrial wetlands (lacustrine, palustrine and estuarine ones) of Costa Rica to improve their management, enhance their conservation, sustainable use, and maintenance of wetland ecosystem services (SINAC-UNDP-GEF, 2018a). We aim to assess and analyze the present status of condition, hazards, and vulnerability of Costa Rican wetlands in a holistic approach. Moreover, we want to expand the NWI of Costa Rica as a powerful tool recognizing wetlands characteristics. With that aim, we constructed a vulnerability index (VI) to rank the different wetland areas according to their risk exposure. Then, we used a cluster analysis to evaluate its construction along with two regression models. The first one relates the cluster analysis with the original index construction, and the second one quantifies the association between anthropic activities in Costa Rican wetlands and their ecological sustainability. This approach and information could be helpful to prioritize the areas to be managed for wetlands restoration, understand the drivers that condition their vulnerability in different parts of the country and, at the end, help comprehend the dynamics of tropical wetlands with field data at a national scale further.

II Study area

The definition of wetlands we are using is based on Article 1 of the Ramsar Convention and Article 40 of the Organic Law of the Environment of Costa Rica. This definition states that wetlands are *"ecosystems dependent on aquatic, natural or artificial regimes, permanent or temporary, lentic or lotic, sweet, brackish or salty, including marine extensions up to the posterior limit of seagrass or coral reefs, or in their absence, up to six meters deep at low tide."* Figure 1 shows the wetland areas in the Costa Rican territory.

Fluvial, volcanic, coastal, glacial, and karstic landscapes are the principal geomorphic environments in Costa Rica (Quesada-Román and Pérez-Umaña, 2020). A continuous chain of cordilleras crosses Costa Rica with an NW-SE orientation defining the Pacific and Caribbean basin (Marshall, 2007). This topographic barrier also controls the amount of rainfall in each basin along with the latitudinal shift of the Intertropical Convergence Zone, El Niño Southern Oscillation (ENSO), northeast trade winds, tropical cyclones, and cold fronts (Maldonado, 2018; Durán-Quesada et al., 2020). As a result, their interaction with topography results in two climatic basins, Pacific (bimodal) and Caribbean (unimodal).

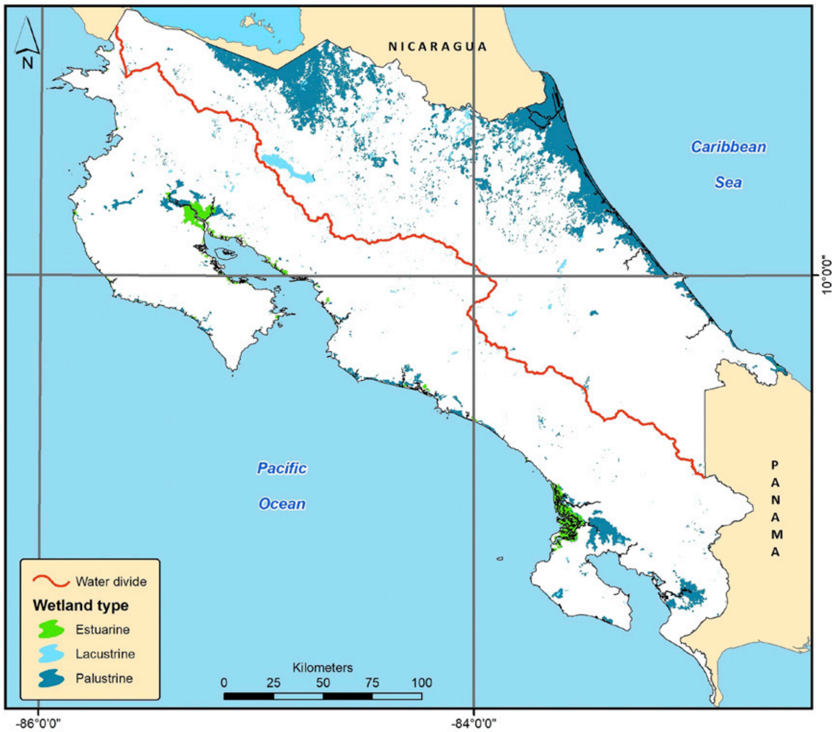

Figure 1. Wetlands identified in the National Wetlands Inventory (SINAC-UNDP-GEF, 2018a). For interpretation of the references to colours in this figure legend, refer to the online version of this article.

Whereas on the Caribbean basin annual rainfall totals are far up to 3000 mm, they are generally below 3000 mm on the Pacific basin (Quesada-Román and Pérez-Briceño 2018).

The interaction between regional and local tectonics plus the intense climatological conditions (high precipitation and temperatures) favor the diverse topography of the country. These dynamic characteristics are key to the wetlands' diversity of Costa Rica. There are wetlands over 3000 m asl in the páramo, some isolated mountain units, and along extensive lowlands in both the Pacific and the Caribbean basins.

Costa Rica is a megadiverse country with a large number of species and endemism comprising páramos, cloud forests, rainforests, dry forests, and wetland ecosystems (Kappelle, 2016). The altitude, significant topographic barriers, and soil complexity justify the distinct ecosystems in the country (Antonelli et al., 2018). Intense land-use changes and deforestation dominated the region from the 1950s to the 1990s. On a positive note, numerous conservation policies inverted deforestation. Moreover, the growth of green tourism and the improvement of sustainable production options helped the country regain a forest cover of 51% (Keenan et al., 2015). The population of Costa Rica reached five million inhabitants in 2018 and, during the last 40 years, its population changed from mostly rural to strongly urban, attaining 75% of the population in 2011. Recently, the Greater Metropolitan Area (or GAM in Spanish) accounts for ~70% of the population (nearly three million inhabitants), lodging 14% of its surface area (Van Lidth De Jeude et al., 2016; Quesada-Román et al., 2021).

III Material and methods

The vulnerability index used field observations, and regulatory information presented in Section 3.1. The indicators were organized and then different weights were assigned to them according to expert criteria; that is, making sure that the lower index values would suggest higher vulnerability. The indicators were then categorized and combined to create a wetland vulnerability index, as explained in Section 3.2. A hierarchical clustering method was used to compare the results from expert criteria, to those from clusters using statistical methods presented in Section 3.3. Finally, two linear regressions were fitted to show (1) the relationship between the vulnerability index and the clustered groups and (2) the association between the vulnerability index and possible hazard variables.

3.1 Data and variables

The base information was extracted from the databases of the new NWI of Costa Rica (SINAC-UNDP-GEF, 2018a). This inventory was carried out from 2015 to 2018 and consisted of three main phases: compilation of previous information and planning, field surveys, and generation of new layers and databases. The first phase consisted of an exhaustive compilation of Costa Rican wetlands previously generated information. After an initial analysis, the fieldwork planning was coordinated with the National System of Conservation Areas (SINAC) and adjusted with two pilot inventories in La Amistad-Pacífico Conservation Area (ACLAP) and Tempisque Conservation Area (ACT).

The fieldwork constituted the longest phase. In presence of at least one ranger from SINAC, a visit was made to each wetland for georeferencing, taking pictures, and completing the NWI Form: 3 pages that contained information about location, characteristics of the wetland, land use in the vicinity, threats, and general comments (SINAC-UNDP-GEF, 2018b). In case of doubt, the primary criterion always was the one of the rangers due to their field experience and knowledge. A total of 149 rangers from 9 of the 10 SINAC regions actively worked in this duty. Due to logistical and funding reasons, the Cocos Island Marine Conservation Area (ACMIC) was not included in the NWI.

Finally, the new layers with the location, and the resulting information databases were made and published for SINAC and the general public. The wetlands included were lacustrine (lakes, ponds, lagoons, and reservoirs), estuarine (mangroves, coastal lagoons, and shrimp farms), and palustrine (swamps, peat bogs, and high-andean seasonal lagoons). Rivers were not included because there is enough spatial information about them and their characteristics.

Because of legal and cadastral reasons, not all estuarine wetlands were mapped. Most of the mangroves in the Pacific coast will be delimited by SINAC in the future. The information taken from the field did not consider bigger and global threats such as climate change, ENSO, or other hydrometeorological phenomena.

The NWI has three layers with its corresponding database. A general table details information such as name, identification code, location, type, artificial or natural, area, perimeter, and whether they are inside protected areas (PA). A second table includes intrinsic characteristics of the wetland, in agreement with SINAC personnel (rangers) and, in case of discrepancy, always privileging their opinion due to their experience and knowledge.

Binary codes represent if they were present (1) or absent (0) inside or around the wetlands, and follow the parameters explained in the previous paragraph. The definitions for the conditions inside the wetlands are the following (Veas-Ayala, 2018):

1. Good condition: Describes if the wetland is in a state of conservation good conditions.
2. Restored: Indicates whether the wetland was ecologically restored prior to the NWI visit.
3. Restoration process: Denotes whether an ecological restoration process is happening or not in the wetland at the time of the visit.

4. Drained: Presence or absence of artificial drainages inside the wetland.
5. Livestock Present: Presence or absence of livestock inside the wetland.
6. Invasive Plants: Presence or absence of invasive plants in the wetland.
7. Dry: Refers to a dry site that maintains wetland conditions, or not.
8. Artificial: Indicated if the wetland formation is not natural.
9. Sedimented: Presence or absence of a sedimentation process inside the wetland.
10. Contaminated: Presence or absence of contamination in the wetland.
11. Silting: Presence or absence of a silting process inside the wetland.
12. Cultivated: Presence or absence of crops inside the wetland.
13. Other: Presence or absence of some alteration factor besides the aforementioned, such as fire or burning, deforestation, fragmented by infrastructure, and/or filled.

A second set of definitions were used for the land use in the surroundings, using a 150 meters buffer, and with the same binary coding as before. The definitions are as follows (Veas-Ayala, 2018):

1. Forests: Presence or absence of forests.
2. Shrubland (*charral*): Presence or absence of shrublands.
3. Savanna: Presence or absence of savannas.
4. Reforestation: Presence or absence of reforestation processes, natural or with plantations.
5. Intensive livestock: Presence or absence of intensive livestock.
6. Extensive livestock: Presence or absence of extensive livestock.
7. Agriculture: Presence or absence of agricultural or forest crops.
8. Aquaculture: Presence or absence of aquaculture for commercial use.
9. Fishing: Presence or absence of subsistence and artisanal fishing.
10. Mollusk: Presence or absence of mollusk extraction.
11. Resource extraction: Presence or absence of extraction of mineral resources (mining).
12. Infrastructure: Presence or absence of infrastructure (roads, buildings, etc).
13. Tourism and commerce: Presence or absence of tourism and/or commerce activities.
14. Aquatic transportation: Presence or absence of aquatic transport.
15. Industry: Presence or absence of some type of industry.
16. Others: Presence or absence of other influencing factors not mentioned above in the surroundings.

3.2 Vulnerability index

To build the vulnerability index, the variables defined in the previous section were used and ranked according to expert criteria. This index includes two dimensions: condition (CI) and hazard (HI). Condition refers to a weighted sum to describe the state of the area. It uses variables collected using the survey: good state, restored, and under a restoring process, each of them being binary, which means that the area either had it (1) or not (0), multiplied by a fixed positive weight. Additionally, nine possible ecological interactions identified in the survey were also summed up, multiplied by a negative weight. In this way, the higher the index value is, the lower the vulnerability.

The formula to calculate the Condition Index (CI) is

$$\begin{aligned} CI = & (Good\ Condition + Restored \\ & + Restoration\ process) * (0.1) \\ & + (Interactions) * (-0.11) \end{aligned}$$

where interactions represent the number of ecological interactions from the following list: drained, livestock, invasive plants, dry, sedimented, contaminated, clogged, cultivated, burned.

Hazard is also a weighted sum that employs different land uses around/near a wetland. Every present land use had a value of one (1) in the formula and multiplied for a value according to the positive or negative impact that each land use can eventually have on the ecosystem.

To calculate the Hazard Index (HI) the formula is

$$HI = Forests*(0.5) + (Savanna + Shrubland)*(0.3) + (Reforestation + Aquaculture + Fishing)*0.1 + (Mollusk + Tourism.Com + Transp.Aqu)*(-0.1) + (Industry)*(-0.2) + ExtensiveLivestock*(-0.2) + ResourceExtraction*(-0.3) + (Agriculture)*(-0.4) + (IntensiveLivestock + Infrastructure)*(-0.5)$$

The results of CI and HI were then normalized from zero (0) to one (1), where zero represents the worst value of all, and one is the best in each case. Moreover, to obtain the "Vulnerability Index" (VI) we weighed the two previous indexes in different interactions (50/50, 40/60, 60/40). The 60/40 interaction had better spatial distribution using a Jenks natural breaks classification method (Jenks, 1967; Jiang, 2013). Moreover, it gives more weight to the actual conditions inside the wetland but maintains an important value for the impacts on the ecosystems that can be influenced by the activities in the vicinity. This process was made for each one of the 10,699 wetland polygons identified in the NWI for the country.

The final formula for the Vulnerability Index (VI) is the following

$$VI = normalized(CI) * 0.6 + normalized(HI) * 0.4$$

3.3 Cluster analysis

The vulnerability index (VI) was calculated for every polygon, obtaining a total of 10,699 measures between 0 and 1. Given the two dimensional nature of the index (condition and hazard) a simple way to group the measures and classify them into interpretable categories was needed. Furthermore, these groups were to be created based on statistical evidence, in order to evaluate the index constructed by expert criteria. For that, a cluster analysis for each of the dimensions (condition and hazard) was performed. Specifically, a hierarchical cluster method was used, using the Ward's clustering criterion included in the hclust function from the stats basic package in R (R Core Team, 2021).

Two sets of clusters were built: the first one using the intrinsic characteristics of the wetland to group areas according to the state of the wetland (good, bad, recovering), that will be labeled as Cluster Condition (CC) from now on, and the second one using the land-use variables to have groups of wetlands according to the land use that surrounds them and try to establish the relationship between vulnerability and possible influence factors. This last set of clusters will be labeled as Cluster Factor (CF) from now on.

The binary nature of most of the variables used is considered when grouping the different areas. Ward's method diminishes the total within-cluster variance by combining the pair of clusters with minimum between-cluster square distance at each step. Once the clusters were built, a regression analysis was performed to compare how the vulnerability index is grouped according to the cluster group. This means that the response variable is the index, and the covariates are the two different clusters built.

3.4 Regression analysis

Two regression analyses were fitted. The first one had the objective of checking that the results from the vulnerability index matched those from the cluster analysis, and the second one was to relate the index values with possible hazard or risk factors that could be associated with the vulnerability index values.

The first regression used the two cluster groupings as covariates, and the vulnerability index as a response, using the following model

$$VI_{\{i,j,k\}} = \alpha + \beta_i + \gamma_j + \epsilon_{\{i,j,k\}}$$

VI represents the vulnerability index for wetland k, α is the baseline coefficient that quantifies the mean VI for all the wetlands that are in cluster 1 from CC and cluster 1 from CF. Each β_i measures the differential effect in the VI mean, for all the wetlands that are in CC cluster j = 2, 3, 4, 5 with respect to the baseline, and in a similar way, γ_j measures the differential effect in the VI mean, for all the wetlands that are in CF cluster j = 2, 3, 4, 5 with respect to the baseline. Errors are assumed to be independent and equally distributed as normal with constant variance σ^2, which is also going to be estimated along with parameters α, β_i and γ_j for i and j = 2, 3, 4, 5.

After fitting the regression model and testing mean differences using a two-way ANOVA, a Tukey HSD test is going to be used to see if there are differences between cluster groups for both CC and CF clusters. The objective in this case is to evaluate if the vulnerability index has a statistically significant difference in its mean according to the different clusters that were defined in the previous section.

The second regression model also includes the vulnerability index (VI) as a response variable. The difference in this case is that the covariates are the variables related to land use, type of wetland, if it is inside PA, and if it is a natural or artificial wetland. The model can be written as

$$VI_i = \beta_0 + \sum_{j=1}^{p} \beta_j x_{\{i,j\}} + \epsilon_i$$

where VI is the vulnerability index for wetland i, β_0 is the baseline coefficient that quantifies the mean VI for all the estuarine wetlands that are not surrounded by woods, extensive cattle, nor savannas and that are inside PA with no fishing but were artificially created. Each of the coefficients β_j measures the differential effect in the VI mean for each of the covariates $x_{\{i,j\}}$ with respect to the baseline. Errors are assumed to be independent and equally distributed as normal with constant variance σ^2, which is also going to be estimated along with all the β_j coefficients.

The objective in this case is to test the hypothesis that the vulnerability index has a subgroup of more important influence or hazard factors that can help explain and predict when a wetland is more exposed or in a fragile condition. In this way, these variables can be monitored carefully in the future.

For all analysis, we used the computing environment R to perform the statistical analyses R Core Team (2021). The code and data to perform each of the analyses cited in this paper are accessible at https://github.com/malfaro2/humedales. A significance level of 0.0001 was used for all the analyses. The collection of R packages *tidyverse* was used to prepare the data formatting and figures (Wickham et al., 2019).

IV Results

A summary of the most important variables is shown in Figures 2 and 3, where the presence or absence within each wetland polygon is presented. They are shown in red and green depending on whether they affect the wetland. These values are used for the CI and HI calculation, but they also show which conditions are relevant in each part of the country. The results are going to be presented in the order described in a diagram on Figure 4.

4.1 Vulnerability index

The results for the VI (Figure 5) are divided by expert criteria into three groups: 0 to 0.5 are considered high risk, 0.51 to 0.75 are medium risk, and 0.76 to 1 are low risk. Figure 2(a) reflects that the worst ecological conditions are mostly located in the northern border of Costa Rica (A). Other regions with low ecological conditions are Tempisque wetlands (C) and Térraba-Sierpe National Wetland (F). PA normally present good ecological conditions, but sometimes, at their borders, they get worse due to a strong pressure from outside activities. The presence of drainage channels (Figure 2(b)) is observed again at the northern Costa Rican border and the south of Caño Negro Wildlife Refuge (A), the border of the Térraba-Sierpe National Wetland (F), and some scattered patterns in Tortuguero National Park (NP) and Colorado River lowlands (B) and in Las Pangas sector (G). Main drainage channels are present outside PA the most.

Livestock presence in wetlands (Figure 2(c)) is very common in the northern border (A) where the natural flood and dry cycles occur every year, leaving very few other livelihoods in those areas. Moreover, the wetlands in the south of Palo Verde NP are vital for cattle during the dry season, sustaining the creation of the Corral de Piedra Palustrine Wetland (C). Another area with cattle presence is the north of the Térraba-Sierpe Wetland (F), where livestock are in the surroundings and sometimes within the protected wetland, which threatens this protected ecosystem. Finally, agriculture is commonly

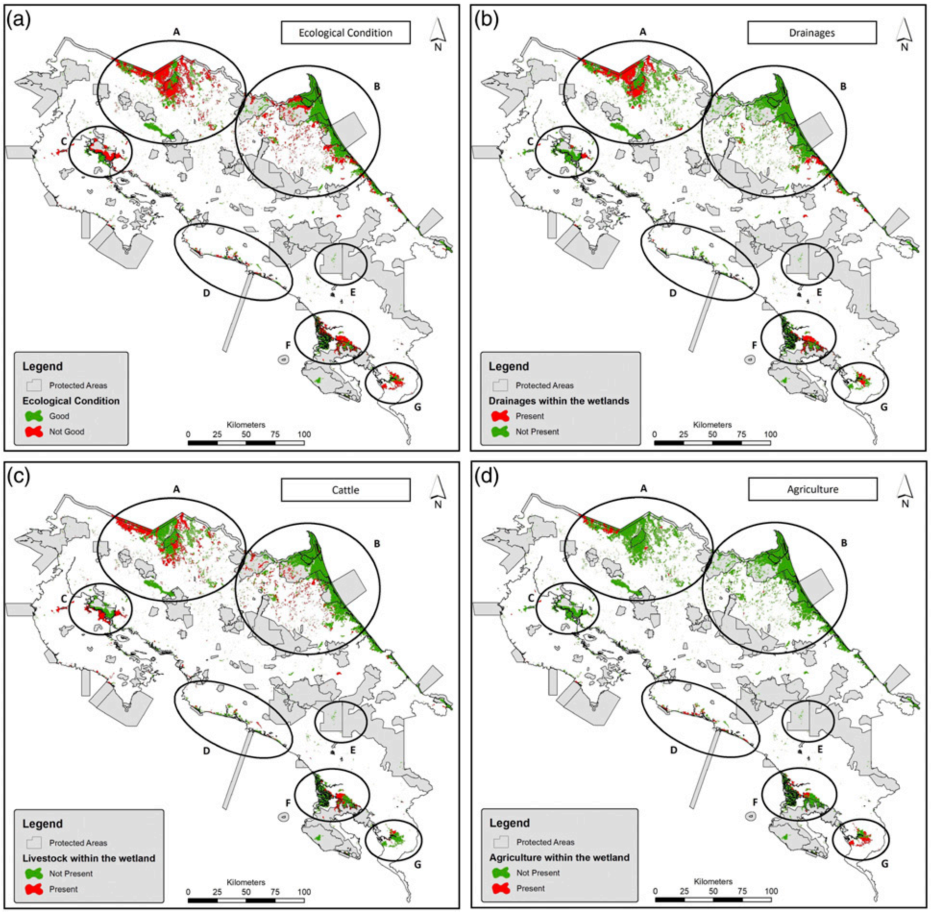

Figure 2. Good ecological conditions, drainage, livestock, and agriculture within the wetlands in Costa Rica. Circles depict the most relevant wetland zones for Costa Rica. For interpretation of the references to colours in this figure legend, refer to the online version of this article.

present along the country (Figure 2(d)). These sites are mostly used for rice crops in the central Pacific (D) and the south of the country (G & F), but there also are some places with sugar cane and palm tree within the wetland, particularly where the water table is close to the soil and gets dry during certain periods of the year, increasing its fertility.

For the HI, Figure 3(a) shows four of the most relevant land uses that were identified in the NWI around wetlands, which can impact them positively or negatively. From the total, 61% of these ecosystems have forests in their vicinity, reflected almost throughout the country, except for some little sectors near the northern border (A) and into the Térraba-Sierpe National Wetland (F). Almost the same relation is observed for the extensive livestock farming (ELF), present in the surroundings of 59% of the wetlands, denoting that some of the landowners combine these two uses in their properties, which is a common practice in Costa Rica, especially in lower and flatter lands (Figure 3(b)). Nearly a quarter of the total wetlands (22%) have agriculture near them. Among the crops named before, there is a growing presence of pineapple and orange crops, particularly in the northern zone of the country (Figure 3(c)). Finally, 58% of wetlands have some kind of

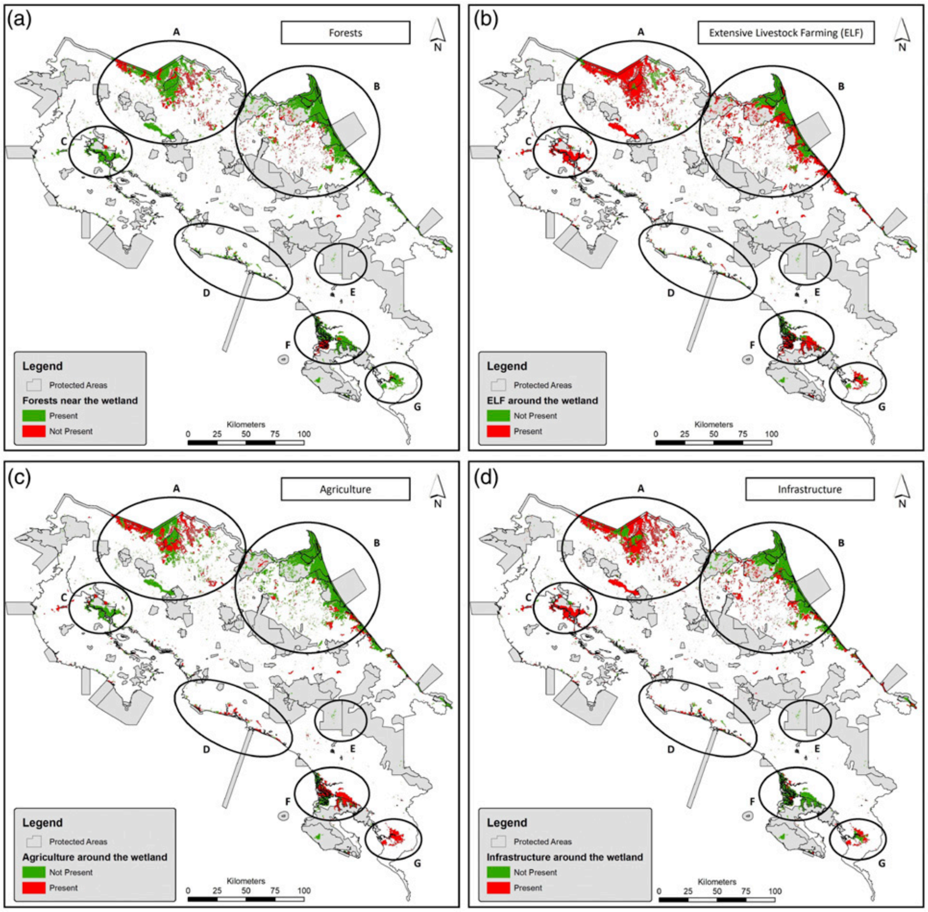

Figure 3. Forests, extensive livestock farming, agriculture, and infrastructure around the wetlands in Costa Rica. For interpretation of the references to colours in this figure legend, refer to the online version of this article.

infrastructure near them, particularly roads and culverts that lead to the different properties and farms near these ecosystems (Figure 3(d)).

When the CI and HI are combined in a 60/40 relation by expert criteria (Figure 5), the VI reflects the sectors where wetlands are more likely to be altered or even disappear. The northern border (A) is the area with the largest surface in high vulnerability. This situation is even more visible in the Caño Negro Wildlife Refuge due to its denomination as a PA. Besides, there are some high areas also in the Palo Verde NP (C) and the Térraba-Sierpe National Wetland (F).

The average VI in wetlands that are within PA is 0.717 (SD = 0.201). This value increases to 0.810 when only wetlands within NPs and Biological Reserves are considered, the two most restrictive management categories of Costa Rican PA. They present a distribution oriented to the higher values, meaning that most of the wetlands have a medium to low vulnerability when protected. This is particularly visible in the Tortuguero NP and Barra del Colorado Wildlife Refuge (B), the Corcovado NP, and in the high-Andean wetlands, located in the Chirripó NP and La Amistad NP (E). In wetlands that are on the limits of a PA, meaning that they are partially within those areas, the average VI reduces

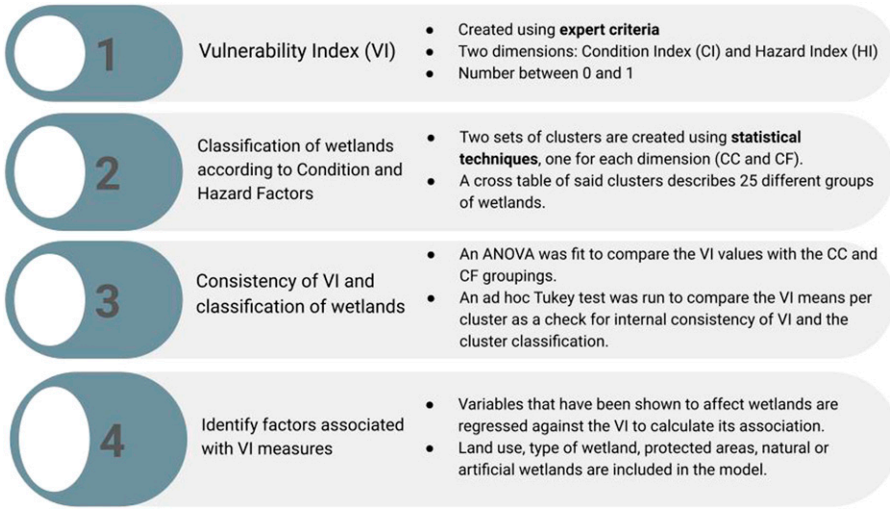

Figure 4. Methods flowchart. Summary from each of the steps followed by this work. For interpretation of the references to colours in this figure legend, refer to the online version of this article.

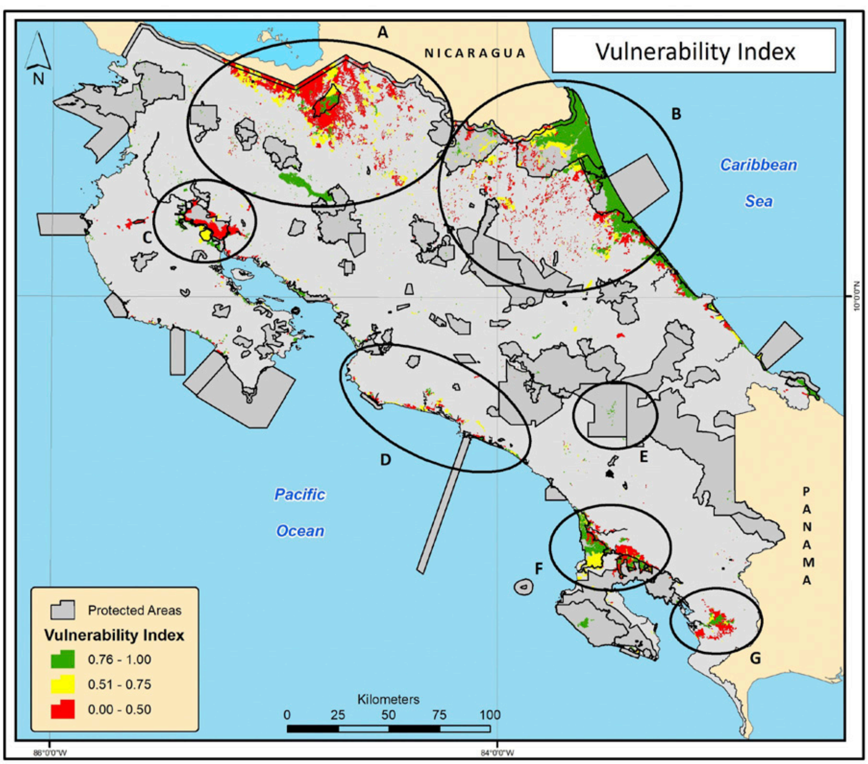

Figure 5. Vulnerability index of the wetlands in Costa Rica. For interpretation of the references to colours in this figure legend, refer to the online version of this article.

to 0.621 (SD = 0.217). This suggests that they are more vulnerable to being in the borders that land uses outside the PA, even though some surrounding areas are protected and more restricted. Finally, the wetlands that are outside of any PA have an average VI of 0.52 (SD = 0.223), right on the edge of being considered of high vulnerability, with an important number of them directly in that classification Wetland polygons within PA have an average area of 26,68 hectares, while the ones outside PA average 10,95 hectares.

4.2 Cluster analysis

A hierarchical cluster analysis was performed on the normalized dataset (each variable had its mean subtracted and then divided by its standard deviation), for each of the data tables: CC and CF. A cut was made at 5 clusters for both cases given that within groups sums of squares were minimized at that point. We presented a summary with the number of areas included in each cluster in Table 1, as a crosstab with the two cluster groups.

For CC, the first cluster included all the wetlands that did not register any of the listed characteristics inside its area; that is, that had 0 in all entries except for the variable called "good condition," in which 86% of the areas had a 1, "Livestock present," with only 3% of the areas with a 1, and "Artificial" with 25% of the areas with a 1. We label this cluster as "Good condition." The second and third clusters grouped wetlands that were in bad condition; in cluster three, only 20.4% of areas were graded as in good condition: the majority had sediments, along with a smaller percentage that presented drains, livestock, invasive plants, and dry areas. The second cluster presented the worst conditions, where only 5.3% was graded as in good condition. In this case, the majority was cultivated, and a smaller percentage was contaminated, silted, or burned. Therefore, we label them as "Very bad, contaminated," and "Bad, Invasive plants," respectively. The fourth cluster included areas with livestock, from which only 23.3% were graded as good condition, and was labeled as "Damaged." Finally, the fifth cluster included all the areas that were either under a restoration process or that were restored in the past. In this group, 52.5% of the areas were in good condition, and we label the cluster as "Restauration."

For CF, the first cluster included the majority of wetlands surrounded mostly by extensive livestock and infrastructure; hence, we labeled it as "Livestock." The third cluster included areas surrounded by woods and properties dedicated to touristic activities, we labeled it as "Forest." The other three clusters included a smaller number of wetlands that were adjacent to savanna, reforested areas, intensive livestock, and industry for the second cluster, aquaculture, resource extraction, and infrastructure in the fourth cluster and, last, scrubland (charral), croplands, fishing, mollusk, and aquatic

Table 1. Cross table with the number of wetland areas included in each of the cluster groupings: Cluster condition and cluster factor.

	Cluster 1 CC—Good	Cluster 2 CC—Very bad	Cluster 3 CC—Bad	Cluster 4 CC—Damaged	Cluster 5 CC—Restauration	Total
CF 1—Livestock	2603	433	218	4227	34	7515
CF 2—Savannah	133	6	22	73	2	236
CF 3—Forest	2012	16	64	92	2	2186
CF 4—Infrastructure	474	0	4	25	2	505
CF 5—Transportation	183	0	0	74	0	257
	5405	455	308	4491	40	10699

CC: Cluster condition; CF: cluster factor.

transportation services in the fifth cluster. The labels are shown in Table 1.

The results on how many polygons are classified in each cluster suggests some relationship between the clusters constructed using variables that describe what is inside the wetland areas and what is around them. These results are better interpreted once the relationship between the empirically constructed vulnerability index and the clusters is established. Therefore, the results of the regressions from the next section are of utmost importance.

4.3 Regression analysis

Two regression analyses were fitted using the vulnerability index as a response. The first regression used the two cluster groupings as covariates, and the objective is to run an ANOVA and then a Tukey test to see if there is a significant difference in the VI values between cluster groups for both CC and CF.

The results are presented in Figure 6(a) and (b), where there is clearly a difference in the vulnerability index between all the clusters (both in CC and CF groupings). This indicates good condition and bad and very bad condition polygons can be discriminated successfully using the clusters, in the same way as the expert criteria. The clusters are preferred to distinguish between wetlands that are in good condition and those that are in a restorative process, given that there is not a statistically significant difference on the VI between clusters 5 and 1 for CC.

The second regression was fitted to test the hypothesis that the vulnerability index has a subgroup of more important influence or hazard factors that can help explain and predict when a wetland is more exposed or in a fragile condition. The results are presented in Table 2, where the coefficients from the regression show that palustrine, natural wetlands inside PA have an average VI of 0.544 (intercept of the regression). Compared to them, wetlands with forests, savannah, surrounded by fishing activities, lacustrine, or estuarine have a statistically better VI (p-value < .0001), by 0.233, 0.176, 0.074, 0.112, and 0.036, respectively. Wetlands that have extensive livestock are outside or partially outside of PA and are artificial have statistically lower index values (p-value < .0001), by 0.129, 0.055, 0.063, and 0.134. Regression assumptions for both models were checked via plots; the normality plots are included in Appendix 1.

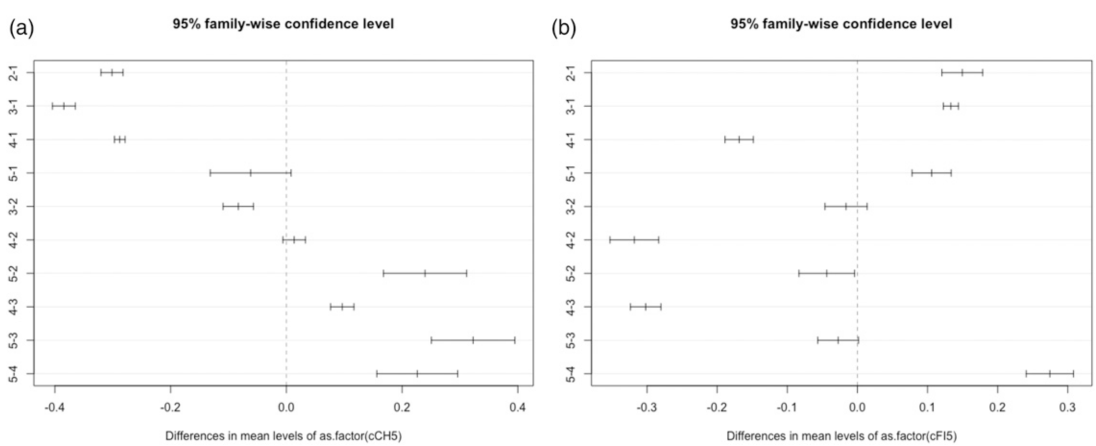

Figure 6. Tukey test results for contrasts between cluster grouping. Bars represent 95% family-wise confidence intervals for differences in the vulnerability index between pairs of clusters for A CC and B CF. Those bars—which represent the contrast between clusters numbered in the label—that intersect 0 are differences that are not statistically important. Labels for clusters are presented in Table 1 and Table 3.

Table 2. Coefficient estimates for the regression Model 2.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)—Inside protected area, palustrine, and natural wetland	0.544	0.005	115.087	<2e-16
Forests	0.233	0.003	66.831	<2e-16
Extensive livestock	−0.129	0.003	−37.717	<2e-16
Savannah	0.176	0.012	14.819	<2e-16
Fishing	0.074	0.008	9.75	<2e-16
Outside protected area	−0.055	0.004	−14.175	<2e-16
Partially outside protected area	−0.063	0.008	−8.292	<2e-16
Lacustrine	0.112	0.004	25.041	<2e-16
Estuarine	0.036	0.007	5.012	5.48E-07
Artificial area	−0.134	0.005	−25.743	<2e-16

Table 3. Average vulnerability index per cluster, for both cluster condition and cluster factor clusters.

Clusters	CC 1—Good condition	CC 2—Very bad, contaminated	CC 3—Bad, invasive plants and silting	CC 4—Damaged	CC 5—Restauration
CF 1—Livestock	0.705	0.324	0.433	0.407	0.64
CF 2—Savannah	0.739	0.349	0.437	0.521	0.834
CF 3—Forest	0.826	0.289	0.482	0.572	0.434
CF 4—Infrastructure	0.505	NA	0.62	0.412	0.913
CF 5—Transportation	0.78	NA	NA	0.827	NA

CC: Cluster condition; CF: cluster factor.

4.4 Statistical highlights

Cluster analysis confirms that the calculated index values are consistent with the groups created using a hierarchical algorithm, given that most of the clusters built using only the binary indicators have average VI values that are aligned with the VI distribution: CC—good condition had the best average, followed very closely by CC—restoration, as presented in Figure 6(a) and (b). From the three clusters that had wetlands with bad conditions, the worst is the CC—contaminated, with a very consistently low index, followed by CC—invasive plants and silting and CC—damaged with similar (and low) values, as presented in Table 3.

The factors associated with low index values are: presenting sedimentation or cultivated areas inside the wetland and livestock in the surrounding areas, as presented in Table 2. Having forest around the area, being inside PA and being a natural wetland (as opposed to an artificial one) are factors associated with higher index values, the results in Table 2 show that these differences are statistically significant. These factors can be interpreted as vulnerability drivers in this case.

V Discussion

5.1 Overview of Costa Rican legislation focused on wetlands

Several environmental efforts to overturn high deforestation and care for natural resources have been made in Costa Rica (Kappelle, 2016; López-Angarita et al., 2016). The National Park Service was created in 1977. During the 1980's, the Ministry of Energy and Mines was founded, shifting in 1982 to the Ministry of Industries, Energy and Mines and transformed in 1988 into the Ministry of Natural Resources, Energy and Mines (MIRENEM). In 1993, through Law N°7412, an amendment was made to article 50 of the Political Constitution of Costa Rica, instituting that *"Every person has the right to a healthy and ecologically balanced environment."* This modification in the Political Constitution started the preparation of a new environmental legislation for Costa Rica. Hence, in 1995, with the creation of the Organic Law of the Environment N°7554 as the base of the environmental policies in Costa Rica, the Ministry of Environment and Energy (MINAE) was established. Finally, the agreement of the Biodiversity Law N° 7788 in 1998 created the Conservation Areas National System (SINAC), an institution with all the jurisdiction of the PA.

Despite the efforts made to safeguard the natural resources of Costa Rica, there was still no legal element to protect the wetlands (Quesada-Román and Pérez-Umaña, 2020). At international and regional level, the country has implemented several policies. Among them, the Central American agreement for the protection of the environment (1989), Ramsar Convention on Wetlands (1991), Convention of Biological Diversity (1992), Mesoamerican Biological Corridor (1997), Central American policy for the Conservation and Rational Use of Wetlands (2002), Marine Corridor of the Eastern Tropical Pacific (2004). At a national level, the Environmental Organic Law made all wetlands of public interest and prohibited all activities that interrupt the natural cycles of these ecosystems. In addition, the Forestry Law (1996) restricts the use and logging of mangroves, among other forestry coverages. Besides, the regulation of the Biodiversity Law of 1998 established the wetland as one type of PA, giving legal protection for the most important ones as well as their ecological functions and the provision of their environmental services and goods. Furthermore, several National Decrees were signed, permitting only a rational use of them, including research and recreation, implementing the National Wetlands Program, the National Wetlands Committee and the technical criteria for identification, classification, and conservation of wetlands. Moreover, the National Strategy for Wetlands (1993) and the National Policy for Wetlands (in 2001 and 2017) were effective. These environmental policy/laws, ecotourism, and environmental awareness transformed Costa Rica into a reforestation hotspot of the neotropics (Nanni et al., 2019). Recently, Quesada-Román and Pérez-Umaña (2020) pointed out that wetlands in the country are key landforms and ecosystems to be protected, evaluated and promoted.

5.2 Wetlands' conditions and threats

The CI describes the ecological status of each wetland, how far it is to its healthy conditions. The analysis of the data demonstrates that the average CI of the country's wetlands is 0.67, but if we take only PA, the average CI rises to 0.80, having 75% of the wetland surface with index values equal and above 0.76. High-andean ecosystems stand out in this item despite their little surfaces (Veas-Ayala et al., 2018) like the seasonal palustrine lagoons present in Chirripó NP (Figure 7(a)). These results show that the wetlands' ecological status inside PA is very good and that current problems are focused on non-PA, where direct and recent impacts on the ecosystem were observed. A number of wetlands smaller than 50 hectares in the Pacific coast need better landowner's attention and management. Some specific artificial wetlands have shown that good management can have a positive impact over the ecosystem health of large wetlands.

The main drivers that condition and directly affect the Costa Rican wetlands (drainage channels, livestock, and agriculture) are also common activities worldwide. Drainage and cultivation induce extreme spatial and temporal variations in the wetlands' water table, inducing their degradation (Dixon, 2002). Clearly, drainage alterations have shifted nutrient and hydrologic dynamics, structure, function, quantity, and configuration of wetland ecosystems (Blann et al., 2009). Linear infrastructure such as drainage channels—present in La Sapera, near the Caño Negro Wildlife Refuge (Figure 7(b)), and access roads have led to fragmentation and retreat of the borders of wetlands in tropical conditions favoring its fragmentation. Moreover, these modifications

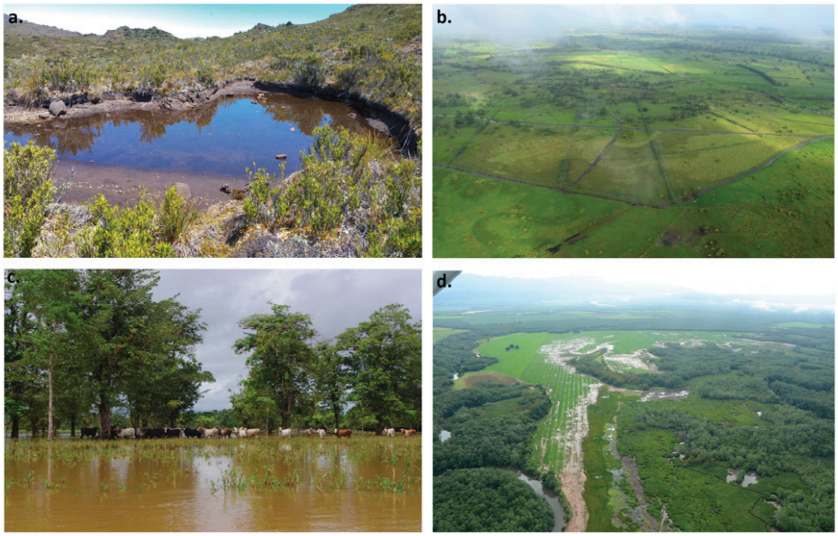

Figure 7. Images corresponding with good ecological conditions, drainage, livestock, and agriculture within the wetlands in Costa Rica. The pictures complement the activities described for the four maps used as an input for the condition index (Figure 2). For interpretation of the references to colours in this figure legend, refer to the online version of this article.

endanger wetlands' stability in both inland and intertidal zones, deteriorating the ecological functions and services of these environments (Berlanga-Robles et al., 2011).

Deforestation historically used to open lands for cattle and agriculture has affected wetlands. ELF, very common throughout the northern zone of Costa Rica (Figure 7(c)), physically damages wetland plants, increases turbidity, compacts the soil, causes soil disturbance, and creates bare ground (Morris and Reich, 2013). Different crops have also impacted the wetlands (Meng et al., 2017). Rice fields have affected the wetlands ecology in many regions of the world due to the intensive use of pesticides and contaminants of emerging concern (Matamoros et al., 2020). This is also present in Costa Rica, for example reaching the edge of the Térraba-Sierpe National Wetland (Figure 7(d)). Another crop with huge impacts is palm oil. Its turn from forests to this crop has inevitably led to a myriad of environmental and socioeconomic impacts (Evers et al., 2017). Agricultural production has drastically transformed the hydrology of landscapes contrasted to historical conditions (Ellison, 2004).

Finally, fire has become an emerging threat for wetlands in recent years. The reduction of the water table plus longer dry seasons and agricultural practices to clear the crop lands (e.g., sugarcane) have had an impact, especially in wooden swamps (SINAC-UNDP-GEF, 2018c). Fires on swamps are particularly difficult to extinguish because they occur on the surface, damaging vegetative structures underground and the seed bank (Page et al., 2009). Fires can also cause the failure of superimposing material, producing further tree mortality (Posa et al., 2011).

5.3 Wetlands hazard triggers

The HI shows the negative or positive impact that nearby land uses and/or activities could cause to the ecological condition of each wetland. Their impacts differ in every wetland, and certain activities such as tourism or water transportation are more local-focused than activities that require bigger extensions enlarging the detrimental consequences (for example, agriculture or extensive livestock farming -ELF-). The land uses and activities that condition the hazard index for Costa Rica had a clearer statistical relation with forests, ELF, agriculture, and infrastructure around the wetlands.

These uses/activities have similar detrimental effects on wetlands around the world. Forest coverage surrounding wetlands is key to reducing their hazard. Nonetheless, wetlands conversion to agriculture has been an increasing threat over the last century worldwide (Reis et al., 2017). Generally, forests seem to be the "charismatic" ecosystems both in conservation and research efforts while wetlands receive less attention (Kandus et al., 2018). Grazing by domestic livestock is another pervasive land use with negative effects on wetlands (Sonnier et al., 2020). Moreover, a clear deterioration of riparian habitats and aquatic ecosystems (including wetlands) have been reported in sites surrounded by pineapple fields during the last decades (Echeverría-Sáenz et al., 2018; Fournier et al., 2018).

Over the last four decades, the built-up structures development continues to be constrained within the boundaries of PA worldwide (De la Fuente et al., 2020). Moreover, infrastructure such as roads is related to considerable biodiversity loss at local and regional scales because of the constrained movement among populations. In addition, other negative effects such as habitat fragmentation, invasion by exotic species, edge effects, increased mortality, or bigger human access to wildlife habitats are likely to grow local extinction rates or decline local recolonization levels (Findlay and Bourdages, 2000). Both road and water infrastructure are the main drivers of change for tropical wetlands favoring its degradation (Ricaurte et al., 2017).

5.4 Wetlands' vulnerability drivers

The VI shows the link between the ecological status of each wetland (CI) in association with the land uses and/or activities performed around it (HI). Cluster analysis served as a confirmatory method for the VI construction, having higher values in wetlands marked in good condition, all the way to lower values in wetlands that were labeled as damaged.

Vulnerability drivers were also confirmed using a regression analysis. Wetlands within PA that have the most restricted activities: NPs and Biological Reserves, where any activity that is not research, recreation in public areas with controlled capacity according to a management plan, and conservation itself is forbidden, have an average VI of 0.81. When all types of PA are included, the average VI is 0.71. The difference relies on human activities as the other PA categories allow the possibility of private owners and, in consequence, activities such as ELF and agricultural crops. Although both VI values are good, when there are no human activities, or they are very controlled, the vulnerability of wetlands is very low. Still, the impact of the PA of Costa Rica on the vulnerability and health of its wetlands is determinant. When going out of PA, the panorama changes drastically, dropping the average VI to 0.52. This means that private lands are drivers for an increased vulnerability on wetlands.

Certain types of wetlands are more vulnerable in Costa Rica. Palustrine are clearly the ones that require more attention according to our results. These ecosystems are often regarded by owners as a problem that limits their activities, recurring to drainages or fires to reduce and even eliminate them, especially for agricultural purposes as mentioned previously. Also, palustrine wetlands are prone to have livestock near and on them, as long as the water table is not very high. Finally, infrastructure is sometimes made close to these wetlands, denoting that human activities are drivers for a higher vulnerability, especially on palustrine, privately owned wetlands. The effect of human activities on wetlands is also common throughout the continent, having examples such as the Pantanal (Roque et al., 2016) and the Atchafalaya Basin (Day et al., 2019) in South and North America, respectively.

Lacustrine wetlands are also present on private lands, but data shows that the high vulnerability relies on small surface ones. They are easier to modify and/or destroy and the problem of diminishing water quality is disturbing in the case of small-scale water bodies such as lakes (Bassi et al., 2014). Contrarily, wetland creation for both retention and diversity purposes benefits the biodiversity of agricultural environments (Thiere et al., 2009). The use of integrated wetlands for livestock wastewater management is key to improve water quantity/quality and increased biodiversity (Harrington and McInnes, 2009).

Estuarine wetlands maintain stability in their VI values regarding their surface, staying at a medium vulnerability. Under Costa Rican law, all mangroves are a maritime public zone that cannot be altered (Acuña-Piedra and Quesada-Román, 2021). As the results show, this does not mean that their vulnerability is low because they have been impacted by the same main drivers in their borders (agriculture, livestock, and fires), reducing their overall surface area. New technologies for monitoring, the importance of having a law that protects them, and the environmental conscience of the people living around make it more difficult to alter them as easily as other wetlands.

VI Conclusions

The role of PA has been widely regarded in Costa Rica (Leguía et al., 2008; Kappelle, 2016; Jovanelly et al., 2020), but they did not repair specifically in the wetland ecosystems. Our results demonstrated that the main difference in vulnerability between these ecosystems in Costa Rica are the occurrence of affecting human activities around them in the first place and the land ownership of their location the second. Wetlands within the borders of PA have an average area of more than twice from those outside them, and are in a good condition, with just 25% of their surface with CI values below 0.76. Within the wetlands, the main actions that affect them in Costa Rica, conditioning the CI, are drainage channels, livestock, and agriculture. The land uses and activities around these ecosystems that determine the HI for Costa Rica are forests, ELF, agriculture, and infrastructure. VI results indicate that the most vulnerable sectors in the country are in the northern border with Nicaragua as well as Caño Negro Wildlife Refuge, Palo Verde NP and the Térraba-Sierpe National Wetland. A positive side is that most of the activities that are considered for the HI can be improved with appropriate management, having a positive impact on wetlands in time. The results of these upgrades will be then observed in the CI, having a better VI as a result. Once again, focusing on the management outside PA is a key piece of advice in this paper. Investing in improvements like water troughs for the cattle, fences on the edges of the wetlands, active measures to manage/use invasive species, low-impact tourism, electric or gas-efficient engines on vehicles, and adapted architecture to appreciate and make a rational use of the wetland constitute solutions for a better management without affecting these ecosystems.

Despite the legal instruments and regulations, there has been a deficient control by the Government and very little capacity for an adequate monitoring of wetlands. Initiatives like the National System of Land Cover and Ecosystems Monitoring (SIMOCUTE) can be a powerful tool, using remote sensing, geographic information systems, and field data from different institutions. Nonetheless, our results indicate that SINAC has to work more outside PA and focus on improving the dialogue with private owners in order to change their actions, which have negative impacts on wetland ecosystems. Biological corridors and Model Forests are legitimate conservation strategies (and currently articulated) to organize conservation efforts outside PA that can be strengthened and promoted as a way of living and provide income while maintaining the quality of the environment.

Costa Rica became a reforestation hotspot of the neotropics due to the last decades' environmental policies implementation, the explosion of ecotourism, and a sensitive consciousness. As with other important ecosystems such as forests, incentives and programs can promote the sustainable use of wetlands as an opportunity for the landowners to improve the ecosystems' management. This work comprises a key contribution to the policy tools that Costa Rica requires with the addition of scientific expertise at the legislative scale. Finally, it is a practical method to be applied at regional scales worldwide.

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Appendix 1

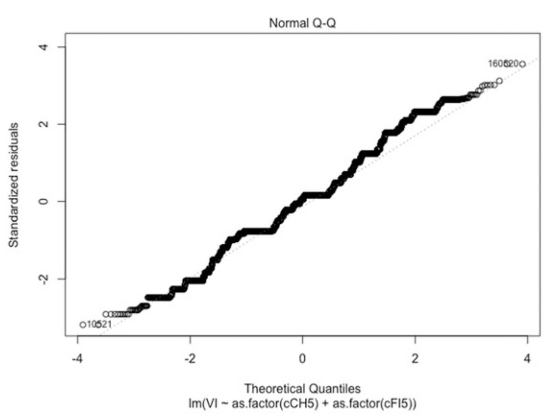

Figure A1. Normality diagnostic for Model 1.

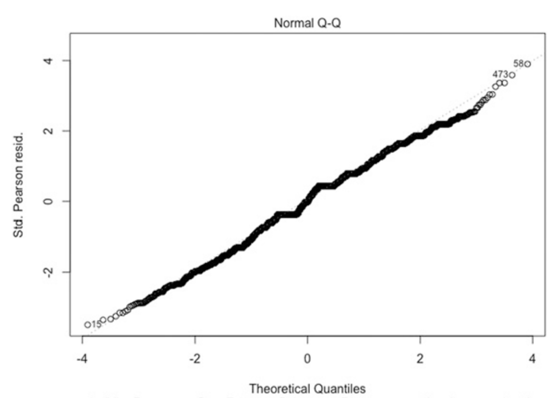

Figure A2. Normality diagnostic for Model 2.