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Conservation

Land cover and land use factors associated with the risk of vegetation degradation in the Arenillas Ecological Reserve

Factores de cobertura y uso del suelo asociados al riesgo de degradación de la vegetación en la Reserva Ecológica Arenillas

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Abstract

Protected areas are priority zones for the conservation of natural and cultural biodiversity, allowing the assurance of goods and services for society. This study evaluates land cover and land adoption factors associated with vegetation criteria risks in the Arenillas Ecological Reserve (REAR) (southern Ecuador), using the Normalized Difference Vegetation Index (NDVI) and anthropic variables to which the vegetation is elucidated as indicators. The analysis procedure was applied using SENTINEL-B2 satellite images based on the Reserve's four ecosystems and the six soil types found. Through multiple linear regression, a risk probability model was determined in relation to the threat variables of agricultural, aquaculture, livestock, population and road zones. The results revealed a higher NDVI value in Flooded Grassland and Mangrove, followed by the Deciduous Shrubland and Deciduous Forest. Correspondingly, 18.7 % of vegetation cover is at high risk throughout the REAR, with the greatest disturbance and threat on the northwestern and northeastern edges of the deciduous shrub forest and southwestern edges of the deciduous forest, and the identical pattern is present at the entrances to the main and secondary roads. On the other hand, for the Mangrove ecosystem, the areas with the greatest variability are those bordering the shrimp aquaculture activity. It is essential to note that if the areas adjacent to the REAR are not protected, the little remaining forest will disappear, limiting connectivity with other natural forests.

Keywords: NDVI, risk factors, dry forest, Arenillas Ecological Reserve, land use.

Resumen

Las áreas protegidas constituyen zonas prioritarias para conservar la biodiversidad natural y cultural, permitiendo el aseguramiento de los bienes y servicios para la sociedad. El presente estudio evalúa los factores de cobertura y uso de suelo asociados a los riesgos del estado de la vegetación en la Reserva Ecológica Arenillas (REAR) (sur de Ecuador), usando como indicador el Índice de Vegetación de Diferencia Normalizada (NDVI en inglés) y variables antrópicas a las que está expuesta la vegetación. El proceso de análisis se efectuó con el uso de imágenes satelitales SENTINEL-B2 con base en los cuatro ecosistemas de la Reserva y los seis tipos de suelo encontrados. A través de regresión lineal múltiple se estableció un modelo de probabilidad de riesgo en relación a las variables de amenaza de zonas: agrícolas, acuícolas, pecuarias, de población y vías. Los resultados revelaron un mayor valor de NDVI en el Herbazal Inundable y Manglar, seguidos del Bosque Arbustal deciduo y Bosque deciduo. Así mismo, 18.7 % de cobertura vegetal se encuentra en alto riesgo en toda la REAR, situándose la mayor perturbación y amenaza en los bordes noroeste y noreste del Bosque Arbustal deciduo y bordes suroeste del Bosque deciduo, y bajo el mismo patrón se presentan en las entradas de las Vías principal y secundarias. En cambio, para el ecosistema Manglar las zonas de mayor variabilidad se ubican en aquellas que limitan con la actividad acuícola camaronera. Es importante indicar que, si no se protegen las áreas adyacentes a la REAR, el poco bosque remanente desaparecerá, limitando la conectividad con otros bosques naturales.

Palabras clave: NDVI, factores de riesgo, bosque seco, Reserva Ecológica Arenillas, uso de suelos.

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1 Introduction

Currently, protected areas (PAs) constitute priority zones for environmental conservation, enabling the proper functioning and safeguarding of biotic and abiotic resources, as well as the maintenance of the goods and services provided by each ecosystem (Union Internacional para la Conservacion de la Naturaleza IUCN, 2005). Globally, PAs encompass a vast expanse of tropical dry forests. Recent studies conducted by the Organización de las Naciones Unidas para la Agricultura y la Alimentación FAO (2020) indicate that of the 218 million hectares of existing forests, 26.7 % are protected. However, unlike rainforests, governments have paid little attention to dry forests, resulting in a lack of protection and a higher risk of human impact (Ramírez et al., 2018); a problem arising from inexperience and a lack of information that has compromised conservation principles (Carey et al., 2000), and which is consequently cause for concern due to the level of threat and vulnerability these ecosystems face (Wright and Muller-Landau, 2006).

In Ecuador, the tropical dry forest, located on the Pacific coast, belongs to one of the 35 biodiversity hotspots (Mittermeier et al., 2011), known as Tumbes–Chocó–Magdalena. Its ecological importance has been the determining factor for the regulation and provision of ecosystem services that are used by society. However, due to their abundant endemic natural wealth, tropical dry forests are the most prone to deforestation and degradation, without a clear understanding of the factors driving the shift to other land uses in these ecosystems. According to Armenteras and Rodríguez (2014), the problem of deforestation in these areas is due to biophysical and social factors such as: the establishment of settlements, easy accessibility due to road construction, proximity to water bodies, as well as inadequate land management and climate change. However, studies conducted by Tapia-Armijos et al. (2015) in the tropical forests of southern Ecuador revealed that the increase in roads in the year 2000 intensified access to previously inaccessible sites, resulting in approximately 46 % of natural forest being converted by 2008 into grassland, agricultural land, and other types of human activity.

According to public data from Ecuador's Ministry of the Environment, Water, and Ecological Transition (MAAE), there are 21 000 ha of dry deciduous forest registered within the National System of Protected Areas (SNAP), equivalent to nearly 50 % of the country's total forest area (41 000 ha) (Riofrío, 2018). Part of this national system is the Arenillas Ecological Reserve (REAR), located in the province of El Oro, which since its creation has faced intense pressure from surrounding communities seeking to carry out agricultural and livestock activities within and around the forest, as well as other human threats such as hunting, logging, and the establishment of aquaculture activities, all of which are direct causes that have impeded the natural regeneration of native species (Ministerio del Ambiente del Ecuador MAE, 2015). According to Ruiz (2018), these types of forests are at high risk, especially due to the human activities taking place within them and in their area of influence. On the other hand, climatic pressures such as rising temperatures and decreasing rainfall are likely to affect the ecological communities of dry forests (Maza-Maza et al., 2021), which means a reduction in ecosystem services related to habitat provision, important for soil conservation and biodiversity (Qian et al., 2022).

Given the great importance of dry forests, and the scarcity of scientific information in the REAR and other areas of Ecuador's Southern Coast, it is necessary to use Geographic Information Systems (GIS) and satellite imagery to gather data on the region. These tools are of great importance and precision for assessing the condition and quality of vegetation, as well as the anthropogenic risks to which ecosystems are exposed. Furthermore, these technologies offer the possibility of conducting analyses at the continental level and over specific time periods (Sudmanns et al., 2020), thereby enabling the timely identification of the most vulnerable areas, the evaluation of land cover and land use transformation processes and their adjacent areas (Faruque et al., 2022), and to assist decision-makers in establishing socioeconomic measures for improved forest conservation management (Baig et al., 2022).

Therefore, the objective of this study is to evaluate the land cover and land use factors associated with vegetation condition risks in the REAR, using the Normalized Difference Vegetation Index (NDVI) as an indicator and considering various anthropogenic variables to which the area is exposed. According to Gonzaga-Aguilar (2015) and Mesa-Sierra et al. (2022), the NDVI is an indicator of active photosynthetic biomass related to crop behavior, condition, and the health of natural vegetation. The study began with the hypothesis that changes in vegetation cover within the reserve are due to the socioeconomic pressure of productive activities carried out in its area of influence. Thus, the results obtained will allow for greater precision and interpretation of information regarding the REAR's area of influence, which will lead to sound decision-making in the proposal and implementation of public policies and restoration and conservation programs in each of the protected area's ecosystems.

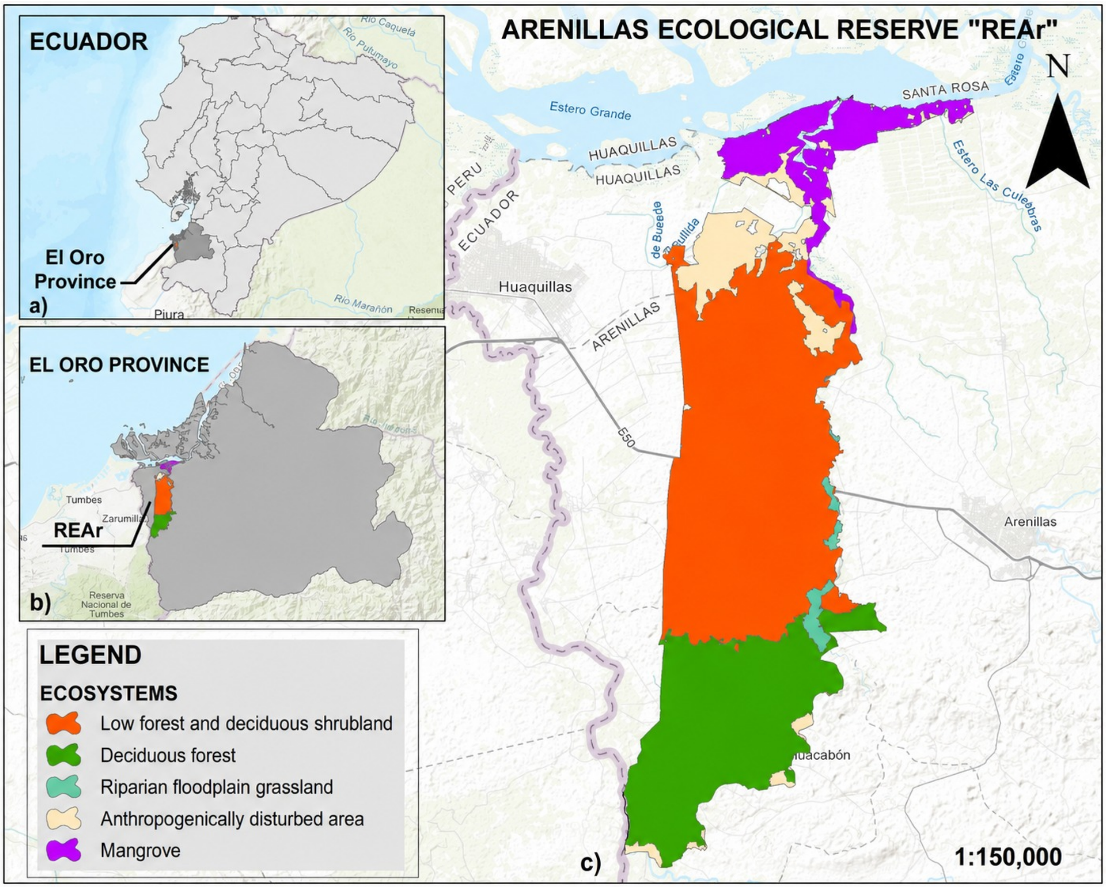

Figure 1. Study area and ecosystems. a) El Oro Province, Ecuador; b) the REAR in El Oro Province; and c) Ecosystems of the REAR

2 Materials and Methods

This study was conducted in the REAR, located in southwestern Ecuador, in the Zarumilla River basin of El Oro Province (see Figure 1). According to the Reserve's management plan, this area covers 13 170.025 ha (Ministerio del Ambiente del Ecuador MAE, 2015). The climate varies by zone, characterized by a warm, arid climate in the lower zone, with annual precipitation of up to 350 mm; a very dry, warm climate in the middle zone; and a warm, dry climate in the upper zone, with annual precipitation ranging from 500 to 1 000 mm (Instituto de Ecología Aplicada ECOLAP and Ministerio del Ambiente del Ecuador MAE, 2007). The elevation ranges from 0 to 300 meters above sea level (masl) and the average temperature is 24 °C. It is the country's most important protected area of xerophytic vegetation, with a recorded 111 plant species, mostly native and endemic, with the *Mimosaceae* family being the most prominent, followed by the *Cactaceae* and *Bromeliaceae*. As for the fauna, the record consists of 159 species, with birds being the most prominent group, comprising around 79 species (Union Internacional para la Conservacion de la Naturaleza IUCN, 2020). Due to its large size, the area also includes mangrove and floodplain grassland vegetation zones.

2.1 Analysis of vegetation status

For this analysis, the Normalized Difference Vegetation Index (NDVI) was applied, which is calculated by combining the reflectance values captured in the spectral range from red to near-infrared (Gonzaga-Aguilar, 2015), as explained in the following equation:

$$NDVI = \frac{NIR - R}{NIR + R} \quad (1)$$

Where NIR is the atmospherically corrected reflectance corresponding to the near infrared; R is the atmospherically corrected reflectance corresponding to the red. SENTINEL-2B images were used for the months with the highest precipitation: January, February, March, April, May, and June 2018; the remaining months were excluded due to their seasonal dryness and the high percentage of cloud cover in the images. The NDVI was calculated for each image scene based on the satellite's bands 4 and 8. Using the various available satellite images and the quality mosaicking method—which involves spatially linking a set of image data (Eraso et al., 2022)—a monthly composite was generated for the months of January through June, and each pixel was assigned the maximum NDVI value. This process was carried out by adapting a specific script (available at http://www.gisandbeers.com/RRSS/Engine/Script-GEE-lista-indices-vegetacion.txt) on the Google Earth Engine (GEE) platform (see Figure 2). This tool stands out for its high processing capacity, which allows for the addition of more resources in parallel when analyzing the data (Gomes et al., 2020).

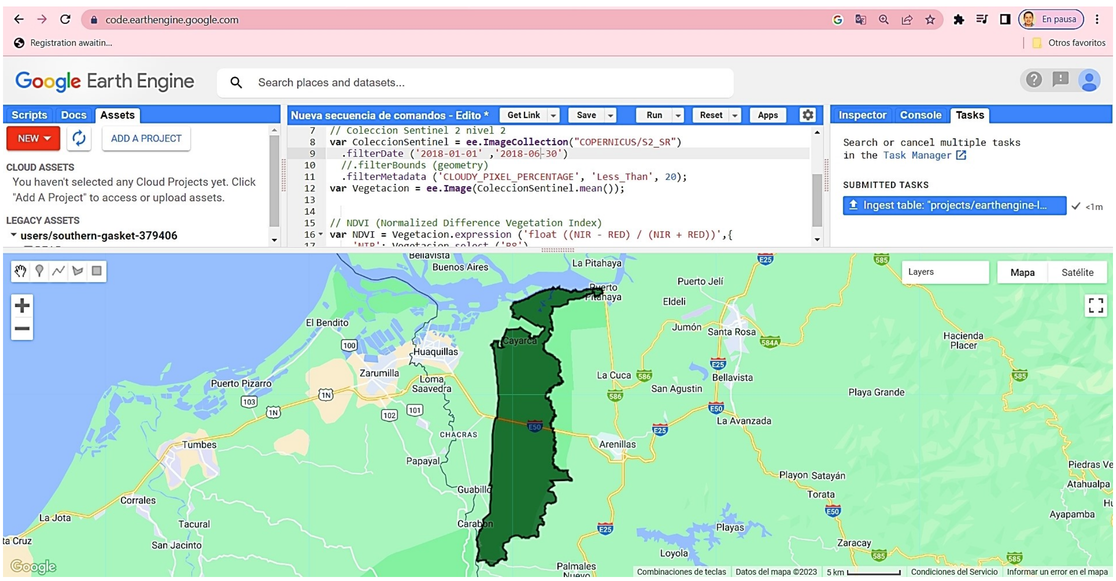

Figure 2. GEE platform interface, identifying the study area and NDVI processing

Once the six monthly NDVI composites were obtained, the mean (average value) and maximum statistics were calculated; the latter was used to analyze the data range and find the largest value per cell across multiple rasters, resulting in two sets of new raster files (mean; January to June; and maximum; January to June). A zonal statistical operation was performed on each raster for the different ecosystems in the study area, creating four raster files for each statistic.

The defined ecosystem types correspond to: (1) Jama-Zapotillo lowland deciduous forest (Deciduous forest), (2) Jama-Zapotillo low forest and deciduous shrubland (Deciduous shrub forest), (3) Jama-Zapotillo mangrove (Mangrove), and (4) Jama-Zapotillo lowland riparian floodplain grassland (Floodplain Grassland) (Ministerio del Ambiente del Ecuador MAE, 2013).

Finally, the created files were merged using the "Mosaic to New Raster" tool, determining the average NDVI of the mean and maximum values for each identified ecosystem. This process was carried out in ArcGIS version 10.2.

2.2 Analysis of vegetation risk factors

As established in the REAR Management Plan (Ministerio del Ambiente del Ecuador MAE, 2015), the main threats affecting the conservation of the dry forest are anthropogenic in origin: land tenure disputes; encroachment into the ecological reserve area; extraction of forest species; and increased pressures due to agricultural and aquaculture activities. Therefore, based on this criterion, a 1-km buffer zone was established outside the reserve, and five land cover and land use categories were considered as risk variables for vegetation, as follows: (1) Aquaculture zone, (2) Agricultural zone, (3) Livestock zone, (4) Population, and (5) Access roads, in accordance with the findings of Barber et al. (2014), who state that the factors most conducive to deforestation are the growth of settlements, the expansion of agricultural and aquaculture activities, proximity to roads and rivers, and soil capacity.

Population and road data were obtained from the National Information System (SNI) platform (**?**). For roads, the following categories were considered: paved two-lane or wider roads, narrow unpaved roads, and summer roads; while for aquaculture, agriculture, and livestock land cover, Google Earth images were used, and each of the areas was digitized using QGIS 3.10 software. These were then cross-referenced with the Ministry of the Environment's (MAE) 2018 land cover and land use map and reclassified in ArcGIS 10.2 software, resulting in a binary map. Subsequently, using the cost distance tool, the shortest weighted distance was determined for each land cover variable (De Smith et al., 2007), yielding distance rasters to the following zones: aquaculture, agriculture, livestock, population, and roads.

2.3 Statistical analysis

Based on the monthly NDVI composites, the average index was estimated for the entire vegetation cover of the REAR. As an initial statistical analysis, considering that different soil types and their characteristics are not always conducive to producing the nutrients necessary for healthy vegetation growth (Moreno et al., 2018), analysis of variance (one-way ANOVA) was used to analyze the potential disturbance effect on vegetation caused by different soil types and ecosystems (Cantón et al., 2020). This developed model allows for comparing the variances among the means of different groups (Liu and Wang, 2021). In this case, it explains whether the quadratic model is significant among the independent variables of ecosystems and soil order based on the dependent variable of NDVI response. Soil information was obtained from the geopedological mapping on the Ecuadorian Agriculture Portal (Ministry of Agriculture and Livestock–MAG, 2016). To analyze whether more than one variable influences or is correlated with the value of a third variable, the multiple linear regression model was applied to fit linear models, which allow us to determine in which of the REAR ecosystems vegetation is at greatest risk of disturbance in relation to independent threat variables such as distances to: (1) agricultural areas, (2) aquaculture, (3) livestock, (4) population, and (5) roads (Cayuela, 2010).

3 Results and Discussion

3.1 Vegetation status in the ecosystems and soil types of the REAR

Based on the results of this analysis, it was determined that within the REAR Ecological Reserve, the average NDVI for each of the ecosystems present ((1) Deciduous Forest, (2) Deciduous Shrub Forest, (3) Mangrove, and (4) Flooded Grassland), as defined by Ministerio del Ambiente del Ecuador MAE (2013), fluctuates within a range of -0.19568 to 0.85521, where values with an NDVI < 0 correspond to non-vegetation cover, and values close to the lower range (below 0) correspond to areas with greater anthropogenic pressure, causing degradation of the ecosystems' natural vegetation, while values close to the upper range indicate dense vegetation cover with low levels of anthropogenic pressure.

Research conducted in forests with characteristics similar to the REAR, such as the Cerro Blanco protective forest located in the Guayaquil canton, where NDVI values exceed 0.50—equivalent to dense and well-developed vegetation—has demonstrated the importance of its ecosystem services and the need to implement conservation measures, due to the anthropogenic threat surrounding it (Cervantes et al., 2022). In fact, most of the vegetation cover within the REAR (see Figure 3a) is an indicator of the effective conservation monitoring work carried out by its park rangers. This pattern is not unique to this region; globally, lower rates of deforestation are also observed within protected areas (Figueroa and Sánchez-Cordero, 2011).

Based on a study of the spatial dynamics of the REAR, with the aim of examining the behavior of outlier data points related to NDVI values in conjunction with variables from the four ecosystem types ((1) Deciduous forest, (2) Deciduous shrub forest, (3) Mangrove, and (4) Flooded grassland), and the six soil orders ((1) Miscellaneous soils, (2) Vertisol, (3) Entisol, (4) Alfisol, (5) Inceptisol, and (6) Aridisol) of the REAR, box plots were created. Figures 3b and 3c compile these graphs, where it was observed that most outliers (vertical lines) lie below the median (2nd quartile), i.e., they are values that are distant from the third quartile and first quartile, 1.5 times greater than the interquartile range (Montealegre, 2017). Likewise, an asymmetric distribution toward high values was observed between the NDVI response factor and the variables of the four ecosystem types, as well as an asymmetric distribution of the NDVI toward medium to high values across the six soil orders.

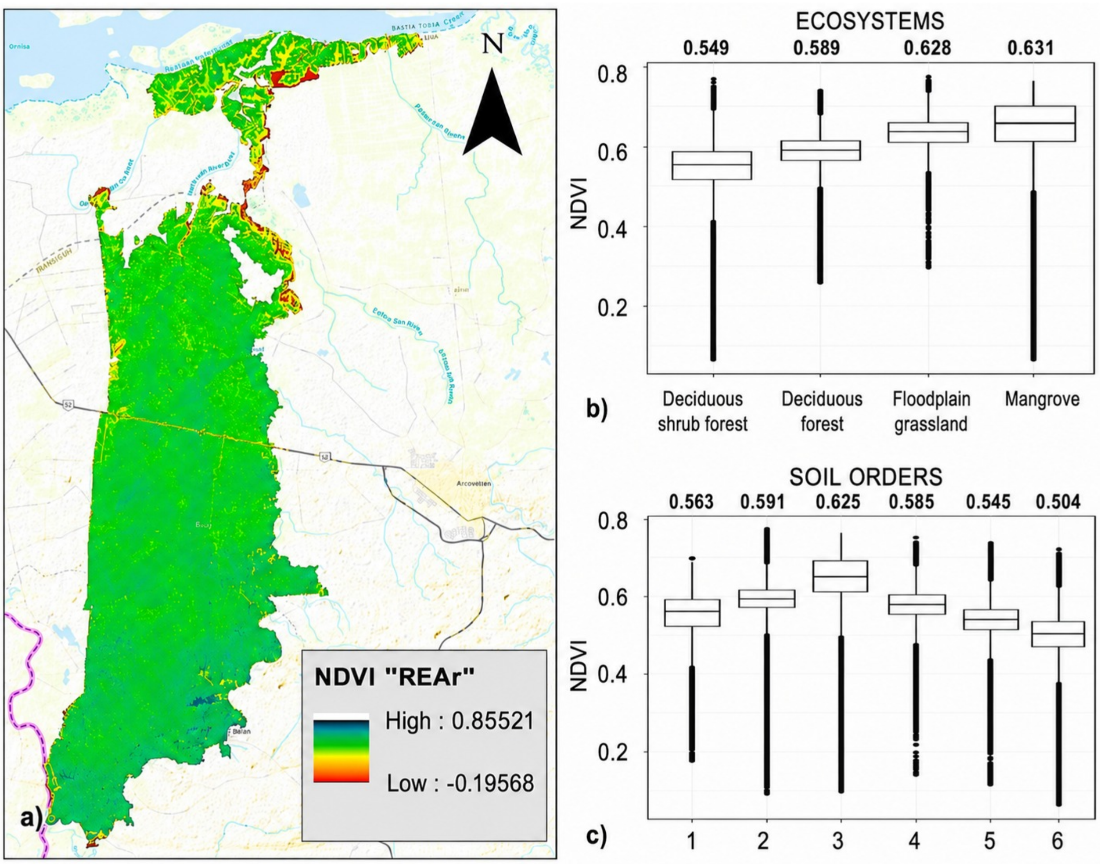

Figure 3. Vegetation status: a) Spatial distribution of the REAR's NDVI, b) box plot with NDVI averages by ecosystem, and c) box plot with NDVI averages by soil order

In Figure 3b, the size of the boxes reveals that the highest NDVI value had a median of 0.631 in the Mangrove ecosystem, covering an area of 1 239 ha, accepting small areas located in the northeast at the edges of the forest patches, a sector adjacent to aquaculture activities, where the lowest NDVI values (NDVI < 0.1) are recorded, indicating a higher level of disturbance and poor vegetation condition. According to Torres et al. (2014), this phenomenon is caused by the proximity of certain patches to disturbed areas, directly impacting the ecological conditions of the vegetation. On the other hand, vegetation with high NDVI values, with medians above 0.628, is also located in the floodplain grassland ecosystem, suggesting that the 184-hectare area comprises vigorous natural vegetation, such that various threats—including population growth, deforestation, and the establishment of agricultural and livestock activities (Aldás, 2019)—do not have a significant influence on the area.

Regarding the NDVI values for the Deciduous Forest and Deciduous Shrub Forest, the size of the median boxes was smaller, corresponding to averages of 0.589 and 0.549, respectively, implying that anthropogenic pressure on the natural vegetation in these ecosystems is significant in certain sectors. For example, for the Deciduous Forest, with an area of 3 597 ha, the areas with the highest degree of disturbance are located at the edges of the remaining vegetation patches in the southwestern sector. In contrast, for the largest ecosystem (6 773 ha), the Deciduous Shrub Forest, the areas under the greatest threat are concentrated at the edges of the remaining vegetation patches in the northern, eastern, and western sectors. This is due to direct contact with areas of agricultural and aquaculture activity, as well as the areas adjacent to the main road and trails that crisscross the zone.

In Figure 3c, for the soil types ((1) Miscellaneous soils, (2) Vertisol, (3) Entisol, (4) Alfisol, (5) Inceptisol, and (6) Aridisol), the highest median NDVI value was dominant for Entisol, with an average of 0.625, followed by Vertisol and Alfisol, with values of 0.591 and 0.585, respectively. In contrast, median values in the moderate range were found in Miscellaneous soils, with an average of 0.563, followed by Inceptisol, with 0.545; for the Aridisol soil type, the average NDVI was the lowest at 0.504. Across the entire study area, 72 % of Entisol soils were located in the mangrove ecosystem, specifically covering 92 % of its surface area, followed by 8 % of Vertisol and Miscellaneous soils. Leiva et al. (2009), in their research in Costa Rica, argue that Entisols, being in a chronosequence of physicochemical changes, could cause water stress in plants.

For the Deciduous Forest, the soils with the greatest coverage were: Alfisol at 56 % and Vertisol at 32 %, followed by Entisol and Inceptisol at 9 % and 3 %, respectively. Meanwhile, in the Deciduous Shrub Forest, due to its extent and geographic location, the area was mostly covered by Inceptisol and Alfisol soils (38 % and 28 %, respectively), followed by Aridisol (18 %), Vertisol (14 %), and 2 % between Entisol and Miscellaneous soils. The Flooded Grassland consisted of 58 % Vertisol and 42 % Alfisol. The diversity of soils present in the Reserve may be due to certain factors such as slope; in flat areas, the process of localized accumulation of water and nutrients is more effective than on steep slopes (Clark, 2002). The seasonal climate in areas with very low precipitation and high temperatures would favor aridisols (Botta et al., 2019). The likely presence of volcanic rocks would be the formers of vertisols and entisols, whereas inceptisols and alfisols are more conducive to undulating and mountainous landscapes (Hartemink and Bockheim, 2013).

Table 1. ANOVA of interaction between NDVI and ecosystem variables and soil orders

Variables	**Degrees of freedom**	**Mean squares**	**Sum of squares**	**F-value**	**Pr (>F) (*p*-value)**
Ecosystems	3	869.5	289.83	107 470	<2e-16 ***
Soil order	5	1 313.2	218.86	81 154	<2e-16 ***
Two-factor interaction	5	78.2	13.04	4 834	<2e-16 ***

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 ''.

Through the calculation of the means in the ANOVA (see Table 1), significant differences were found between the NDVI response factor and the ecosystem and soil order variables. It was shown that the F-value for the two study variables was significant at the $\alpha = 0.05$ significance level, since Pr $> F$ (probability greater than the calculated F) is equal to $< 2 \times 10^{-16}$, the latter value being less than 0.05. The interaction variable of the two factors showed the same level of significance, thus determining that both soil and ecosystem, as well as their interactions, are highly significant; i.e., the ecosystem and soil condition the NDVI response, and the effect of each depends on the other. In this case, soil has the greatest influence; all ecosystems exhibit a nearly identical response with minor differences in the Flooded Grassland and Mangrove ecosystems, and their productivity is highly conditioned by soil (see Figure 4), relative to the results obtained by Mesa-Sierra et al. (2022), where NDVI and soil fertility values were uniformly distributed between 0.21 and 0.34, considered unhealthy vegetation due to its location in regions with high anthropogenic impact and ecological degradation.

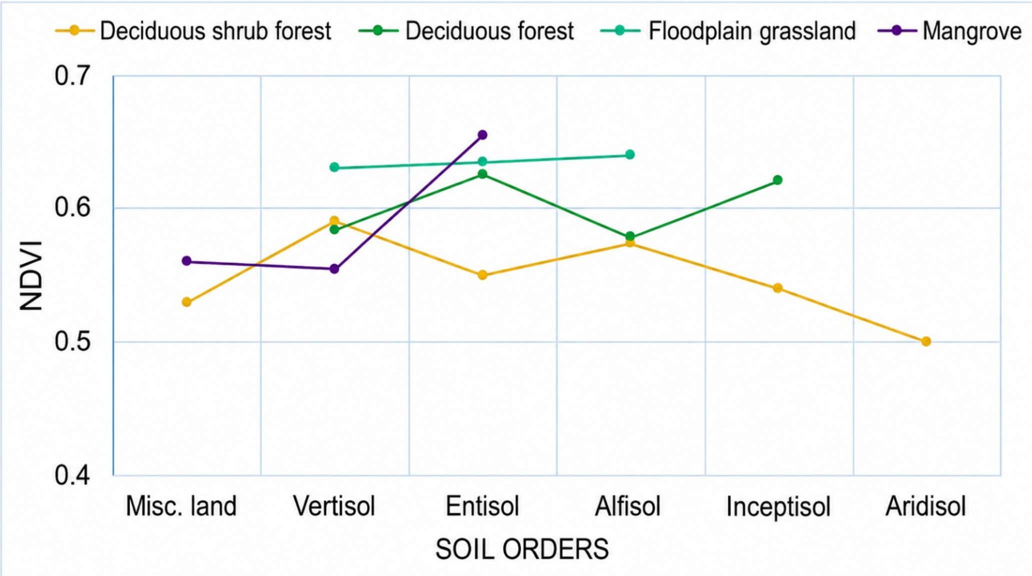

Figure 4. Interaction of NDVI averages with ecosystems and soil orders in the REAR

3.2 Factors and degree of risk to vegetation in the REAR

The data obtained in this analysis highlighted the influence of the different ecosystems within the REAR on the interactions and relationships between the various land covers and land uses located in the area of influence—i.e., factors that jeopardize the condition and quality of the vegetation.

The analysis revealed that of the total area of the four ecosystems studied ((1) Deciduous forest, (2) Deciduous shrub forest, (3) Mangrove, and (4) Flooded Grassland), 18.7 % of the vegetation cover is at high risk, with the greatest disturbance and threat occurring along the northwest and northeast edges of the Deciduous Shrub Forest and the southwest edge of the Deciduous Forest; a similar pattern is observed at the entrances to the main and secondary roads. The at-risk areas for the two ecosystems were 2 438 and 950 ha, equivalent to 36 % and 26.4 %, respectively. In contrast, for the Mangrove ecosystem, the areas of greatest variability are located where the ecosystem borders shrimp aquaculture activity, with a low-risk area of 126 ha, corresponding to 10.2 %. The ecosystem that did not present a significant risk was the floodplain grassland, whose value reached 2 %, equivalent to 4 ha (see Figure 5).

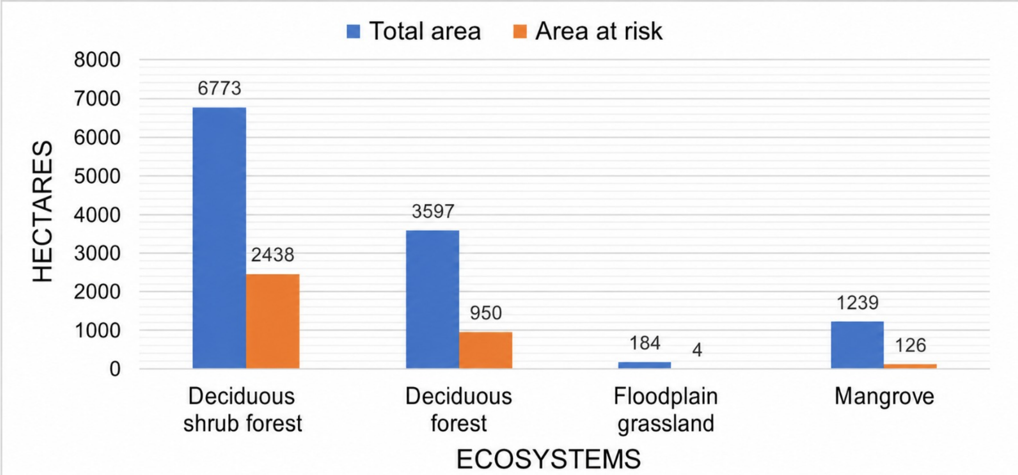

Figure 5. Degree of risk to the vegetation of the REAR ecosystems

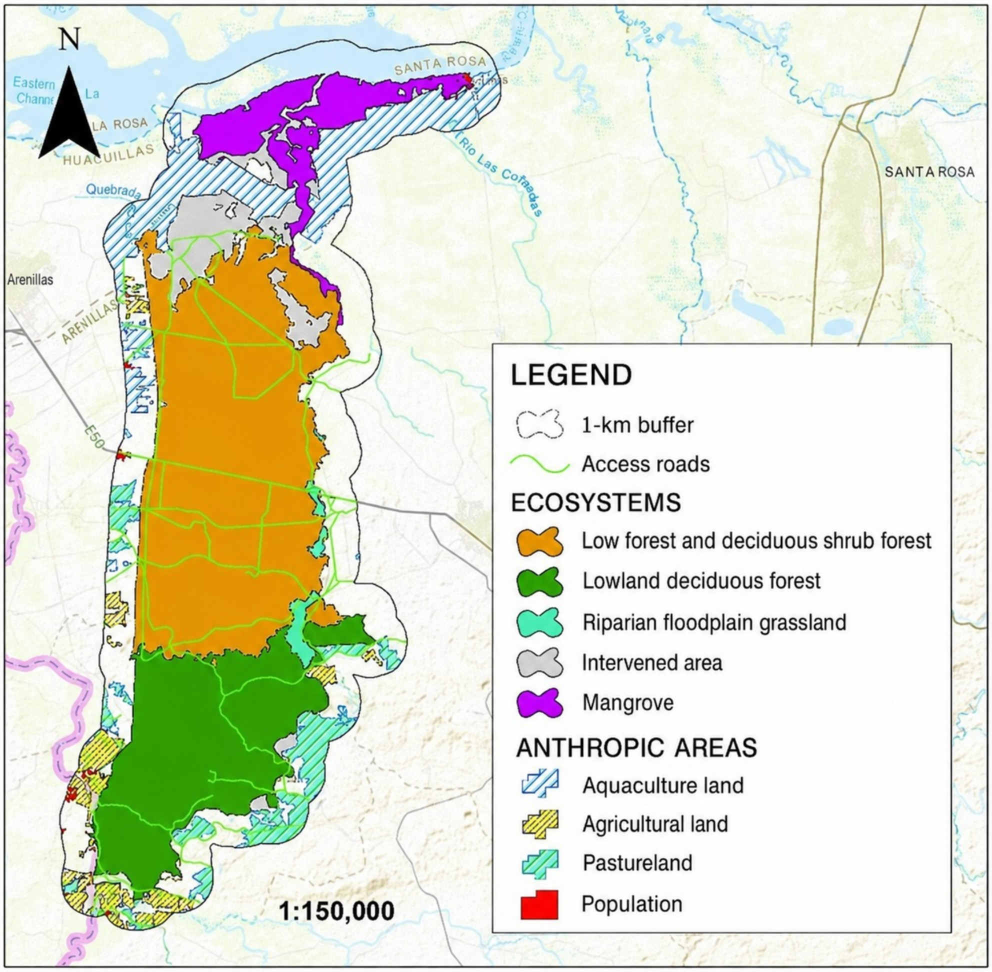

Figure 6. Land cover and land use in the REAR's area of influence

Figure 6 shows that the dominant land cover in the REAR's area of influence corresponds to aquaculture zones, covering 1 994 ha, followed by livestock farming, covering 1,137 ha, and agriculture, covering 657 ha. The land cover with the smallest area corresponds to population settlements, covering 46 ha. The main access roads within and outside the REAR covered a total length of 148 km.

Table 2. Coefficients obtained from the multiple linear regression model

Distance of variables	**Shrubland deciduous**		**Forest deciduous**		**Grassland floodplain**		**Mangrove**	
	Beta	*p*-value	Beta	*p*-value	Beta	*p*-value	Beta	*p*-value
Aquaculture	**0.596**	0.000	0.017	0.000	0.030	0.000	**0.234**	0.000
Agricultural	**0.221**	0.000	**0.345**	0.000	**0.188**	0.000	**-0.553**	0.000
Livestock	**0.151**	0.000	**0.145**	0.000	**-0.334**	0.000	**-0.480**	0.000
Population	**0.123**	0.000	0.083	0.000	-0.060	0.160	**0.180**	0.000
Roads	0.016	0.000	**0.106**	0.000	0.056	0.000	0.040	0.000
R^2	**0.360**		**0.264**		**0.020**		**0.102**	

In Table 2, based on the model established by Sierra (2013), we sought to estimate the risk of change in vegetation cover for each deforestation factor, such as distances to aquaculture, agricultural, livestock, population, and road areas. These deforestation variables showed the same level of significance, excepting the population variable in the Flooded Grassland ecosystem, where the *p*-value $= 0.000$ is less than the significance level $\alpha = 0.05$; i.e., the distances of the variables influence the response of vegetation status in the study ecosystems to a greater or lesser degree. The Beta values corresponded to the model coefficients, which represent the elasticity of the tendency for the vegetation cover of a site with coordinates to be converted to another land use. In contrast, R^2 as a coefficient of determination explains how much of a factor's variability can be attributed to its relationship with another related factor; i.e., it quantifies the model's goodness of fit, allowing an approximation of the deforested fraction of each REAR ecosystem. This means that R^2 values for 100 % of the cells with that value indicate a risk of threat to vegetation cover in 36 % of Deciduous Shrub Forest, 26.4 % of Deciduous Forest, 2 % of Flooded Grassland, and 10.2 % of Mangrove.

It was found that the variable for aquaculture zones exhibited positive beta coefficients in all four ecosystems, indicating a higher probability of change in vegetation in the deciduous shrub forest, followed by a moderate probability of change in the mangrove ecosystem. Its values of 0.596 and 0.234 demonstrated that the variable for distance from aquaculture zones is related to the condition and health of the vegetation in the two ecosystems, a pattern that does not occur with the same intensity in the Deciduous Forest and Flooded Grassland (see Figure 6). The increase in intensive aquaculture activity in recent years in the northwestern part of the Reserve has occupied large areas, where market forces and deficient agricultural policy have contributed to this productive growth (Agila and Lalangui, 2019). A similar finding is revealed in the research by Faruque et al. (2022), which notes an increase in aquaculture area relative to agricultural area during the 1990–2020 period, a transformation that could negatively impact the mangrove forests in southwestern Bangladesh.

Regarding the agricultural area variable, positive beta coefficients were found in the Deciduous Forest, Deciduous Shrub Forest, and Flooded Grassland ecosystems; their values of 0.345, 0.221, and 0.188 indicate a moderate to low probability of forest change, respectively, i.e. the greater the distance from agricultural activities, the lower the forest loss will be. In the case of the Deciduous Shrub Forest ecosystem, the probability of change could be contradictory, since despite the proximity of agricultural areas, this activity is regulated under a sustainable production plan, resulting from the concession of nearly 3 800 ha of land granted in 2014 by the State to producer groups in the area (Ministerio del Ambiente del Ecuador MAE, 2015). For the Mangrove ecosystem, the coefficient value was negative (-0.553), indicating an uncertain probability of vegetation change due to agricultural activities.

For the livestock area variable, the analysis reveals an average Beta coefficient value of 0.148 for the Deciduous Forest and Deciduous Shrub Forest ecosystems, indicating a moderate probability of change in their forest cover. According to Hidalgo et al. (2020), the increase in livestock activity depends on the geography and climate, particularly in the Deciduous Forest, with approximately 95 % of livestock farming occurring in the border area of the southeastern sector of the REAR. On the other hand, for the Flooded Grassland and Mangrove ecosystems, the Beta coefficient values were negative at -0.334 and -0.480, respectively, indicating an indirect relationship that suggests the vegetation in these areas faces no significant risk from grazing activities.

The variable of distance to settlements also influenced risk, particularly in the Deciduous Shrub Forest and Mangrove ecosystems. Their Beta coefficient values of 0.123 and 0.180, respectively, indicate a moderate probability of localized landscape change along the edges of remaining forest patches. The socioeconomic status of the population, linked to illiteracy and low wages, could be the cause of these changes (Cruz et al., 2017; Pineda et al., 2009). According to Figure 6, the settlement closest to the mangrove ecosystem is Pitahaya in the north. In contrast, for the lowland forest and deciduous shrubland, the villages of Cooperativa Valdivia, El Cruce, El Telégrafo, El Mango, and Carcabón are located in the south. The soil suitability characteristics of these populated areas have served as attractions for progressive human settlement. It is important to note that the Reserve contains no residential settlements within its boundaries; i.e., there is no human impact within the Reserve. In line with the findings of Baig et al. (2022), the persistent degradation of unprotected forest cover in Selangor, Malaysia, is closely linked to the expansion of human settlements and land conversion for agricultural purposes, identified as the determining factors in land-use transition.

The beta coefficient for the variable "distance to roads" was positive in all four ecosystems (see Table 2); however, the values for the Deciduous Shrub Forest, Flooded Grassland, and Mangrove ecosystems revealed a very low probability of change in vegetation. In contrast, for the Deciduous Forest ecosystem, the probability of change is significant, with a value of 0.106. The construction of main roads allows people from neighboring communities to enter the forest, creating new trails for the purpose of logging or clearing land to establish agricultural areas (Delgado, 2012; García-Villacorta, 2009). This pattern is largely located in the southwest of the Reserve, while in the eastern sector, disturbance and threats have not been significant due to limited accessibility caused by steep slopes and high altitude. According to the findings of Qian et al. (2022) derived from their impact model, ecological risks at the landscape level are conditioned by a multivariate interaction. In this regard, distance from anthropogenic elements, land use, slope, and precipitation emerge as the primary determinants of these dynamics. Conversely, our study did not consider the latter two factors because they have no direct connection to human-induced changes; however, we deemed it important to relate slope and precipitation to aspects of other ecosystem services, such as water quality.

4 Conclusions

The analysis of vegetation indices (NDVI) using Sentinel-2B satellite imagery allowed us to estimate the condition and health of natural vegetation in the four ecosystems (deciduous forest, deciduous shrubland, mangrove, and floodplain grassland) that make up the REAR. The average values of the indices obtained differed for each zone. The highest values were recorded in the Flooded Grassland and Mangrove ecosystems, while the Deciduous Shrub Forest and Deciduous Forest ecosystems had low values, indicating greater disturbance and threat to vegetation cover. This could be due to the optimal fertility conditions of their soils, as well as atmospheric conditions and the progressive human settlement that seeks to establish agricultural and aquaculture activities in the area every day.

The statistical interaction of the average NDVI with ecosystem variables and soil suitability allowed us to establish that these variables condition the NDVI response, determining that the effect of each depends on the other. This pattern resembles the reality of the disturbed ecosystem within the REAR, particularly in the northwestern sector bordering the Deciduous Shrub Forest, where progressive soil degradation caused by intensive aquaculture and agricultural activity is altering its physical, chemical, and biological properties—aspects critical for healthy vegetation development.

Regarding the analysis of risk factors and levels, it was found that the eastern and western edges of the Deciduous Shrub Forest and Deciduous Forest ecosystems present high probabilities of landscape change. This increased risk is related to the ease with which people can establish productive activities within the buffer zone. Specifically, the buffer zone—despite being regulated by the state—does not comply with the stipulated requirement to protect the natural resources of protected areas.

It is important to note that if the areas adjacent to the REAR are not protected, the little remaining forest will disappear, limiting connectivity with other natural forests; for this reason, it is important that the Reserve's management plan take high-risk zones into account through the efficient implementation of good agricultural, livestock, and aquaculture practices within its area of influence, since ensuring their proper functioning could contribute to the creation of biological corridors linking the municipal conservation area "El Conchal" in the northern sector and the "Río Arenillas-Presa Tahuín" protective forest on the southeastern side.

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Declaration on the use of Artificial Intelligence

The authors DECLARE that, during the preparation of the manuscript entitled "Land cover and land use factors associated with the risk of vegetation degradation in the Arenillas Ecological Reserve", no generative artificial intelligence tools or automated assistance systems were used for writing, data analysis, interpretation of results, content generation, translation, or manuscript editing.

The authors assume full responsibility for the content, originality, integrity, and final version of the manuscript.

Author Contributions

J.E.M.M.: Conceptualization, Data curation, Investigation, Methodology, Project administration, Software, and Writing – original draft. **H.E.A.L.:** Formal analysis, Supervision, and Writing – review & editing. **D.A.P.L.:** Investigation, Resources, Validation, and Visualization. **A.D.L.F.:** Data curation, Formal analysis, and Writing – review & editing.

References

Agila, R., and Lalangui, M. (2019, octubre). Análisis de los factores estratégicos que inciden en la producción camaronera ecuatoriana. En *Xxiv congreso internacional de contaduría, administración e informática* (pp. 1–29). Ciudad Universitaria, Ciudad de México, México.

Aldás, A. (2019). *Análisis de la dinámica temporal del índice de vegetación de diferencia normalizada (NDVI) para los años 1986, 2001 y 2017 en la reserva ecológica cotacachi cayapas, imbabura, mediante el uso de google earth engine* (Tesis de grado). Pontificia Universidad Católica del Ecuador, Quito, Ecuador.

Armenteras, D., and Rodríguez, N. (2014). Dinámicas y causas de deforestación en bosques de latino américa: una revisión desde 1990. *Colombia Forestal*, *17*(2), 233–246. Online: https://shortlink.uk/1rmld

Baig, M. F., Mustafa, M. R. U., Baig, I., Takaijudin, H. B., and Zeshan, M. T. (2022). Assessment of land use land cover changes and future predictions using CA-ANN simulation for selangor, malaysia. *Water*, *14*(3), 402. Online: https://doi.org/10.3390/w14030402

Barber, C. P., Cochrane, M. A., Souza, C. M., and Laurance, W. F. (2014). Roads, deforestation, and the mitigating effect of protected areas in the amazon. *Biological Conservation*, *177*, 203–209. Online: http://dx.doi.org/10.1016/j.biocon.2014.07.004

Botta, G. F., Bienvenido, J. F., Antille, D. L., Rivero, E. R. D., Contessotto, E. E., Ghelfi, D. G., ... Pelizzari, F. M. (2019). Effect of traffic with a light-weight tractor on physical properties of an aridisol soil in almeria, spain. *Revista de la Facultad de Ciencias Agrarias*, *51*(2), 270–279. Online: https://shortlink.uk/1wNro

Cantón, Y., Chamizo, S., Rodriguez-Caballero, E., Lázaro, R., Roncero-Ramos, B., Román, J. R., and Solé-Benet, A. (2020). Water regulation in cyanobacterial biocrusts from drylands: Negative impacts of anthropogenic disturbance. *Water*, *12*(3), 720. Online: https://doi.org/10.3390/w12030720

Carey, C., Dudley, N., and Stolton, S. (2000). *Squandering paradise?: The importance and vulnerability of the world's protected areas*. Gland, Switzerland: WWF-World Wide Fund For Nature International.

Cayuela, L. (2010). *Modelos lineales generalizados (GLM)*. Granada, España: EcoLab, Centro Andaluz de Medio Ambiente, Universidad de Granada.

Cervantes, F., Imbaquingo, J., and Leon, D. (2022). Valoración económica de los servicios ecosistémicos del bosque protector cerro blanco, guayaquil ecuador. *Revista Geoespacial*, *19*(1), 50–63. Online: https://shortlink.uk/1wNrr

Clark, D. B. (2002). *Los factores edáficos y la distribución de las plantas*. Cártago, Costa Rica: LUR.

Cruz, M. A., Rodríguez, D. A., Villanueva, A., and Santillán, J. (2017). Factores sociales de uso del suelo y vegetación asociados a los incendios forestales en hidalgo. *Revista Mexicana de Ciencias Forestales*, *8*(41), 139–163. Online: https://shortlink.uk/1wNru

Delgado, V. (2012). La responsabilidad civil extracontractual por el daño ambiental causado en la construcción u operación de las carreteras. *Revista de Derecho (Valdivia)*, *25*(1), 47–76. Online: https://dx.doi.org/10.4067/S0718-09502012000100003

De Smith, M., Goodchild, M., and Longley, P. (2007). *Geospatial analysis: A comprehensive guide to principles, techniques and software tools* (2nd ed.). Troubador Publishing Ltd.

Eraso, O., Badia, A., and Gisbert, M. (2022). Google earth engine aplicado al monitoreo de superficies quemadas y cambios de coberturas y usos del suelo. *GeoFocus: Revista Internacional de Ciencia y Tecnología de la Información Geográfica*, *29*, 89–113. Online: https://dx.doi.org/10.21138/GF.764

Faruque, M. J., Vekerdy, Z., Hasan, M. Y., Islam, K. Z., Young, B., Ahmed, M. T., ... Kundu, P. (2022). Monitoring of land use and land cover changes by using remote sensing and GIS techniques at human-induced mangrove forests areas in bangladesh. *Remote Sensing Applications: Society and Environment*, *25*, 100699. Online: https://doi.org/10.1016/j.rsase.2022.100699

Figueroa, F., and Sánchez-Cordero, V. (2011). Evaluación de la efectividad de las áreas protegidas para contener procesos de cambio en el uso del suelo y la vegetación. ¿un índice es suficiente? *Revista Mexicana de Biodiversidad*, *82*(3), 951–963. Online: https://shortlink.uk/1rmln

García-Villacorta, R. (2009). Diversidad, composición y estructura de un hábitat altamente amenazado: los bosques estacionalmente secos de tarapoto, perú. *Revista Peruana de Biología*, *16*(1), 81–92. Online: https://shortlink.uk/1wNry

Gomes, V., Queiroz, G., and Ferreira, K. (2020). An overview of platforms for big earth observation data management and analysis. *Remote Sensing*, *12*(8), 1253. Online: https://doi.org/10.3390/rs12081253

Gonzaga-Aguilar, C. (2015). Aplicación de índices de vegetación derivados de imágenes satelitales para análisis de coberturas vegetales en la provincia de loja, ecuador. *Revista CEDAMAZ*, *5*(1), 30–41. Online: https://shortlink.uk/1rmlt

Hartemink, A., and Bockheim, J. (2013). Soil genesis and classification. *Catena*, *104*, 251–256. Online: https://doi.org/10.1016/j.catena.2012.12.001

Hidalgo, M., Vargas, O., and Vite, H. (2020). Análisis situacional de la actividad ganadera en la parroquia palmales del cantón arenillas. *Revista Metropolitana de Ciencias Aplicadas*, *3*(2), 124–130. Online: https://shortlink.uk/1wNrF

Instituto de Ecología Aplicada ECOLAP, and Ministerio del Ambiente del Ecuador MAE. (2007). *Guía del patrimonio de Áreas naturales protegidas del ecuador*. Quito, Ecuador: ECOFUND, FAN, DarwinNet, IGM.

Leiva, J., Rocha, O. J., Mata, R., and Gutiérrez, M. (2009). Cronología de la regeneración del bosque tropical seco en santa rosa, guanacaste, costa rica: II. la vegetación en relación con el suelo. *Revista de Biología Tropical*, *57*(3), 817–836. Online: https://shortlink.uk/1wNrJ

Liu, Q., and Wang, L. (2021). t-test and ANOVA for data with ceiling and/or floor effects. *Behavior Research Methods*, *53*(1), 264–277. Online: https://doi.org/10.3758/s13428-020-01407-2

Maza-Maza, J. E., Sánchez-Asanza, A. W., Añazco Loaiza, H. E., and García-Ochoa, J. A. (2021). Estudio de las características físico-químicas del suelo en áreas prioritarias de la reserva ecológica arenillas. *Revista Científica Agroecosistemas*, *9*(3), 30–40. Online: https://shortlink.uk/1rmlB

Mesa-Sierra, N., de la Peña Domene, M., Campo, J., and Giardina, C. (2022). Restauración de bosques secos tropicales mexicanos: una revisión nacional. *Sustentabilidad*, *14*, 3937. Online: https://doi.org/10.3390/su14073937

Ministerio del Ambiente del Ecuador MAE. (2013). *Sistema de clasificación de los ecosistemas del ecuador continental*. Quito, Ecuador: Ministerio del Ambiente del Ecuador.

Ministerio del Ambiente del Ecuador MAE. (2015). *Plan de manejo de la reserva ecológica arenillas* (Inf. Téc.). Quito, Ecuador: Ministerio del Ambiente del Ecuador.

Mittermeier, R. A., Turner, W. R., Larsen, F. W., Brooks, T. M., and Gascon, C. (2011). Global biodiversity conservation: The critical role of hotspots. En F. E. Zachos and J. C. Habel (Eds.), *Biodiversity hotspots: Distribution and protection of conservation priority areas* (pp. 3–22). Berlin, Heidelberg: Springer Berlin Heidelberg. Online: https://doi.org/10.1007/978-3-642-20992-5_1

Montealegre, F. (2017). *Evaluación espacio temporal de la productividad agrícola con índices de vegetación de diferencias normalizadas (NDVI) como herramienta para el ordenamiento territorial. caso de estudio: cuenca alta del arroyo napaleofú, provincia de buenos aires, argentina* (Tesis de Grado). Universidad Nacional de la Plata, La Plata, Argentina.

Moreno, A., Carda, V., Reyes, J. L., and Cano, P. (2018). Rizobacterias promotoras del crecimiento vegetal: una alternativa de biofertilización para la agricultura sustentable. *Revista Colombiana de Biotecnología*, *20*(1), 68–83. Online: https://doi.org/10.15446/rev.colomb.biote.v20n1.73707

Organización de las Naciones Unidas para la Agricultura y la Alimentación FAO. (2020). *El estado de los bosques del mundo 2020: Los bosques, la biodiversidad y las personas*. Roma, Italia: FAO.

Pineda, N. B., Bosque, J., Gómez, M., and Plata, W. (2009). Análisis de cambio del uso del suelo en el estado de méxico mediante sistemas de información geográfica y técnicas de regresrión multivariantes: Una aproximación a los procesos de deforestación. *Investigaciones Geográficas*, *69*, 33–52. Online: https://shortlink.uk/1wNrV

Qian, Y., Dong, Z., Yan, Y., and Tang, L. (2022). Ecological risk assessment models for simulating impacts of land use and landscape pattern on ecosystem services. *The Science of the Total Environment*, *833*, 155218. Online: https://doi.org/10.1016/j.scitotenv.2022.155218

Ramírez, V., Aranda, L., , and Rico-Gray, V. (2018). La resiliencia del bosque seco tropical: un seguro de vida para su conservación. CONABIO. *Biodiversitas*, *137*, 12–16. Online: https://shortlink.uk/1rmlN

Riofrío, I. (2018). *El bosque seco, una joya amenazada en el ecuador.* Mongabay. Online: https://es.mongabay.com/2018/07/ecuador-bosque-seco/ (Publicado el 05 de julio de 2018)

Ruiz, M. (2018). *Evaluación de la calidad y riesgo de la vegetación del bosque protector la ceiba y su área de influencia* (Tesis de grado). Universidad Técnica Particular de Loja, Loja, Ecuador.

Sierra, R. (2013). *Patrones y factores de deforestación en el ecuador continental, 1990-2010. y un acercamiento a los próximos 10 años*. Quito, Ecuador: Conservación Internacional Ecuador y Forest Trends.

Sudmanns, M., Tiede, D., Lang, S., Bergstedt, T., Trost, G., and Augustin, H. (2020). Big earth data: disruptive changes in earth observation data management and analysis? *International Journal of Digital Earth*, *13*(7), 832–850. Online: https://doi.org/10.1080/17538947.2019.1585976

Tapia-Armijos, M., Homeier, J., Espinosa, C., Leuschner, C., and de la Cruz, M. (2015). Deforestation and forest fragmentation in south ecuador since the 1970s – losing a hotspot of biodiversity. *PLoS ONE*, *10*(9), e0133701. Online: https://doi.org/10.1371/journal.pone.0142359

Torres, R. C., Giorgis, M. A., Trillo, C., Volkmann, L., Demaio, P., Heredia, J., and Renison, D. (2014). Post-fire recovery occurs overwhelmingly by resprouting in the chaco serrano forest of central argentina. *Austral Ecology*, *39*(3), 346–354. Online: https://doi.org/10.1111/aec.12084

Union Internacional para la Conservacion de la Naturaleza IUCN. (2005). Benefits beyond boundaries: Proceedings of the vth IUCN world parks congress. En *The vth iucn world parks congress.* Durban, South Africa.

Union Internacional para la Conservacion de la Naturaleza IUCN. (2020). *Red list quadrennial report 2017-2020* (Inf. Téc.). IUCN.

Wright, S. J., and Muller-Landau, H. C. (2006). The future of tropical forest species. *Biotropica*, *38*(3), 287–301. Online: https://doi.org/10.1111/j.1744-7429.2006.00154.x