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Estimation of the current erosion of the Northen Ecuadorian Highlands,

using geoinformation

Estimación de la erosión actual de la Sierra Norte ecuatoriana, mediante geoinformación

Estimativa da erosão atual das terras altas do norte do Equador, usando geoinformação

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Abstract

Inadequate agricultural practices and deforestation in the Ecuadorian Sierra Norte have eliminated soil cover, accelerating the erosive effect caused by strong winds and rains in the area. The aim of this research was to carry out a multi-temporal study of the study area to determine the state of the degree of erosion indicated in 1986 by PRONAREG-ORSTOM, by processing LANDSAT images (1986 and 2017) and their respective vegetation indices (inverted SAVI, IB and IC), adapting the methodology proposed by CIREN-Chile to the country. The results show that there is an increase of approximately 251,000 ha (16%) of eroded surface during this period, warning that severe erosion has increased, decreasing the degree of moderate erosion, suggesting that pressure on the land and poor soil management are promoting an accelerated erosion process.
KEYWORDS: current soil erosion; geoinformation; image processing; Landsat; multitemporal.

Resumen

Las prácticas agrícolas inadecuadas y la deforestación de la Sierra Norte ecuatoriana han eliminado la cobertura del suelo acelerando el efecto erosivo provocado por los fuertes vientos y lluvias de la zona. El objetivo de la presente investigación ha sido realizar un estudio multitemporal de la zona de estudio para determinar el estado del grado de erosión indicado en 1986 por el PRONAREG-ORSTOM, mediante el procesamiento de imágenes LANDSAT (1986 y 2017) y sus respectivos índices de vegetación (SAVI invertida, IB e IC), adaptando al país la metodología propuesta por CIREN- Chile. Los resultados obtenidos muestran que existe un incremento de aproximadamente 251 000 ha (16 %) de superficie erosionada, durante este período, advirtiendo que ha aumentado la erosión de grado severa, disminuyendo el grado de erosión moderada, lo que sugiere que la presión sobre la tierra y el mal manejo del suelo están fomentando un proceso erosivo acelerado.
PALABRAS CLAVE: erosión del suelo presente; geoinformación; procesamiento de imágenes; Landsat; multitemporal.

Resumo

As práticas agrícolas inadequadas e o desmatamento na Serra Norte equatoriana eliminaram a cobertura do solo, acelerando o efeito erosivo causado pelos fortes ventos e chuvas na área. O objetivo desta pesquisa foi realizar um estudo multitemporal da área de estudo para determinar o estado do grau de erosão indicado em 1986 pelo PRONAREG-ORSTOM, através do processamento de imagens LANDSAT (1986 e 2017) e seus respectivos índices de vegetação (SAVI invertido, IB e IC), adaptando a metodologia proposta pelo CIREN- Chile ao país. Os resultados obtidos mostram que há um aumento de aproximadamente 251.000 ha (16%) de superfície erodida, durante esse período, alertando que a erosão severa aumentou, diminuindo o grau de erosão moderada, sugerindo que a pressão sobre a terra e o mau manejo do solo estão promovendo um processo de erosão acelerado.
PALAVRAS-CHAVE: erosão atual do solo; geoinformação; processamento de imagens; Landsat; multitemporal.

1. Introduction

The soil, as an integral part of the river basin, directly affects the behavior of all other resources, especially water, particularly when agricultural production is considered (Echeverría-Puertas *et al.,* 2023; Cayambe *et al.,* 2023). However, the intense and careless management of this resource promotes its degradation and decreases its current and potential capacity to produce goods and services in a quantitative and qualitative way (Porta *et al.,* 2003; CARE, 2012; Segarra, 2017; Viera-Torres *et al.,* 2020; Guascal *et al.,* 2020; Reyes-Pozo *et al.,* 2020). It is considered that anthropic action is responsible for around 333,000 ha suffering active erosive processes in Ecuador, becoming this process the greatest threat to the environment in the Ecuadorian Highlands (Custode *et al.,* 1999; MAG, 1999; Pacheco, 2009; Espinosa, 2014; Merizalde Mora *et al.,* 2021).

The use of Geographic Information Systems (GIS) in the evaluation of soil degradation consists of generating geoinformation from different data sources to indicate the areas most affected or susceptible to this process (Petersen *et al.,* 1997; Heredia-R *et al.,* 2021; Luna *et al.,* 2023). These geoinformatics tools allow conducting powerful spatial data processing, classifying and transforming the nature of the observed terrestrial objects into information, such as that required for quantification studies of the erosive process in Ecuador (Zapata *et al.,* 2020).

This information may be used to model the potential risk of erosion in different areas and at different scales, generating valuable support for the global and integrated management of river basins, particularly in areas with greater erosive processes, as well as in the implementation of techniques of soil conservation, and in decision-making in its territorial management, such as policies, plans, programs, projects and activities (Gómez-Orea, 2007; Posada, 2010; Patil, 2018; Toulkeridis *et al.,* 2020).

Although the devastating effect of erosion in the inter-Andean alley is known, it is also true that there is no updated information on the exact surface of soils affected by erosion, nor is the dynamics and form of dispersion of soil loss known over the years, except due to the documents published by Almeida *et al.*, (1984) and De Noni & Trujillo (1986), which have been used until now as a reference point with respect to the magnitude of erosion in Ecuador.

Considering the aforementioned approach, the present study has been developed with the objective of determining the state of the erosive process of the northern Ecuadorian Highlands, based on information generated by the Ministry of Agriculture and Livestock (MAG) and the Scientific and Technical Research Office Abroad (ORSTOM) in 1984.

2. Methodology

The present study was performed in the northern highlands of Ecuador, specifically in the inter-Andean slopes, up to a height of 3600 meters above sea level (a.s.l.), and the ground of the basins with recent volcanic deposits, located between the eastern and western mountain ranges. This section extends over 350 km from the Colombian border, in the north, to approximately latitude 2°30'S, at the outlet of the Alausí-Chunchi valley (Winckell *et al.,* 1997; Custode *et al.*, 1999; Espinosa & Moreno, 2018; Macías *et al.*, 2023).

Hereby, the work scale is 1:250 000, in which approximately 15 575 km^2 were analyzed. The study was divided into three phases, which began with the collection of information (raster and vector format) on soils, at a scale of 1: 50 000 and 1: 200 000, used for the generation of the 1984 map, being the main erosive processes of Ecuador, at a scale of 1: 1,000,000 (Almeida *et al.,* 1984; Gondard *et al.,* 1986), in order to be processed and to obtain a map at higher detail (1:250,000). This map, which was initially adjusted to be used to compare results with current erosion information, was not used for the expected purpose and it was necessary to generate cartography for the 1986 period, as the Almeida map was prepared with another methodology compared to that of the present investigation, in such a way that in the next phase the degrees of erosion of the period 1986, by using information from the years 1978, 1979, 1985 and 1986, respectively. However, while the current one (2017) was determined, LANDSAT images (L2, L5 and L8) were processed and classified unsupervised as well as visually interpreted. For this work, GIS tools (ArcGIS and ERDAS) were used, following the methodology proposed by the Natural Resources Information Center (CIREN) for the determination of current erosion, allowing the respective adaptation for the characteristics of the country (TABLE 1), (Pouget *et al.*, 1996; CIREN, 2010; IEE, 2014).

TABLE 1. Landsat images used in the present study

Satellite & Year	**Metadata**
Landsat 2 1978	"LM02_L1TP_010059_19780826_20180421_01_T2"
Landsat 2 1979	"LM02_L1TP_010060_19790204_20180418_01_T2"
Landsat 5 1985	"LM05_L1GS_010062_19850405_20180406_01_T2"
Landsat 5 1986	"LM05_L1TP_010060_19860323_20180331_01_T2"
Landsat 8 2017	"LC08_L1TP_010059_20170920_20171012_01_T1"

In order to determine the changes in land use and land cover in the study area, comparing previously classified images, the results of the research conducted by Palacio & Luna (1994) were considered. This occurred in such a way that when conducting the tests between the classification supervised and unsupervised, the supervised classification was discarded because its results lacked to agree with information from soil studies in the area, performed by the IEE (2016).

In order to conduct the unsupervised classification of satellite images with the IGAC Methodology (Posada *et al.*, 2012), the geometric and radiometric correction of the images was previously performed, and the combination of bands to obtain the vegetation indices (SAVI) and indices to discriminate the soil (IC for color and IB for its brightness), (TABLE 2). Subsequently, when performing the reclassification to group the cover classes, according to each spectral response, twenty cover classes were obtained corresponding to vegetation and severity of erosion in each period (CIREN, 2010; Campbell & Wynne, 2011). From this processing, the eroded units were obtained, whose yellow color intensities corresponded to soils with light, moderate and severe erosion. It is indicated that for this classification a direct relationship was established between the indices and soil loss processes using their highest digital indices - tending towards white - to express the highest degree of uncovered soil (IC and IB). Therefore, for SAVI, an inverse relationship was conducted in order to determine the bare soils, because in SAVI [1], without inverting, its highest indices - white - illustrate a greater degree of vegetation (FIGURE 1). Therefore, when performing the inverted SAVI, the three spectral indices were directly related to the percentages of bare soils and deterioration currently exposed, achieving the composition of inverted SAVI bands [2], brightness [3 and 4] and color [5], in channels 2, 1 and 3 (FIGURE 2), to display them in RGB (Red-Green-Blue), respectively (CIREN, 2010).

TABLE 2. Spectral Indexes

Índex		Equation	
SAVI		$SAVI\_I = \frac{NIR-Br}{Br+NIR+L}(1+L)$	[1]
SAVI_Inverted		$SAVI\_I = \frac{Br-NIR}{Br+NIR+L}(1+L)$	[2]
Brightness- IB	a) L2 y L5	$a)\ IB = \sqrt{\frac{B_v^2 + B_r^2 + B_{NIR}^2}{3}}$	[3]
	b) L8	$b)\ IB = \sqrt{\frac{B_a^2 + B_v^2 + B_r^2}{3}}$	[4]
Color-IC		$IC = \frac{Br - Bv}{Br + Bv}$	[5]

Where, *NIR* corresponds to the near infrared band; *Br* is the spectral band of red; *L* corresponds to a correction factor; a value of L = 0.5 allows to improve the adjustment, especially for intermediate densities of vegetation (Huete, 1988; CIREN, 2010). While *Ba* and *Bv* correspond to the blue and green bands, respectively (Madeira, 1993; Ochoa & Parrot, 2007).

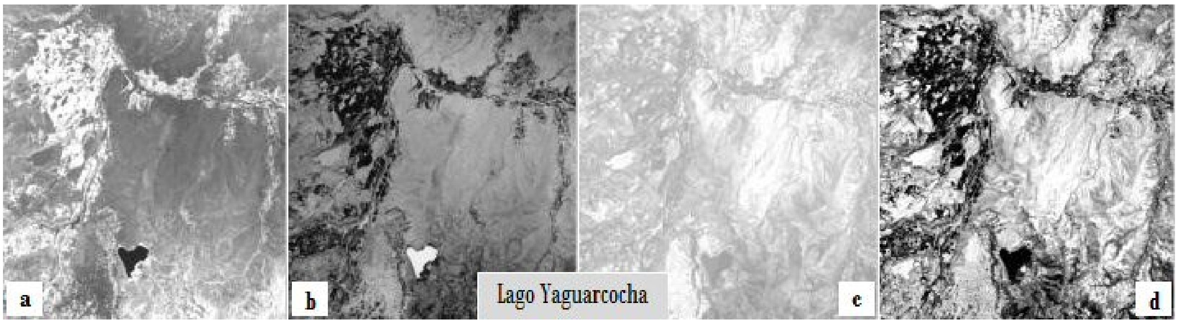

FIGURE 1. a) SAVI index, light tones correspond to greater vegetation cover; b) Inverted SAVI index, light tones correspond to bare soils; c) IB index, light tones correspond to soils with greater erosion; d) IC index, light tones correspond to bare soils.

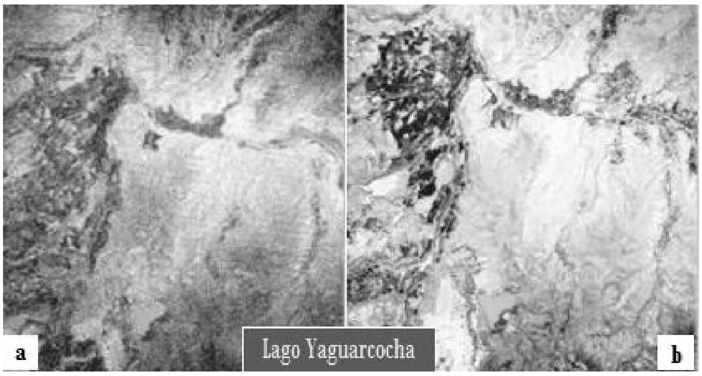

FIGURE 2. Composition of 2-1-3 bands with SAVI-IB-IC bands: a) 1986 and b) 2017

The analysis and adjustment of the three established degrees of erosion (Light, Moderate and Severe) (TABLE 3; FIGURE 3), classified from the images, was conducted, for the recent period (2017), with the help of secondary information such as panoramic photographs of soil profiles of the area, map of cangahua, information on use and coverage, among others, and field trips based on prior knowledge of the study area and agrological work (IEE and SIGTIERRAS-MAG). Meanwhile, the adjustment of the severity of erosion for the 1986 period was realized through secondary information, such as vegetation cover maps, plant landscapes and images that were used to generate the 1984 map, based on images from 1979 of lower spatial resolution (80 m), completing the information with information from images 1978 (80 m) and 1985 (30 m), which were used to corroborate the eroded surfaces, especially the 1986 image.

FIGURE 3. a) Without erosion; b) Light erosion; c) Moderate erosion; d) Severe erosion

TABLE 3. Degrees of erosion (CIREN, 2010)

Degree of erosion	Description
No apparent erosion	Soil surface that does not present alterations or signs of soil loss
Light erosion	It corresponds to slightly inclined soils (slopes <12%) with semi-dense vegetation cover (>50% and <75%), which is slightly altered
Moderate erosion	Soils that have a clear presence of the subsoil in at least 30% of the surface of the unit under study. The original soil has been lost between 40 to 60%. There is occasional presence of grooves
Severe erosion	Soils that occasionally present furrows and gullies. The loss of soil is of the order of 60 to 80%, with outcropping of cangahuas, in more than 60% of the surface

Subsequently, the validation of the map obtained from the year 2017 was performed, with the intention of estimating its reliability. For this purpose, a confusion matrix was used (TABLE 10), which collected the data predicted on the map and those observed in the field, as well as the successes or errors of the degrees of erosion presented, in such a way that the global reliability was known. of the classifications (Equations 6 and 7). The KAPPA index (global percentage of success) allowed to numerically validate the results of the classifications, establishing the degree of agreement of the map generated versus reality (Equation 8), (TABLE 4), (Chuvieco, 2010).

Calculation of observed successes (Abraira, 2001); $Po = \frac{a+e+i}{N}$ [6]

Where, Po are the observed successes; a, e, or i are observed data; N the number of samples.

Calculation of estimated successes (Abraira, 2001); $Pe = \frac{tq+ur+vs}{N^2}$ [7]

Where, Pe are the expected successes; q, r, s, t, u, v are the sum of observed and expected agreements; N the number of samples.

Kappa Index (Landis & Koch, 1977); $K = \frac{Po-Pe}{1-Pe}$ [8]

TABLE 4. Assessment scale of the KAPPA index (Landis & Koch, 1977)

Kappa	Degree of agreement or concordance
< 0	whitout deal
0 - 0,2	mild
0,21-0,4	fair
0,41-0,60	moderate
0,61- 0,80	considerable
0,81 - 1	almost perfect

To validate the two cases, secondary geoinformation was used, being the information from the maps of land use and plant coverages of the Highlands at a scale of 1: 50,000 the way to validate the erosion map for the period 1986, which indicates in its information the code "E" for eroded areas and "e" for areas in the process of notable erosion (Gondard, 1984). While, for the recent period, a survey of field files was carried out, which allowed corroborating the information generated, following what was suggested by Chuvieco (2010), to obtain the sample size in this type of study (images classified), where the population is large (millions of pixels in Landsat images), the sample size need not be a percentage of the population. In this case, an approximation of the sample size is detailed in Equation 9 (used to measure a binomial variable, success-error), with a reliability of 80%, averaged from the results of similar studies (Segura *et al.*, 2003; Arango & Branch, 2005; Marini *et al.*, 2007).

The stratification of samples was carried out based on the percentage of the area covered by each degree of erosion on the map, so that the degree of erosion that occupies the largest surface has a greater number of samples (Chuvieco, 2010). To determine the sampling sites, the convenience technique (Otzen & Mantereola, 2017) was applied, which allowed a prior random selection of the places to be sampled, using the ArcGIS *Create random points* tool, prior to sample stratification, biasing those sites where there is no access due to lack of roads, or contain information from previously surveyed soil profiles (IEE, 2018).

Sample size; $n = \frac{z^2pq}{E^2}$ [9]

Where, z is the abscissa of the normal curve for the determined level of probability; p, the estimated percentage of hits; q, the percentage of errors (q=1-p); E, the allowable level of error.

Finally, the current state of erosion was determined by comparing the erosion of 2017 with the areas affected by this phenomenon in the period of 1986, being able to determine at the same time the erosion rate for each grade. In this way, the significance of the changes produced in the surface affected by the severity of the erosive processes was determined. To corroborate the significance of the changes, a Student's t test (Equation 10) was used, considering that there are two independent samples with unequal data variances of less than 30, making it necessary to use the modification of the t test, known as the test of Welch (Equation 11), whose distribution is approximately equal to an ordinary t distribution, but the calculation of the degree of freedom will depend on Equation 12 (Data analysis, Excel software).

The confidence level applied was 0.05, using the means of the results of the erosive degrees at the province level for the calculation (Pértega & Pita, 2001; Samperl *et al.*, 2010; Guisande *et al.*, 2013; Reyes, 2016).

t-test; $t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{(\frac{S_1^2}{N_1} + \frac{S_2^2}{N_2})}}$ [10]

Where, X_1 is the mean of the first data set, X_2 is the mean of the second data set, S_1^2 is the standard deviation of the first data set, S_2^2 is the standard deviation of the second data set, N_1 is the number of items in the first data set and N_2 is the number of items in the second data set.

Two-sample t-test assuming unequal variances;

$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{\bar{X}_1 - \bar{X}_2}} S_{\bar{X}_1 - \bar{X}_2} = \sqrt{(\frac{S_1^2}{N_1} + \frac{S_2^2}{N_2})}$ [11]

Being, S_2 the unbiased estimator of the variance of the two data sets, N the number of data, 1 = data 1, 2 = data 2. In this case $Sx_1\text{-}x_2^2$ (it is not the combined variance).

Degrees of freedom; $Gl = \frac{(\frac{S_1^2}{N_1} + \frac{S_2^2}{N_2})}{\frac{\frac{S_1^2}{N_1}}{N_1 - 1} + \frac{\frac{S_2^2}{N_2}}{N_2 - 1}}$

[12]

3. Results

Once the analysis of the information was generated, the map of the main erosive processes of Ecuador in 1984 was obtained, in greater detail, which was obtained through photointerpretation, being used to validate the information from the first period 1986, indicating the three intensities of proposed erosion, being very active, active and the association active and potential, which have correspondence with the present work to the severe, moderate and light degrees, respectively (Almeida *et al.*, 1984). According to the information in this input, it can be observed that the last degrees of erosion occupied similar surfaces, while the degree of light erosion occupied a smaller surface (TABLE 5). Thus, it can also be observed that approximately 49% of the study area would have been eroded by this time, while the remaining 51% presented a very slight degree of erosion or no erosion.

TABLE 5. Degrees of erosion related to the 1984 map

Year	Degree of Erosion (ha)			
	Light	Moderate	Severe	Total
1984	139 042,03	307 669,96	312 197.58	758 909,57
%*	8,93	19,75	20,04	48,72

* The percentages are based on the surface area of the study area, which is 1,557,587.75 ha (see text)

According to Phase 2 (image processing and digitization) of the study, the same categories or degrees of erosion indicated in the previous point were obtained, which are expressed in terms of surface for the two periods. It should be noted that the results between 1984 (TABLE 5) and 1986 (TABLE 6) differ between each category, which will be discussed later. TABLE 6 details the results obtained in both periods (1986 and 2017), observing the increase in the eroded surface for the Light and Severe grades, while for the Moderate grade a decrease is observed (FIGURE 4), which is evidenced in FIGURES 5 AND 6.

TABLE 6. Degrees of erosion for the period 1986 and 2017

	Degree of Erosion (ha)			
Year	**Light**	**Moderade**	**Severe**	**Total**
1986	409 353,55	59 388,54	4 760,18	**473 502,27**
%*	26,28	3,81	0,31	**30,40**
2017	540 653,83	41 280,51	142 540,90	**724 475,25**
%*	34,71	2,65	9,15	**46,51**

* The percentages are based on the surface area of the study area, which is 1,557,587.75 ha (see text)

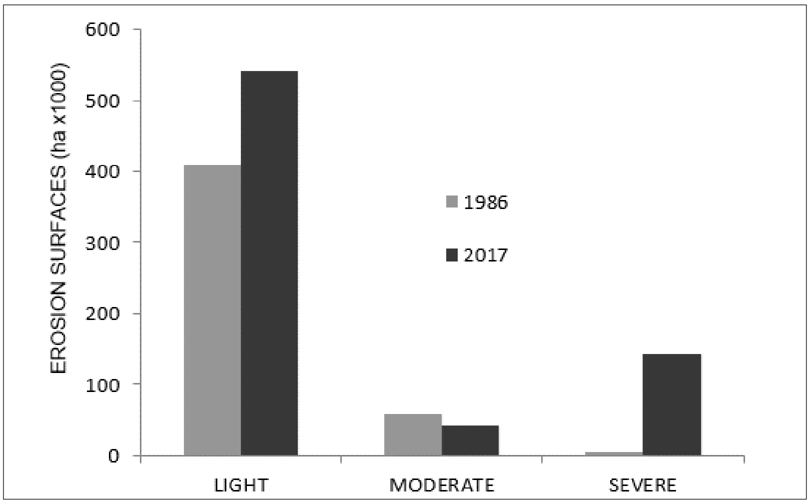

FIGURE 4. Erosion surfaces for the periods 1986 and 2017

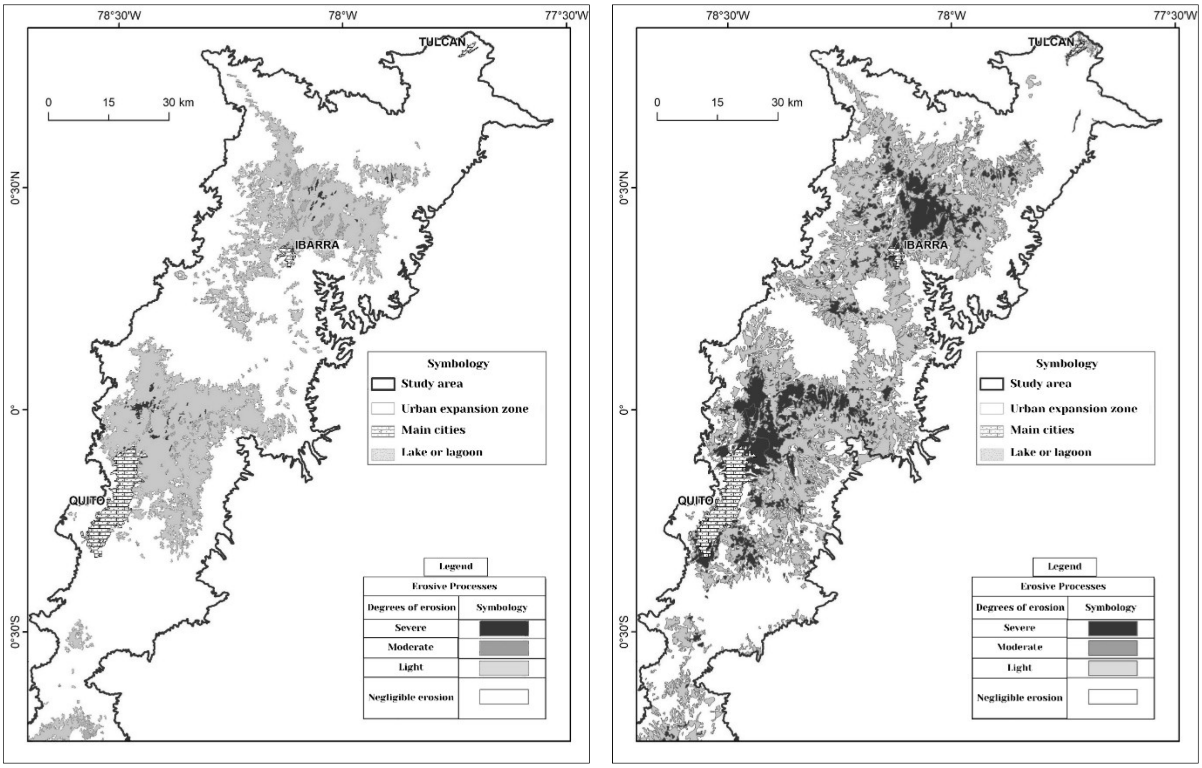

FIGURE 5. Degrees of erosion in the northern area of the area under study: a) 1986 and b) 2017

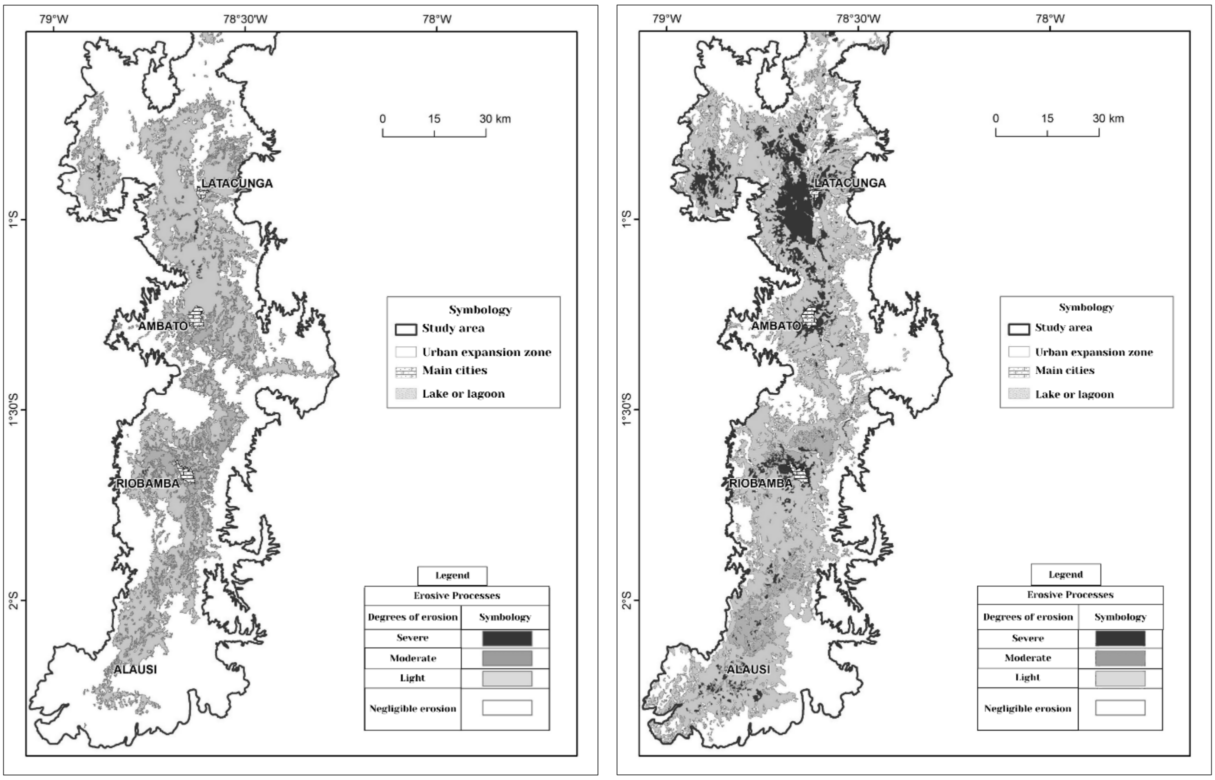

FIGURE 6. Degrees of erosion in the southern area of the study area: a) 1986 and b) 2017

In order to identify the areas most affected and the changes in the severity of the erosive processes, the areas corresponding to each province in the study area are presented (TABLE 7, FIGURES 7, 8 AND 9). It can be observed that the most representative changes correspond to light and severe erosion in the provinces of Cotopaxi, Chimborazo and Pichincha, while in Tungurahua, Carchi and Cotopaxi there is a representative decrease in moderate erosion, but the same on the surface. with severe increase in 2017.

TABLE 8 presents the average results of the calculations corresponding to erosion for the years 1986 and 2017. The "t test" between two independent samples with unequal variances, applied in the study, indicates that there are no statistically significant differences ($p \leq 0 .05$) in erosion for the light and moderate degree, while there is a difference for the severe degree. Likewise, the comparison between the result of the two years is observed, indicating that there is no statistical difference between 1986 and 2017 (TABLE 9), rejecting the alternative hypotheses (there are changes in the country's erosion). However, the arithmetic difference indicates a 16 % increase in eroded surfaces in this period, with an approximate referential erosion rate of 8,096 ha/year (determined by the difference between eroded areas, for the number of years elapsed).

TABLE 7. Degrees of erosion for the period 1986 and 2017 at the province level

Province	Grade of Erosion	1986 Area/ province	1986 Total	2017 Area/ province	2017 Total
		------------------------hectars--------------------			
Carchi	Light	20 456,58	409 353,55	38 653,09	540 653,83
Cotopaxi		94 192,91		103 826,68	
Chimborazo		90 438,68		160 154,99	
Imbabura		50 395,04		750 19,77	
Pichincha		97 057,00		107 833,76	
Tungurahua		56 813,34		55 165,55	
Carchi	Moderade	1 252,46	59 388,54	772,21	41 280,51
Cotopaxi		7 269,70		3 515,25	
Chimborazo		29 981,44		29 773,88	
Imbabura		3 005,19		3 865,19	
Pichincha		2 500,36		2 973,91	
Tungurahua		15 379,39		380,09	
Carchi	Severe	690,57	4 760,18	7 129,14	142 540,90
Cotopaxi		1 226,73		40 196,68	
Chimborazo		177,50		14 513,88	
Imbabura		353,63		20 125,58	
Pichincha		2 076,35		51 510,39	
Tungurahua		235,41		9 065,24	
Total		473 502,27		724 475,25	
%*		30,40		46,51	

* The percentages are based on the surface area of the study area, which is 1,557,587.75 ha

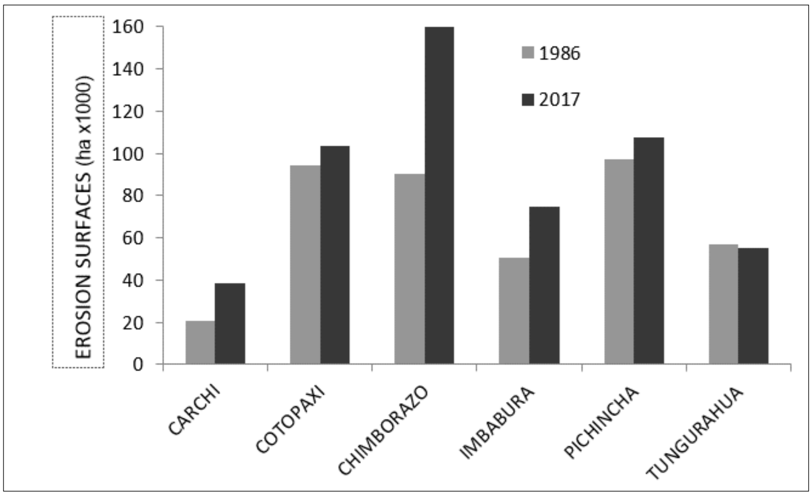

FIGURE 7. Degree of light erosion of 6 provinces of Ecuador in 1986 and 2017

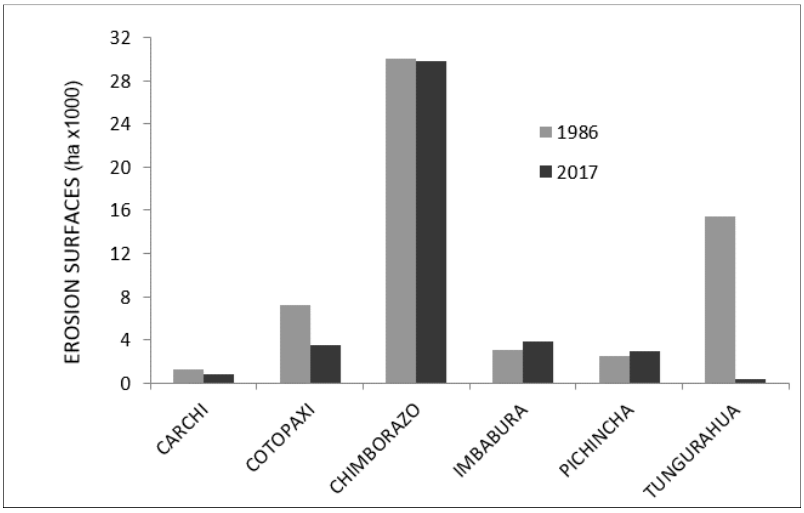

FIGURE 8. Degree of moderate erosion of 6 provinces of Ecuador in 1986 and 2017

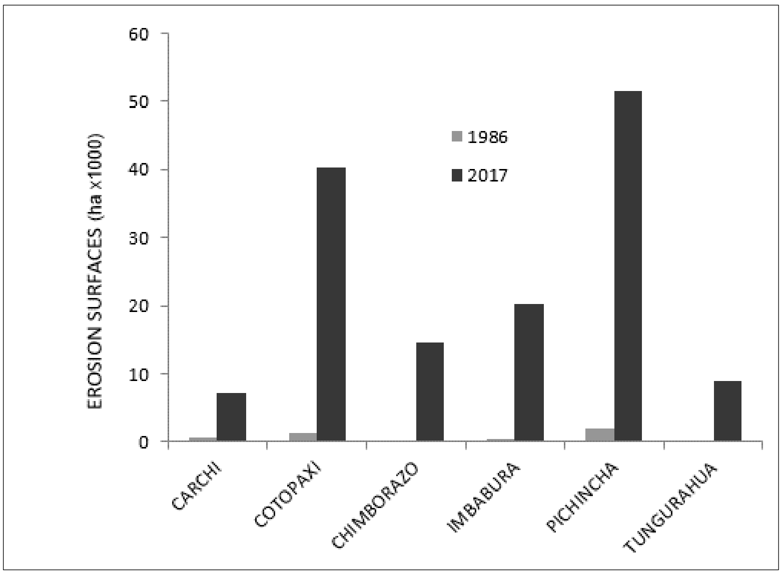

FIGURE 9. Degree of severe erosion of 6 provinces of Ecuador in 1986 and 2017

TABLE 8. Test t for the degree of erosion for the years 1986 and 2017

Degree of erosion and year		Mean	Variance	Data	GL	t-Statistic	P (T<=t) 1 tail
Light	1986	68 225,59	945 803 876,06	6	9	-1,00	0,17
	2017	90 108,97	1 901 044 605,61				
Moderate	1986	9 898,09	123 455 914,67	6	10	0,47	0,33
	2017	6 880,09	127 870 368,01				
Severe	1986	793,36	545 678,23	6	5	-3,11	0,013
	2017	23 756,82	326 293 894,84				

TABLE 9. Test t for the erosion of the years 1986 and 2017

	1986	2017
Mean	157 834,091	241 491,751
Variance	48 192 593 020	6,9687E+10
Observations	3	3
Degrees of freedom	4	
t-Statistic	-0,42	
P(T<=t) one tail	0,35	
Critical value of t (one tailed)	2,13	

The verification of the reliability of the information was obtained using the confusion matrix in which the data predicted on the map (2017) and those observed in the field were compared (TABLE 10). The resulting KAPPA index is close to 1, so the information is considered substantial. This result is attributed to the high number of samples for light severity, considering that most of the soils of the inter-Andean valley suffer some type of erosion (Acosta Solís, 1956; Almeida *et al.*, 1984; Custode *et al.*, 1999), so that the observed and the estimated agree approximately 100%.

TABLE 10. Confusion matrix to validate the current erosion map (2017)

Map \ Land	Degrees of erosion: Light	Moderate	Severe	Total	
Light	183a	0b	0c	183 q=(a+b+c)	Kappa index = 1
Moderate	4 d	10 e	0f	14 r=(d+e+f)	
Severe	0g	10h	39i	49 s=(g+h+i)	Agreement percentage = 94 %
Total	185 t=(a+d+g)	22 u=(b+e+h)	39 v=(c+f+i)	246 N=a+e+i	

The number of samples to verify the reliability of the map was 246, which were stratified according to the percentages of area occupied by the degrees of erosion (TABLE 11). In this case, it is necessary to clarify that the tour of the study area was conducted, collecting 88 samples, completing the 246 samples with information on soil profiles surveyed in the area (IEE, 2016).

TABLE 11. Number of samples verified in the field

			246 layered erosion samples	
	z =	1.96		
Equation 9	p =	80	Light	183
	q =	20	Moderate	14
	E =	±5	Severe	49

4. Discussion

As a result of the analysis of the geoinformation generated by Almeida *et al.*, 1984, it was possible to determine the surfaces and percentages of the different erosive processes, which are presented in the same degrees of severity of the present work. This information served as support for the analysis of the results obtained by describing the factors that promote erosion in these areas, such as runoff, which acts with greater intensity on the materials that are part of the pyroclastic materials that cover the Inter-Andean Valley (medium to thick textures), (Almeida *et al.*, 1984; MAG, 1999; Espinosa & Moreno, 2018), especially on the severely eroded surfaces of Imbabura, Pichincha and Chimborazo (FIGURE 9).

It was considered, after analyzing the information resulting from the 1984 map (The Main Erosive Processes of Ecuador - in greater detail), that the cartography obtained covers areas whose exposed erosion does not correspond to the ranges described and that its limits enclose areas of different categories, as observed in the cartography of the 1986 period (TABLE 6), whose results are different from what is indicated in TABLE 5. This could be due to the different methodology used (photointer-pretation and field work, mainly, described in Gondard, 1984). and to the confusions in the interpretation and classification in that period (1984), as demonstrated by Loza, 2018 and Morocho, 2018. They indicated that during the analysis of the information in paramo areas (light erosion), having a vegetation cover close to the soil, present a spectral response similar to that of bare soil (moderate category for the present study). It may also be due to the different working scale used or the time of the image survey used in 1984. For the present study, the dry season was considered, with low or no precipitation (TABLE 1). This is the reason for the difference in results between the information on the 1984 map and the recent one (2017), as illustrated in FIGURE 10, which indicates that over the course of this period of time eroded areas have been regenerated or changed management, use or coverage.

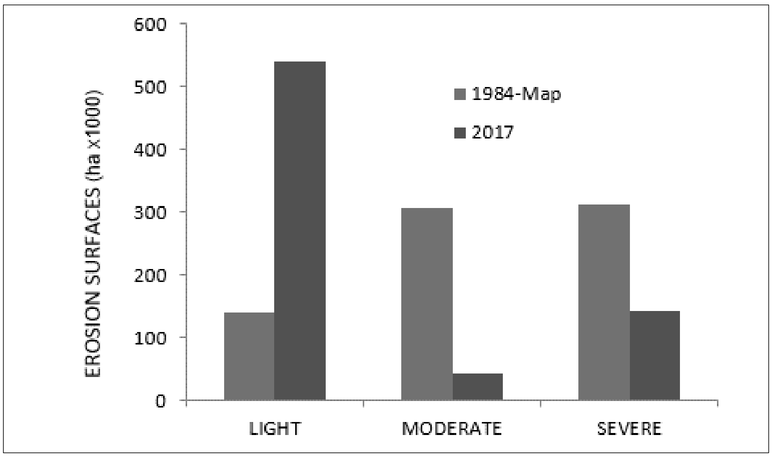

FIGURE 10. Degree of erosion obtained on the 1984 map and the current one (2017)

In the results of the unsupervised classification, it can be observed that the degree of erosion of the study area is greater for the year 2017. However, due to the scale of work, all units smaller than 16 ha were excluded (Bernal & Vargas, 2019), considering that this was the minimum mappable unit for the work scale (Lencinas & Siebert, 2009; Chuvieco, 2010; Bernal & Vargas, 2019).

The results of the statistical tests indicated that there is only significance for the degree of severe erosion, accepting the alternative hypothesis, where there is a change between the two periods. This was verified through the field checking that allowed to observe that the current rates of soil loss are considerable (Santos & Castro, 2012), a situation that is explained by the increase in areas where cangahuas have emerged (Prat, 2015; MAG, 2017) and as suggested by previous studies (Acosta Solís, 1952; Almeida *et al.*, 1984). This increase in severe erosion is related to the decrease in the degree of moderate erosion, which has been reduced in relation to the year 1986, going in part from moderate to severe erosion (FIGURE 4), as can be seen graphically in FIGURE 5 AND 6.

Although there was no statistical difference in the total eroded area, which groups together the different degrees of erosion, the 16-point increase in the percentage of eroded surfaces, between the 1986 and 2017 cartography, is of considerable mathematical significance. This result could be related to the work scale used, which led to the exclusion of some areas (minimum mappable unit 16 ha), apparently reducing the area affected by erosive processes (Lencinas & Siebert, 2009). The statistical test used could be another factor that influenced the results, since the number of data from the two periods is less than 30, which means that the t test used is not adequate to detect a difference between the means. even when it really exists, because the samples are very small (MINITAB, 2006). On the other hand, and although one of the image selection criteria was the dry season, it was considered that the date of acquisition of the images could have influenced the results, since the coverage and phenological state of the vegetation in the area, as well as the soil moisture, could have been different, affecting the spectral response of the soil (Chuvieco, 2010). However, the review and adjustment of the information with images from August 1986 and other inputs decreased this error factor.

The analysis of the information at the province level shows that the provinces of Cotopaxi, Chimborazo and Pichincha have suffered important changes in the degrees of erosion, which could be due to urban growth. Therefore, the concern lies in knowing to what extent the erosive process has been accelerated by man's action, considering that erosion is recognized as a problem only when and where it has been the dominant process of landscape wear, clearly decreasing production potential. of agricultural properties and influencing their ability to generate environmental goods or services (Kirby & Morgan, 1994; Custode *et al.,* 1999; MAG, 1999; De la Rosa, 2008).

On the other hand, it is important to have a comprehensive vision of the erosion problem that considers not only the triggering factor, be it an active agent (water, wind) and the use and management of the land, but also the elements that are involved in this process (texture and soil structure, slope, production of crops, food sustainability, etc.) so that those responsible for the care of this resource and heritage have clear criteria that allow the development of actions that reduce erosion to acceptable limits (Acosta Solís, 1952; Custode *et al.,* 1999; Espinosa, 2014; Espinosa & Moreno, 2018). The environment in which these processes take place is an important element to consider. The Inter-Andean Valley, being enclosed between two mountain ranges that are joined by transversal mountain ranges (knots), forms geographical valleys within it that constitute areas with landscapes of different appearances and particular climates that range from very dry to very humid. In addition, the internal slopes of the catchments, with steep slopes, are more susceptible to runoff and dragging of materials. The type of soil, as well as the intermittent vegetation cover, between crops, bare soil and fallow, reduce the erosive effect of water; however, the cover may not be the most appropriate, in many cases due to problems of land use conflicts (Almeida *et al.,* 1984; Winters *et al.,* 1998; Santos & Castro, 2012; Cárceles *et al.,* 2017).

On the other hand, in areas where the xerophytic vegetation reveals low rainfall (close to 600 mm annual average) there are high-speed winds that promote erosion, a process that is particularly evident in the province of Pichincha (San Antonio) and Chimborazo (Palmira), (Cañadas, 1983; Hidalgo, 1998; Tello *et al.,* 2019). These dry zones coincide with the mapped surfaces that have the highest percentage of severe erosion (Cañadas, 1983; Hidalgo, 1998). Some authors indicate that these active erosive processes in dry areas contribute to desertification in the country's Sierra (Almeida *et al.,* 1984; Espinosa & Moreno, 2018).

The soil structure is an important factor so that the soil can withstand erosive processes. The use of excessive doses of lime to improve the pH destroys the structure by dispersion of clays, which reduces infiltration and predisposes the soil to erosion (Kirby & Morgan, 1994; Mejía, 2009; Almorox *et al.,* 2010; Navarro & Navarro, 2013). The elimination of the vegetal cover and consequent loss of SOM facilitates the destruction of the soil structure by excessive tillage and/or use of heavy machinery in humid soil, destroys the porosity and compacts the soil, making it more susceptible to erosion (Navarro & Navarro, 2013; Porta *et al.,* 2014). While soils that have a high moisture retention capacity (complex aluminum humus-Andisols) and high SOM content, such as páramo soils, facilitate the retention of water that, when accumulated, can cause landslides (Navarro, 1994; Crissman *et al.*, 2003; Mejía, 2009).

In many areas of the Ecuadorian highlands, all the land that can be used in agriculture, even with serious limitations, has been used and only small areas with very steep slopes (> 70%) remain unused. The need to use the land for subsistence has meant that farmers have apparently forgotten the foundations of the old balance between production and consumption established by pre-colonial communities (De Noni & Trujillo, 1986; IICA-PROCIANDINO, 1995; Winters *et al.*, 1998). This region is considered one of the regions with the greatest pressure on land in the world, without a doubt, due to the impulse of the erosive processes of agricultural production (Almeida *et al.*, 1984; Brassel *et al.*, 2008). The area of the inter-Andean region destined for agricultural work was 3 140 000 ha in 2009, but in 2018 this amount increased to 5 300 000 ha, much of this increase due to the expansion of the agricultural frontier to lands fragile and marginal (Santos & Castro, 2012; Tello *et al.*, 2019). The highlands occupies 1 658 600 ha of that area for agricultural activities, Pichincha corresponding to 211 645 ha, demonstrating that this province has the largest cultivated areas in this region, a situation that correlates with the results of this study, which indicate that Pichincha is the province with the largest eroded surface (TABLE 6 and FIGURE 9). The provinces with the least arable area are Carchi, with 73 499 ha, and Tungurahua, with 75 285 ha (Santos & Castro, 2012; Tello *et al.*, 2019).

The adoption and efficient use of irrigation improves yields, reduces the risk of erosion and opens the possibility of diversifying production. However, irrigation is one of the agricultural activities that encourages the erosion process. The dominant irrigation system in the Sierra is irrigation by gravity or flooding (more than 90 % of the irrigated surface), despite its limitations in terms of greater water consumption and soil degradation, particularly due to erosion, when this type of irrigation is used in sloping areas (Winters *et al.*, 1998; Zapatta & Gasselin, 2005; Gaybor, 2018).

The solution to the problems caused by erosion in Ecuador could be aimed at specific solutions such as the rehabilitation of cangahuas to increase cultivable areas (Prat, 2015) or increase the use of agrochemicals to improve crop production. crops growing on deteriorated soils (Yang *et al.*, 2003) or seek the use of incentives to induce farmers to conserve soil and water (Winters *et al.*, 1998; Gaybor, 2018). However, there are comprehensive solutions to control erosive processes that have already been proposed by several authors who propose the creation of a Soil Conservation Program or a National Erosion Control Program (Acosta Solís, 1952, 1956; Custode *et al.*, 1999; Segarra, 2017; Espinosa & Moreno, 2018).

Whatever the path proposed for erosion control in the country, it must first determine which are the priority areas to control erosive processes and for this the results obtained in this study that presents the distribution of eroded areas can be used, degrees of intensity and areas where intervention is urgent. The results of this study are also evidence of the carelessness of the State and its representatives in making efforts to control erosion, either due to the lack of the necessary technical and financial assistance, the lack of adequate legal and institutional provisions, and the ignorance of the magnitude of the problem. Soil conservation and erosion control are not very well received in political circles because they do not produce immediate returns and are considered expensive programs of little use (Acosta Solís, 1952; Custode *et al.*, 1999; Hidalgo, 1998).

It should be considered that the soil is the basis of all terrestrial ecosystems, the physical environment in which most human activities take place and is the provider of multiple services such as water purification and regulation of the hydrological cycle, etc., which justifies its conservation. Therefore, accessing and understanding the information developed by studies such as this one is one of the fundamental prior tasks for the allocation of land uses in a territory, especially if it is considered that the soils lack a uniform behavior and that its formation depends on a very slow renewal rate, a condition that makes it a non-renewable natural resource on a human scale (Tomás *et al.*, 1998; Custode *et al.*, 1999; Porta *et al.*, 2008).

5. Conclusions

There is a mathematical difference in the eroded surfaces, with a 16% increase in eroded areas of the northern Ecuadorian Highlands for the year 2017 compared to 1986. No significant statistical differences were found when comparing the total results of the areas affected by erosion in the two periods.

There are significant differences between 1986 and 2017, only when comparing areas affected by the type of severe erosion, indicating that there is a real increase in eroded surfaces to this degree. No statistical difference was found between the two years, for the comparison of surfaces with moderate and light degrees of erosion.

A general reliability percentage of 94% was determined for the current erosion cartography, with a kappa index approximately 1, corresponding to a very good degree of agreement, which indicates the validity of the methodology proposed and adapted from CIREN-CHILE.

The image selection times are a criterion that can influence the results of the study because it depends on the state of the coverage (physiology, humidity, daylight hours, among others) to capture its spectral response.

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