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Spatial Analysis of Environmentally Sensitive Areas to Soil Degradation Using MEDALUS Model and GIS in Amazonas (Peru): An Alternative for Ecological Restoration

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Abstract: Land degradation is a permanent global threat that requires an interdisciplinary approach to addressing solutions in a given territory. This study, therefore, analyses environmentally sensitive areas to land degradation using the Mediterranean Desertification and Land Use (MEDALUS) and Geographic Information System (GIS) method through a multi-criteria approach in the district of Florida (Peru). For the method, we considered the main quality indicators such as: Climate Quality Index (CQI), Soil Quality Index (SQI), Vegetation Quality Index (VQI), and Management Quality Index (MQI). There were also identified groups of parameters for each of the quality indicators analyzed. The results showed that 2.96% of the study area is classified as critical; 48.85% of the surface is classified as fragile; 15.48% of the areas are potentially endangered, and 30.46% are not threatened by degradation processes. Furthermore, SQI, VQI, and MQI induced degradation processes in the area. Based on the results, five restoration proposals were made in the study area: (i) organic manure production, (ii) cultivated and improved pastures and livestock improvement, (iii) native forest restoration, (iv) construction of reservoirs in the top hills and (v) uses of new technologies. The findings and proposals can be a basic support and further improved by decision-makers when implemented in situ to mitigate degradation for a sustainable use of the territory.

Keywords: land degradation; quality indicators; spatial analysis; ESAI; sustainability

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Citation: Meza Mori, G.; Torres Guzmán, C.; Oliva-Cruz, M.; Salas López, R.; Marlo, G.; Barboza, E. Spatial Analysis of Environmentally Sensitive Areas to Soil Degradation Using MEDALUS Model and GIS in Amazonas (Peru): An Alternative for Ecological Restoration. *Sustainability* **2022**, *14*, 14866. https://doi.org/10.3390/su142214866

Received: 1 October 2022
Accepted: 8 November 2022
Published: 10 November 2022

1. Introduction

One of the most critical global environmental problems is soil degradation [1,2]. The main causes of degradation are over-tillage, inappropriate crop rotations, overgrazing, deforestation, mining, infrastructure construction and urban sprawl [3,4]. It has been estimated that one fifth of the land is degraded and that 5–10,000 Mha are degraded per year [5,6]. This problem affects 40% of agricultural land, costing approximately USD 500 billion per year [7]. Consequently, it limits agricultural production, since, by 2050, ~70% of current agricultural production will be required to supply the world's population [8].

In the last decade, several methodologies have been developed to identify and evaluate degraded areas. Among the most widely used methods for assessing land degradation and desertification are field studies [9]. Some studies use spectral biophysical indicators [10–12], but others integrate social, economic, and environmental factors [13,14]. A large number of mathematical models have also been proposed as methods for quantifying soil sensitivity to desertification and detecting areas under high vulnerability [15]. However, the Mediterranean Desertification and Land Use (MEDALUS) method, successfully developed, has been largely used to identify lands sensitive to degradation [16]. The methodology was validated and applied in Mediterranean conditions [17–19]. Subsequently, it has been applied in non-Mediterranean areas [20–22], allowing for adopting preventative measures to tackle degradation process [23]. An integrated representation of land degradation processes can be achieved using qualitative and quantitative methods [9,24]. Thus, the use of geographic information system (GIS) tools and remote sensing (RS) techniques, key for soil assessment, enables the analysis, assessment, monitoring, and representation of degraded soil dynamics [25].

Peru is also affected by land degradation; as of recent data, one-third of its population works in the agricultural sector, with a 29.6% contribution to the gross domestic product (GDP) [26,27]. Traditional agricultural practices, which include slash-and-burn activities, have a negative impact on soil quality [28,29]. In Peru, overgrazing, mining, and forest fires are the drivers for about 180,123.79 km^2 of land degradation [30], and this problem spreads throughout the country [31–40]. In the department of Amazonas in 2020, 115.72 km^2 was deforested, and 10878.04 km^2 was degraded [30,41]. Experiences have been documented and guidelines implemented for forest restauration in degraded ecosystems [42–46]. However, further efforts to estimate degradation require an in-depth process with a multi-criteria approach, such as MEDALUS [47]. Notwithstanding, reducing degradation risks is a difficult and complex process, especially in small areas [15].

In this research work, we applied the MEDALUS methodology to analyze environmentally sensitive areas to soil degradation in the district of Florida (Amazonas, Peru). For this purpose, (i) we evaluated environmentally sensitive areas to degradation; (ii) we applied four main indices of the original MEDALUS method: climate quality index (CQI), soil quality index (SQI), vegetation quality index (VQI), and management quality index (MQI); (iii) we analyzed the possible causes of land degradation; and (iv) we aim to contribute with ecological restoration strategies in Amazonas lands.

2. Materials and Methods

2.1. Study Area

The district of Florida is located in northern Peru between parallels 5°45′25″ and 5°60′ South latitude and meridians 77°51′ and 78°8′ West longitude, in the province of Bongará in the southeast of the department of Amazonas (Figure 1). The study area covers 222.40 km^{2,} at an altitude of 1500 to 3800 m a.s.l. The climate is characterized by a humid tropical climate with average annual temperature and precipitation between 14.3–17 °C and 682–1092 mm, respectively, and a relative humidity of 87% [48]. There are two distinct seasons during the year, the dry season from May to October and the wet season from November to April [49,50]. The physiography is characterized by high mountains with steep to extremely steep slopes [51]. In turn, the vegetation cover is represented by altimontane forest, montane forest, and jalca formation [52]. The soil type is developed on residual sandstone and limestone materials with AC profiles from medium to moderate texture and pH between 4.5 to 7.0 (Condor and Apurimac Series) and ABC profiles with medium to moderately fine texture, good drainage, and strongly acidic pH (3.9 to 4.8) (Calera I-Pillualla and Calera I-Teata Associations) [53].

In the most recent census conducted by the Statistics and Informatics Institute (INEI), Florida district had a total population of 5999 inhabitants, distributed among 2117 homes [54]. Most of the population here depend on livestock and agriculture for their livelihoods [31,55], especially the production of dairy products, which are distributed to local and regional markets [48]. These activities lead to deforestation, overgrazing, soil degradation, and water pollution [31,56,57], causing the significant loss of biodiversity; in fact, between 2001 and 2019, around 2270 m^2 ha was deforested, causing land degradation [41]. This is a consequence of agricultural expansion, the installation of new pasture areas, and the immigration of people to the area mainly from Cajamarca [31,48].

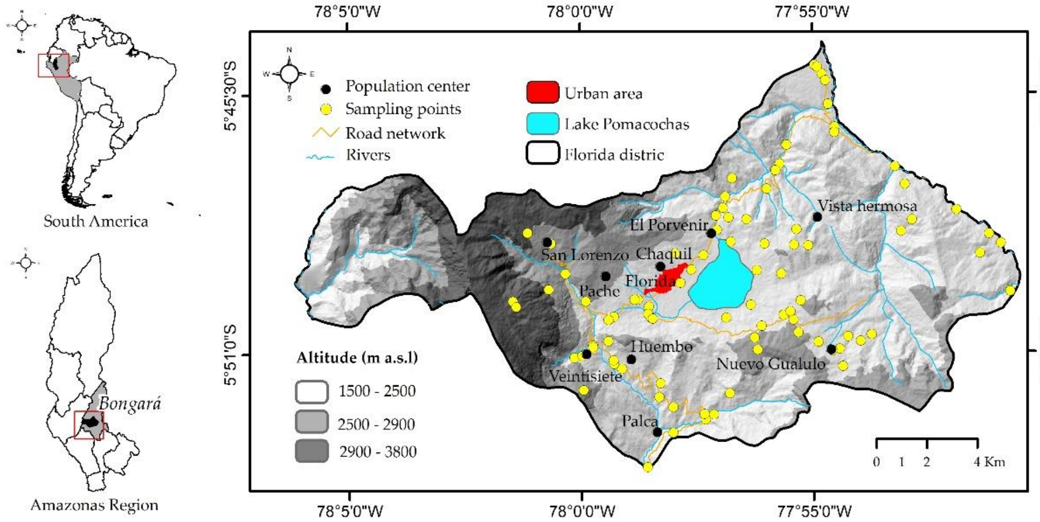

Figure 1. Localization of Florida district in the department of Amazonas (Peru).

2.2. Data Used and Processing

To generate the mapping of environmentally sensitive areas susceptible to degradation in district Florida, the ASTER digital elevation model (DEM), obtained from (https://lpdaac.usgs.gov/, accessed on 16 June 2022) with a spatial resolution of 30 m, was used with an accuracy of ±16 m [58]. The DEM generated the slope and terrain aspect.

For the calculation of the aridity index and erosivity, raster data of monthly precipitation from 1970 to 2000 with a spatial resolution of 1 km^2 were used [59], available at (http://www.worldClim.org, accessed on 29 May 2022). The geological map was obtained from the Amazonas Ecological Economic Zoning (ZEE-A) [60]. The map regarding mass movement susceptibility was obtained from the Geological, Mining and Metallurgical Institute (INGENMET) [61]. We used a Sentinel-2 space satellite image, obtained from the United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov/, accessed on 5 April 2022), to generate the coverage map. The image was acquired on 2 August 2019. Automatic supervised classification using the maximum likelihood algorithm with ArcGIS version 10.5 was used [31,32,62,63]. Therefore, coverages were classified into five classes, namely, urban area, grassland, pasture and crops, water bodies, and forests. Thematic accuracy was evaluated based on 210 validation points, randomly distributed for each class and the whole study area, obtaining a kappa index of 92%.

Soil organic matter (SOM) and textural class layers were generated from specific data of 91 arable land samples collected in field sampling (Figure 1). The approximate arable sampling depth was 25 cm. The samples were distributed according to the variability of the physiographic units, accessibility to the area and based on the regulations (D.S. N° 13-2010-AG), a document for soil sampling by the Ministry of Agriculture (MINAGRI) [64] in Peru. These samples were analyzed at the Water and Soil Research Laboratory (LABISAG) of the National University Toribio Rodríguez de Mendoza de Amazonas (UNTRM). Then, the results of the SOM samples were interpolated by the Ordinary Kriging (OK) method using the geostatistical analysis extension of ArcGIS 10.5 based on three models Gaussian, spherical and exponential [65–70]. Cross-validation statistically reported that the Gaussian model achieved the best results with a with a coefficient of determination (R^2) of 0.04 and root mean squared error (RMSE) of 1.85. On the other hand, to determinate textural class, sand, silt, and clay data were individually interpolated with the Gaussian model and then integrated into the QGIS 3.12 raster calculator to obtain the textural class [71]. In sum, 12 thematic layers were constructed (constituent parameters of the indicators) and classified as stated in the United States Department of Agriculture (USDA) at a spatial resolution of 30 m.

2.3. Methodology

MEDALUS, a successful tool for assessing, mapping, and identifying environmentally sensitive areas (ESAs), using the environmentally sensitive areas index (ESAI), was employed for this methodology [15,23]. The simplicity and flexibility of the model allows for adjusting or changing the number of indicators (parameters or variables) to be used to assess the quality [9,15,18,22,47,72,73]. In that sense, users can easily add and adjust further spatial factors according to local conditions [15,23]. It is calculated according to the geometric mean value of indices SQI, CQI, VQI, and MQI. Figure 2 shows the Methodological flowchart used to evaluate Environmentally Sensitive Areas to degradation in Florida district.

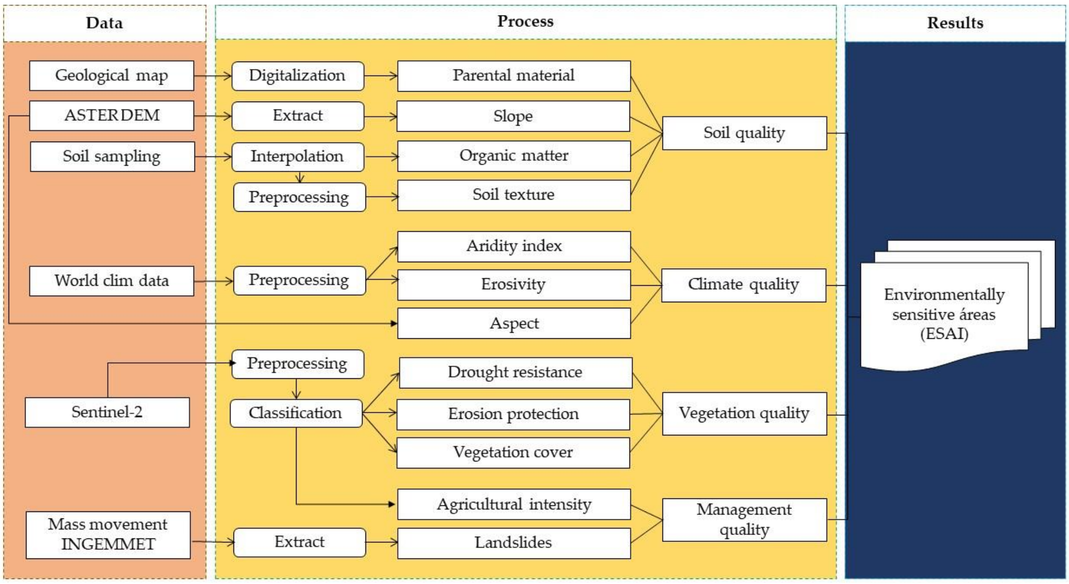

Figure 2. Methodological flowchart to evaluate Environmentally Sensitive Areas to degradation in Florida district, department of Amazonas (Peru).

2.3.1. Soil Quality Index

Desertification and land degradation are determined by the cohesive strength between soil particles, water retention capacity, level of development of the surface horizon, texture, and structure [74]. The soil quality involves measuring fertility and predisposition to be preserved against climate hazards using agricultural techniques and intrinsic characteristics [46,74]. Therefore, to determine the SQI, four parameters were considered and evaluated, three soil characteristics (parent material, soil texture, and topsoil organic matter) and topography (slope), the result was obtained by geometric mean (Table 1). Scores were then assigned to each parameter [16,21,75]. The SQI, finality, was calculated using the following Equation (1):

$$\text{SQI} = (\text{parent material} \times \text{slope} \times \text{soil organic matter} \times \text{soil texture})^{1/4} \quad (1)$$

2.3.2. Climate Quality Index

The CQI reflects the impact of climatic variation on land degradation and desertification, where precipitation, the most important factor, influences drainage and soil water capacity [16,76,77]. To determine this index, three parameters were evaluated: aridity, soil erosion, and aspect indices (Table 2): namely the aridity index, which influences the availability of water for plants [16]; soil erosion, which is the estimate of the aggressiveness of rainfall [23]; and aspect, which is driven by the distribution of solar irradiation surface temperatures. The three have important effects on vegetation growth and the rate of soil erosion [76,78]. Each parameter was measured in the following way:

Table 1. Parameters, description, classes, and quality scores used for soil quality parameters.

Parameters	Description	Classes	Quality Scores
Parent material	Pucara group	Low	1.55
	Mitu group	Medium	1.60
	Sarayaquillo formation, Goyllarisquizga group, and Chulec formation		1.65
	Chonta formation	High	1.70
Slope	<2 Nearly level	Low	1
	2–6 Gentling sloping	Low	1.2
	6–12 Moderately sloping	Medium	1.4
	12–18 Strongly sloping	Medium	1.6
	18–25 Moderately steep	High	1.7
	25–35 Steep	High	1.8
	35–60 Very steep	High	1.9
	>60 Very steep	High	2
Organic matter content	>6.0	High	1
	2.1–6.0	Medium	1.3
	2.0–1.1	Low	1.6
	<1.0	Very low	2
Soil texture	Loam, Sandy slay loam, Sandy loam, Loamy sand, Clay loam good	Very Low	1
	Sandy clay, Silt loam, Silty clay loam moderate	Low	1.2
	Silt, And clay, Silty clay poor	Medium	1.6
	Sand very poor	High	2

Table 2. Parameters, description, classes, and quality scores used for climate quality parameters.

Parameters	Description	Classes	Quality Scores
Aridity index	<0.05 Hyper-arid zone	Very high	2
	0.05–0.2 Arid	High	1.8
	0.2–0.5 Semiarid	Medium	1.60
	0.5–0.65 Dry subhumid	Medium	1.4
	0.65–1 Subhumid	Low	1.2
	>1 Humid	Very low	1
Erosivity	0–60 Very low	Very low	1
	60–90 Low	Low	1.2
	90–120 Moderate	Medium	1.5
	120–160 Severe	High	1.8
	>160 Very severe	Very high	2
Aspect	North, Northwest, Northeast, West, flat areas	Low	1
	South, Southwest, Southeast, East	High	2

Aridity Index

The aridity index (AI) was estimated using the following Equation (2), set by the United Nations Environment Programme (UNEP) [79], where P is mean annual precipitation and PET is potential evapotranspiration, calculated by the method of Thornthwaite.

$$AI = P/PET \tag{2}$$

Soil Erosion

It was estimated according to the modified Fournier index (MFI) [80] by the following Equation (3) where Pi is monthly precipitation and P is annual precipitation.

$$\text{MFI} = \sum_{i\ 1}^{12} Pi^2/P \tag{3}$$

Finally, descriptions and scores of the climate quality parameters were assigned [20,22,23]. The CQI was calculated using the following Equation (4).

$$\text{CQI} = (\text{Aridity index} \times \text{erosivity} \times \text{aspect})^{1/3} \tag{4}$$

2.3.3. Vegetation Cover Index

Vegetation makes a vital contribution to preventing landslides by fixing soil with the root system [81] and by rain obstruction with foliage [82]. Vegetation thus reduces the impact of raindrops and runoff, promoting water infiltration, enriches the soil surface with organic matter, and improves its structure and cohesion [74]. In that sense, to determine the VQI, three parameters were considered and evaluated (Table 3): drought resistance, which directly indicates the ability of an ecosystem to adapt to climatic aridity and severe drought events [78]; erosion protection, which is provided by plants against soil erosion; and vegetation cover, which reduces runoff and loss of sediment [23]. Descriptions and quality scores for the three parameters of vegetation quality were assigned according to Pravalie et al. [22]. The VQI was obtained using the Equation (5).

$$\text{VQI} = (\text{Drought resistance} \times \text{Erosion protection} \times \text{Vegetation cover})^{1/3} \tag{5}$$

Table 3. Parameters, description, classes and quality scores used for vegetation quality parameters.

Parameters	Description	Classes	Quality Scores
Drought resistance	Forests	Very low	1
	Grasslands	Medium	1.4
	Pastures and crops	High	1.7
	Rainfed crops; bare floors	Very High	2
Erosion protection	Forests	Very low	1
	Pastures and crops	Low	1.3
	Grasslands	Medium	1.6
	Rainfed crops; bare floors	High	2
Vegetation cover	Forests, Grasslands	Low	1
	Pastures and crops	Medium	1.8
	Rainfed crops; bare floors	High	2

2.3.4. Management Quality Index

The MQI assesses the anthropogenic impact on the environment through the various anthropogenic activities (overgrazing, water supply, and agriculture), which lead to land degradation and desertification [9,22]. The MQI was calculated by combining agricultural intensity and landslide (Table 4). The latter proposed by Momirović et al. [23] and the hazard/susceptibility assessment thereof. Descriptions and quality scores for the MQI parameters were assigned as follows: for agricultural intensity according to Salvati and Bajocco [19] and Pravalie et al. [22] and for landslide according to Momirović et al. [23]. The MQI was evaluated as the product of the aforementioned parameters using Equation (6).

$$\text{MQI} = (\text{agricultural intensity} \times \text{Landslides})^{1/2} \tag{6}$$

Table 4. Parameters, description, classes, and quality scores used for management quality parameters.

Parameters	Description	Classes	Quality Scores
Agricultural intensity	Forests	Low	1
	Grasslands, pastures and crops	Moderate	1.5
	Rainfed crops; bare floors	High	2
Landslides	Stable terrain	Very low	1
	Conditionally stable slope	Low	1.4
	Fossil landslides	Medium	1.5
	Dormant landslides		1.6
	Active landslides with dormant sliding process	High	1.8
	Active landslides with present sliding process	Very high	2

2.3.5. Environmentally Sensitive Areas (ESA)

The environmentally sensitive areas (ESA) to degradation were determined using SQI, CQI, VQI, and MQI, which were integrated in the QGIS raster calculator. The environmentally sensitive areas index (ESAI) of the studied area was calculated from Equation (7) based on the MEDALUS approach [16]: Finally, correlations were calculated between indices (SQI, CQI, VQI and MQI) using the Band Collection Statistics tool in ArcGIS [23,83].

$$ESAI = (SQI \times CQI \times VQI \times MQI)^{1/4} \quad (7)$$

3. Results

3.1. Spatial Assessment of Constituent Parameters of Quality Indicators

Figure 3 show the 12 geographic parameters processed. It highlights significant spatial differences in terms of land sensitivity to degradation in the study area. The constituent parameters in SQI were shaped by the geology that was represented by Mitu Group, which are reddish layers composed of reddish-toned sandstone conglomerates (Figure 3a). On the other hand, the slope presented gradients ranging from flat to very steep (Figure 3b). In the study area, the organic matter content was distributed from very low to high (Figure 3c). Soil texture was largely sandy clay loam (in the center-east in the study area), with fine granular structure and moderately slow permeability (Figure 3d).

As for the CQI constituent parameters, the study area is characterized by continuous rainfall, consequently, and the area is classified as nonarid (Figure 3e); however, the aggressiveness of rainfall generates low to high erosivity (Figure 3f). Aspect classes varied from low to high, which has a positive impact on vegetation growth but facilitates erosion (Figure 3g). Meanwhile, the VQI parameters, as expected, reflect the fact that due to agricultural and livestock practices, there is limited protection against erosion (Figure 3i) as a result of loss of vegetation (Figure 3j), generating low resistance to drought (Figure 3h). Finally, among the MQI parameters, the agricultural intensity, largely rated as moderate (Figure 3k), positively affects the susceptibility of the land to landslides (Figure 3l).

3.2. Spatial Assessment of Quality Indicators

Based on the 12 geographic parameters processed (Figure 3), the 4 quality indicators (SQI, CQI, VQI, and MQI) were obtained (Table 5 and Figure 4). The first indicator, SQI of the total area 88.61% (197.07 km^2), is of moderate quality, followed by low quality of 6.99% (15.54 km^2) and high quality of 2.16% (4.8 km^2) (Table 5). Moderate quality covers mainly areas of extensive agriculture and livestock farming, distributed in the west and central-east of the study area (Figure 4a), with low quality and high quality throughout the west. The CQI analysis revealed that in the study area, 52.14% (115.97 km^2) was of high quality, and 45.61% (101.44 km^2) was of moderate quality in relation to the total area (Table 5).

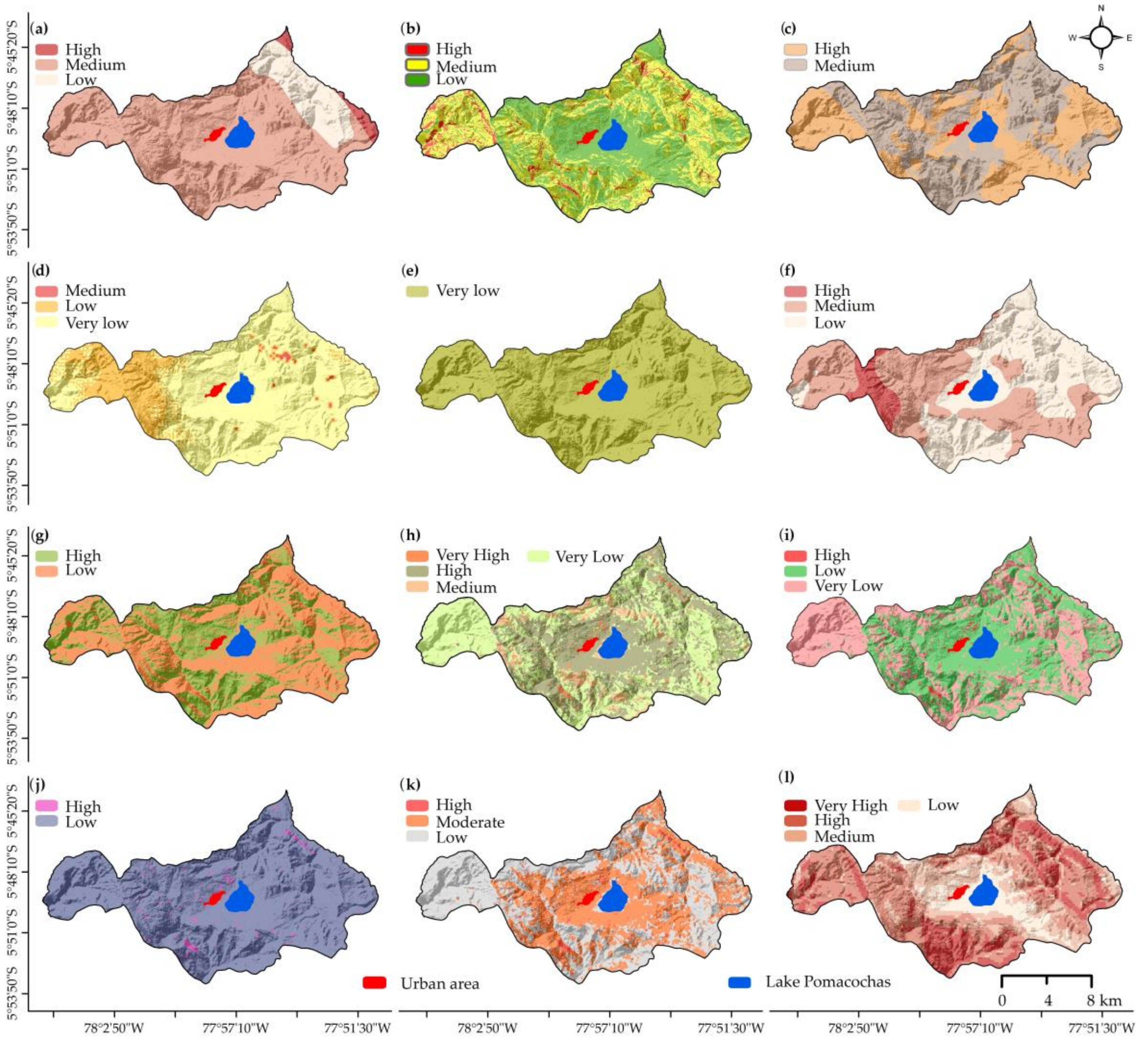

Figure 3. Spatial representation of the constituent parameters SQI: (**a**) Parental material, (**b**) Slope, (**c**) Soil organic matter y (**d**) Texture; CQI: (**e**) Aridity, (**f**) Erosivity y (**g**) Aspect; VQI: (**h**) Drought resistance, (**i**) Erosion protection y (**j**) Vegetation cover; MQI: (**k**) Agricultural intensity y (**l**) Landslides.

Table 5. Area (km^2) and percentages (%) corresponding to the four indicator quality classes in Florida district.

Indicator	Quality Description	Range of Scores	Total Area (km^2)	%
SQI	High	<1.13	4.8	2.16
	Moderate	1.13–1.45	197.07	88.61
	Low	>1.46	15.54	6.99
CQI	High	<1.15	115.97	52.14
	Moderate	1.15–1.81	101.44	45.61
	Low	>1.81	-	-
VQI	High	<1.13	101.03	45.43
	Moderate	1.13–1.38	113.16	50.88
	Low	>1.38	3.22	1.45
MQI	High	1–1.25	118.37	53.22
	Moderate	1.26–1.50	97.17	43.69
	Low	>1.51	1.88	0.84
Urban area			0.74	0.33
Lake Pomacochas			4.25	1.91

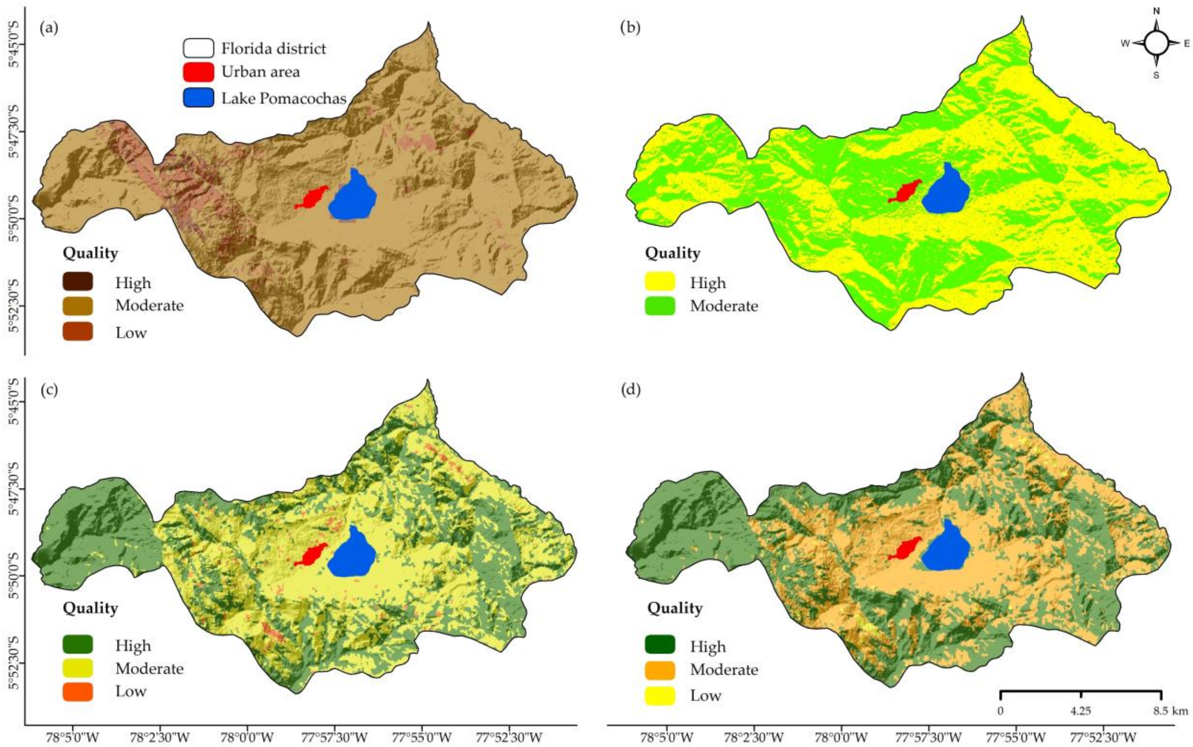

Figure 4. Spatial representation of quality indicators: (**a**) SQI, (**b**) CQI, (**c**) VQI, and (**d**) MQI.

The indicator CQI showed moderate to high quality and was distributed in the west and east throughout the study area (Figure 4b). Therefore, this indicator may contribute less to the aridity process, which is confirmed by the limited presence of the low class in the CQI.

The vegetation quality assessed using the VQI (Figure 4c), reported from the total area that 50.88% (113.16 km^2) was of moderate quality, 45.43% (101.03 km^2) was high quality, and 1.45% (3.22 km^2) of low quality (Table 5). Moderate quality zones, therefore, are exposed to degradation; most of this land is used for agriculture and livestock farming. While the high-quality zones is extended by forests with little anthropic intervention, the low-quality zones are characterized by barren lands and rainfed crops.

The MQI of the study area, 53.22% (118.37 km^2), is characterized by forested areas with fragments of small crops (Figure 4d). 43.69% (97.17 km^2) of the territory presents moderate management and is generally located in pastures and crops. On the other hand, only 0.84% (1.88 km^2) reports low management quality and is located in barren soils and urban crops.

3.3. Environmentally Sensitive Area Index (ESAI)

The spatial analysis of the ESAI final product of the four indices (SQI, CQI, VQI, and MQI) pointed out lands highly sensitive to degradation throughout the study area. The areas in the critical classes (C1, C2, and C3) represented 2.96% with scores > 1.38 and clearly are of great importance in terms of sensitivity to degradation (Figure 5 and Table 6).

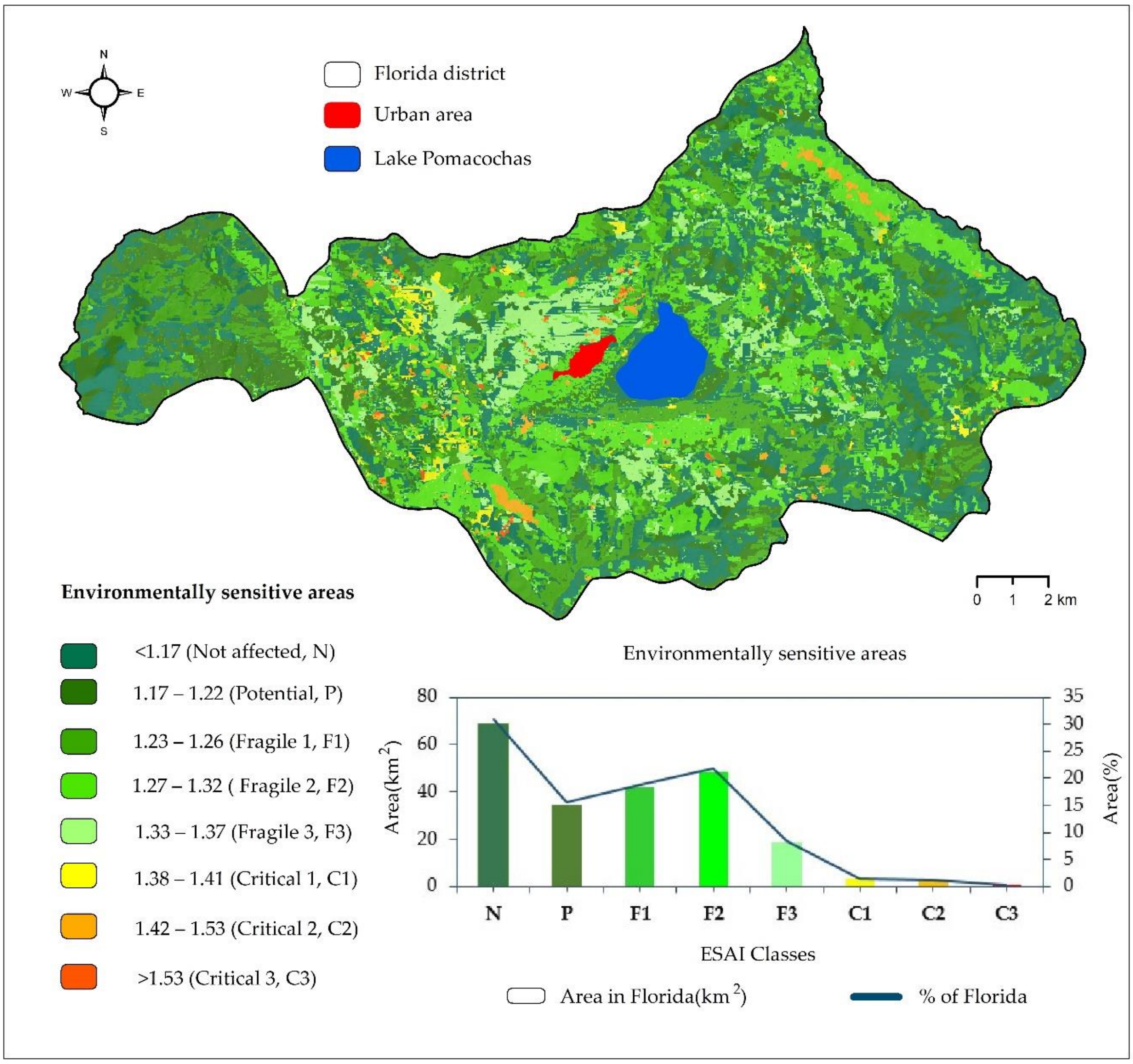

Figure 5. Environmentally sensitive areas to degradation in Florida district.

Table 6. Environmentally sensitive areas to degradation in km^2 and %, in Florida district.

Class	Sub Class	Range of Scores	Total Area (km^2)	%
Non-affected	N	<1.17	67.74	30.46
Potential	P	1.17–1.22	34.43	15.48
Fragile	F1	1.23–1.26	41.72	18.76
	F2	1.27–1.32	48.38	21.75
	F3	1.33–1.37	18.56	8.34
Critical	C1	1.38–1.41	3.47	1.56
	C2	1.42–1.53	2.68	1.21
	C3	>1.53	0.44	0.20
Urban area			0.74	0.33
Lake Pomacochas			4.25	1.91

The fragile class (F1, F2, and F3) covers the most area, 108.65 km^2 (48.85%), with respect to the other classes, while the potential class (P) covers 15.48% and the non-affected class (N) covers about 30.46% areas in Florida (Figure 5). The water body (lake Pomacochas) and urban area, which represent 1.91% and 0.33%,, respectively, were not included in the calculation.

In critical areas we found bare soils, non-irrigated crops, eroded soils and abandoned lands, while the fragile class, spread both in the flat parts and largely throughout the study territory, were found mainly on agricultural and livestock lands. Meanwhile, in the potential class areas, there are small patches of natural vegetation and occasional silvopastoral systems. Finally, the non-affected areas with no intervention at all included forests distant from urban populations or on steep slopes.

3.4. Validation of the Index of Environmentally Sensitive Areas

Field observations throughout the study area revealed critical areas (C1, C2, and C3), and fragile areas (F1, F2, and F3), which were subject to severe economic and ecological land decline (Figure 6). The validation results were consistent with the theoretical data characterizing the ESAI's three critical and fragile classes (Table 6). Therefore, several forms of in situ land degradation were concretely identified in the study area, especially in human-intervened areas (Figure 6a). Forested areas that have been transformed into pastures for cattle raising (Figure 6b–e) are over-exploited with little vegetation, which favors erosion and active landslides and consequently land degradation in the study area (Figure 6f–i). In addition, there are partially developed soils (Figure 6j,k) with degradation processes of the granular structure (Figure 6l), and reddish soils with a sandy clay loam texture (Figure 6m).

3.5. Correlation Coefficients between Quality Indices

Table 7 displays the correlation coefficient between the indices (SQI, CQI, VQI, MQI) and the ESAI. The CQI showed the lowest correlation (0.05), in relation to the VQI (0.79), SQI (0.86), and MQI (0.93).

Table 7. Correlation between quality and ESAI indices.

Indices	SQI	CQI	VQI	MQI	ESAI
SQI	1	−0.11	0.53	0.78	0.86
CQI	−0.11	1	−0.46	−0.27	0.05
VQI	0.53	−0.46	1	0.85	0.79
MQI	0.78	−0.27	0.85	1	0.93
ESAI	0.86	0.05	0.79	0.93	1

3.6. Ecological Restoration Proposal

The results of the ESAI identified that land in the critical class (2.96%) covers a smaller percentage of the studied territory than land in the fragile class (48.85%); hence, taking corrective measures may improve soil quality in the long term. It is clear that degradation is a complex process involving a holistic approach [84]. Specifically, we provide five proposals, in contribution to the Sustainable Development Goals (SDG) particularly 15.3, by 2030 [15,84,85]. Restoration should focus on the following proposals: (i) organic manure production, (ii) cultivated and improved pastures and livestock improvement, (iii) native forest restoration (iv) construction of reservoirs in the top hills, and (v) uses of new technologies (Figure 7). However, for these activities to be implemented, local stakeholders and institutions must be involved, and committed with clear ideas and leadership [15,84,85].

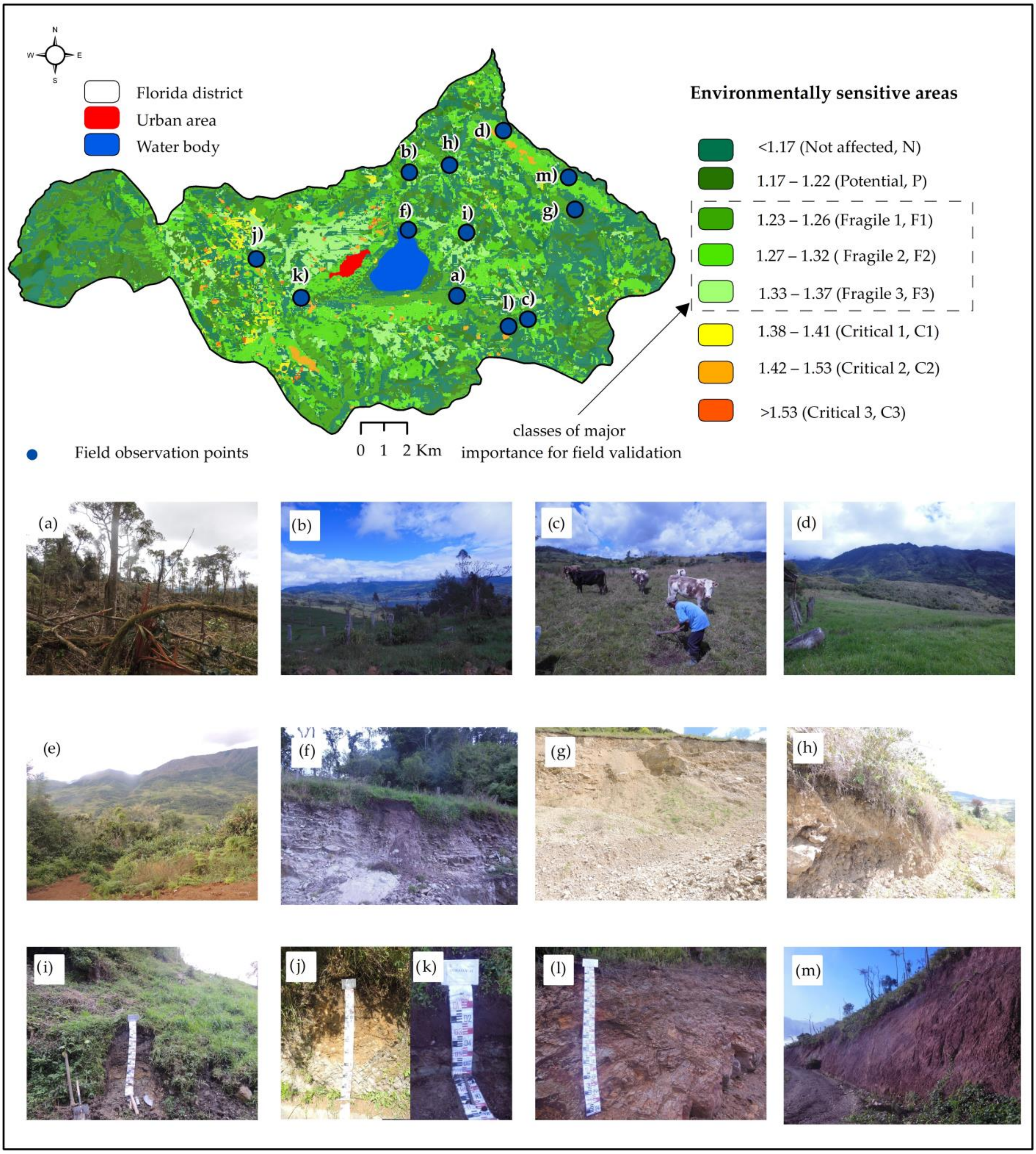

Figure 6. In situ validation of environmentally sensitive areas to degradation in Florida district, fragile areas (**a**–**d**), and critical areas (**e**–**m**).

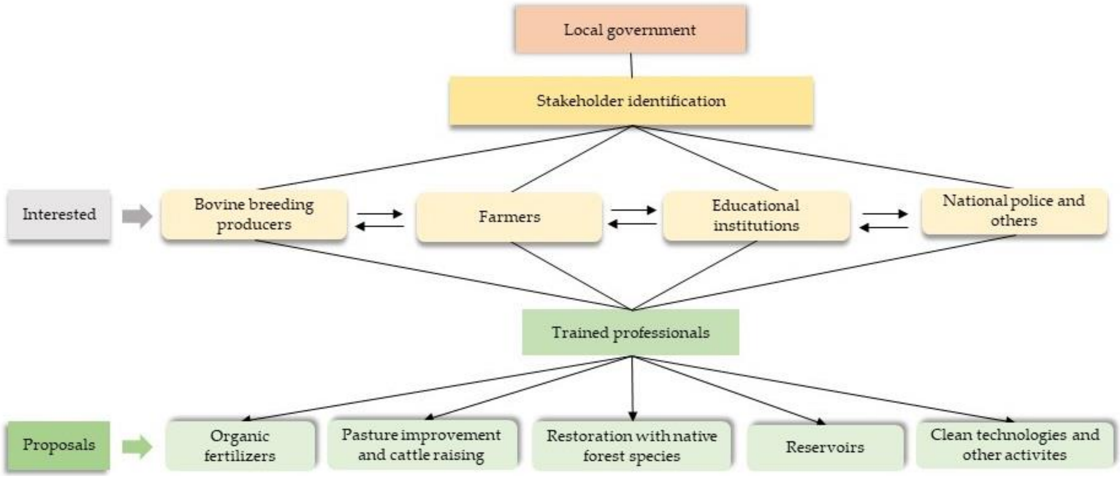

Figure 7. Restoration proposal flowchart in Florida district.

The public and private sectors' involvement in land restoration processes, is definite-ly, a good way to achieve sustainable development goals [84]. Some governmental programs related to pasture and livestock improvement, and application of production technologies may contribute to land restoration [15,48,86,87], like the production of organic manures could increase soil fertility, reduce soil erosion [15]. It could also mitigate fragile areas in this sector.

It is important to install a forest nursery with native plants for the production of seedlings to accelerate forest succession on degraded land [48,88]. These native species may be Mahogany (*Swietenia macrophylla King*), *Alchornea* sp., *Parathesis* sp., *Alnus acuminata* [48], *Cedrelinga cateniformis*, *Ceiba pentandra*, *Apuleia leiocarpa*, *Cariniana decandra* and *Cedrela montana* [15,89–91]. Another alternative, also practiced in Florida district, is silvopastoral systems (SPS), giving several benefits (fertilizing the soil, providing better forage, providing a high-protein diet for livestock and essential chemical elements) [92–95]. This practice can be retributed to farmers by environmental services payment [96].

The construction of friendly environmentally reservoirs for water storage, strategically located at the top of the hill on agricultural land or pasture, will allow better distribution of water through gravity pipe networks, which could be used in various local activities [15]. The improvement of firewood stoves and anaerobic biodigesters will contribute to fuelwood and electricity saving, mitigating greenhouse gases [97–99]. Once implemented, it is important to continuously monitor and raise awareness in the communities.

4. Discussion

4.1. On Quality Indicators

The SQI, more than 85% of Florida's territory is classified as moderate, which may result in two possible scenarios in the near future. In The first scenario low quality land could increase due to anthropogenic activities, and the second high quality land could increase with good land management, both depending on human activities. On the other hand, to determine the SQI, the parameters of parental material, slope, organic matter and texture were used for the flexibility of MEDALUS [9,15,18,22,47,72,73]. External parameters based on the characteristics in degraded areas can successfully lead to ecological succession for re-establishment of secondary forests and cost-effective restoration [48,100]. In Florida, there is a variation in organic matter, which varied from medium to high. This is consistent with a previous study [48], where it was determined that the organic horizon is thicker in forests than in grasslands. This parameter consequently provides so far nutrient availability, gas exchange and water supply to the soil [101]. Nevertheless, it should be noted that SOM content responds rapidly to anthropogenic manipulation and alteration, in contrast to texture and mineralogy, which change slowly over time [102–104]. Regarding soil texture, soils are mostly sandy loam clay loam, according to the classification of Komas et al. [16], classified with a very low susceptibility, consequently, the soil is not of low quality. However, Walentowski et al. [48], found high percentages of sandy soils under forests and more clay conditions in grasslands. Unfortunately, slope is one of the most important parameters driving degradation in different soil types [75]. In this study, we confirm such statement as slopes greater than 21% present high susceptibility to soil degradations, as it facilitates soil erosion [9,75,77]. Finally, SQI should be understood as the degree of sensitivity to soil degradation according to the parameters used and not as agronomic quality [105].

With regard to CQI, more than 50% is qualified as high quality and more than 40% as moderate quality, this could be related to the high precipitation (up to 1092 mm per year) [48,106]. This high precipitation means that the study area does not present arid lands, and as a consequence, there is no low class in climatic indicator. In this sense, aridity is an indicator of desertification and degradation [9,47]. However, regular rainfall causes soil erosivity [23,75], and here a classification of susceptibility to erosivity from low to high was determined. On the other hand, we expect that the aspect and type of climate of the Humid Cold Tropics [48], characteristic of the study area, influence even in the CQI, which is the reason for moderate to high CQI values. As supported by Xu et al. [76] and Salvati et al. [78], the aspect has important effects on vegetation growth and soil erosion rate. However, we suggest that further studies should be conducted to evaluate the effect of climate change in Amazonia and other areas of the world, as there is a probability that new areas will become arid in a short period of time [9,15,20,23,47,74,77,107–109].

The VQI, moderate class predominates with more than 50%, it is spread over agricultural and livestock lands. Lamentably, the forests have been exploited for timber sales since 1960 [48,106], and the establishment of pasture and crop plots, which practice continues today [31,48]. Forests mitigate degradation processes, in comparison to fragmented forests which ease the sensitivity of areas [73]. Therefore, cultivated and bare soils present a greater vulnerability to erosion and drought, unlike forests that are well protected by their root system and foliage [74]. Walentowski et al. [48], point out that abandoned pastures, degraded areas left for succession, do not guarantee landscape sustainability. By continuing with these negative practices, low quality areas of the VQI may increase in the future. Positive or negative changes will therefore occur depending on forests management.

The results reflect the need for further policy work on conservation, environmental education, training and monitoring programs for agricultural producers locally and nationally. It is important to coordinate the work with public and private organizations. Likewise, restoration actions should be taken with experiences from the country [43,110,111] and elsewhere [15,88,112,113]. We consider that immediate intervention should be given to low and moderate quality from the management point of view, for a sustainable use of the land.

4.2. On the Environmentally Sensitive Areas Index

The spatial analysis of the ESAI reported that the critical classes cover >2% of the territory, the fragile class with more than 45% of extension, while the potential class covers >15% and the unaffected >30%. In fact, the fragile class predominates in the study area and is similarly described as such by Walentowski et al. [48]. The ESAI depends directly on the SQI, CQI, VQI and MQI indices and these in turn depend on the parameters. In that sense, the major triggering indices that determine fragility were the VQI, SQI and MQI and are in agreement with other studies [9,23,75]. The results of the VQI and SQI are greater than 50% in moderate quality in the study area, thus a direct relationship with the low percentage of the critical area is inferred. Although, according to the results of the MQI there is a high-quality management of 53%, however, in comparison with the moderate quality it is close to this value. Therefore, there is still a deficiency in the management of sustainable land management. On the other hand, the high and moderate quality results of the CQI contribute to the fact that the critical areas do not increase due to the absence of the low class and are related to aridity [9,74]. Likewise, the correlation coefficients express in the same way the most triggering indices were VQI, SCI, and MQI, and the least triggering was

CQI, in relation to the ESAI. The correlation values of the indices closer to one influence the sensitivity of the degradation [23,83].

n general, prioritization of control and mitigation measures for restoration should be focused on areas with medium to low sensitivity. Critical areas are in an advanced state of degradation, which means costly interventions to revert to a natural state. Regarding MEDALUS model, it demands a large geographic database, anticipating gaps and missing values for the time series. In this study, the model generated from the MOS was low-performing, for further studies, more sampling points should be considered to reduce bias. In addition, due to scarce local meteorological data, the WorldClim global data was used as a free platform. Therefore, the lack of historical data (climatological and socio-economic data on soil characteristics) is one of the limitations for ecosystem monitoring and degradation assessment in developing countries such as Peru. However, it should be noted that these methodological shortcomings are generally present in other European studies with similar analyses of land sensitivity to degradation [9,18,19,47,74]. The results and proposals can be improved by decision-makers when implemented in the field in order to mitigate degradation processes for sustainable land use.

5. Conclusions

This study assessed ESAI using MEDALUS model and GIS based on four indices (SQI, CQI, VQI, and MQI) and 12 parameters in Florida district. Fragile class lands (48.5%) were predominant in most of the study area with degradation process lands, wich may result in the increasing or decreasing of either classes (Crítico, Potencial, No-affected) in future scenarios. VQI, SQI, and MQI were the most triggering indices determining land fragility in Florida district.

The ESAI map proved to be a good source of information to identify degradation problems, and accordingly five ecological restoration proposals were stablished in order to achieve sustainable development towards 2030: (i) production of organic fertilizers, (ii) cultivated and improved pastures and livestock improvement, (iii) native forest restoration, (iv) construction of reservoirs in the communities, and (v) use of new technologies. These proposals are key to work towars management policies locally and nationally.

Author Contributions: Conceptualization, G.M.M. and E.B.; Data curation, G.M.M. and C.T.G.; Formal analysis, G.M.M. and R.S.L.; Funding acquisition, C.T.G.; Investigation, G.M.M., C.T.G., M.O.-C. and E.B.; Methodology, G.M.M., R.S.L. and E.B.; Project administration, C.T.G. and M.O.-C.; Resources, G.M.M., M.O.-C. and R.S.L.; Software, G.M.M.; Visualization, G.M.M., R.S.L., G.M. and E.B.; Writing—original draft, G.M.M. and G.M.; Writing—review & editing, G.M.M., C.T.G., M.O.-C., R.S.L., G.M. and E.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was executed with the support from the CUI 2261386 "Creation of the Services of a Biodiversity Laboratory and Conservation of Genetic Resources of Wild Species of the Toribio Rodríguez de Mendoza National University, Amazonas"—BIODIVERSITY and executed by the Research Institute for Sustainable Development of Ceja de Selva (INDES-CES).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study are available from the corresponding author upon request.

Acknowledgments: The authors recognize and appreciate the support of the Research Institute for Sustainable Development of Ceja de Selva (INDES-CES) of the National University Toribio Rodríguez de Mendoza (UNTRM) and Instituto Nacional de Innovación Agraria (INIA).

Conflicts of Interest: The authors declare no conflict of interest.

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