# Contribution of fractional cover analysis for monitoring degraded ecosystems at the watershed level

## ABSTRACT

The purpose of the research was to use the data generated on degradation and perform spectral mixture analysis to determine the changes in photosynthetic, non-photosynthetic vegetation and soil fractions, in tactically selected sites, verifying degradation and on the other hand to use this analysis to verify the recovery of degraded ecosystem surfaces that have had recovery projects. Fractional coverages were determined through Normalized Difference Fraction Index (NDFI) by analyzing spectral mixtures using Google Earth Engine. In this sense, the degradation identified in the Ponasa watershed is related to specific degradation values indicated by the NDFI values, to prove that in effect the degradation of these ecosystems is linked to loss of photosynthetic activity, increase in bare soil values and non-photosynthetic activity derived from the process of disturbance of the vegetation cover. In the case of the present study, the NDFI finally explains the degradation processes produced by the loss of vegetation cover and the loss of net primary productivity of the ecosystem, but it is not related in the same way in the case of fragmentation.

*Keywords: fractional cover, ecosystems, degradation, satellite imagery, satellite images.*



## 1. INTRODUCTION

In Peru, specific research has been carried out in watersheds, using the methodology for the identification and categorization of degraded areas, it has been determined that certain ecosystems have lost their functionality and, consequently, their capacity to provide ecosystem services (1). However, validation or corroboration of the identified degradation has its limitations because it depends on the use of visual interpretation of images(2), which often involves uncertainty linked to interpreter bias or field evaluations that for cost/efficiency reasons are not possible to develop in order to maintain a high level of statistical relationship.

In this sense, it is proposed that the exhaustive use of multitemporal imagesapplying spectral mixture methods(3), in which the percentages of photosynthetic, non-photosynthetic, soil and water activity at sub-pixel level are determined, would be a robust support to validate the degradation identified in known areas and be the basis for monitoring degraded areas in their regressive evolution (greater degradation) or their recovery.Therefore, the purpose of the research is to use data generated on degradation and perform spectral mixture analysis to determine the changes in the fractions of photosynthetic, non-photosynthetic vegetation, soil, water in tactically selected sites, verifying the degradation and on the other hand to use this analysis to verify the recovery of degraded ecosystem surfaces that have had recovery projects.

The general problem posed by the present research was Does the spectral mixture analysis that measures the percentages of photosynthetic, non-photosynthetic and soil activity at the pixel level of satellite images, allow to verify the identified degradation and recovery at the watershed level?The specific problems were: a) What proportion of photosynthetic vegetation, non-photosynthetic vegetation and soil that are fractional covers are present in the Ponasa watershed? b) What changes occur in the percentages of photosynthetic, non-photosynthetic and soil activity compared to previous analyses showing ecosystem degradation? c) Is it feasible to use fractional coverages, resulting from spectral mixture analysis, to perform multi-temporal monitoring of ecosystem degradation and recovery?. This research has improved the understanding of ecosystem degradation by using fractional coverages to assess key factors such as photosynthetic activity and primary productivity. In addition, it seeks to optimize the monitoring of degraded areas, both in their deterioration and recovery.

The general objective of this research was to apply fractional cover analysis in the Ponasa watershed, which has been studied with respect to the degradation of forest ecosystems; to compare results to determine its contribution to the monitoring of degraded ecosystems at the forest watershed level.The specific objectives were: a) Identify photosynthetic vegetation, non-photosynthetic vegetation and soil, being these the ones considered for the fractional cover analysis in the Ponasa watershed. b) Compare the results obtained from the fractional cover analysis with those obtained in the degradation recovery research carried out in the Ponasa watershed. c) Validate the use of the fractional covers resulting from the spectral mixture analysis to carry out multi-temporal monitoring of ecosystem degradation and its recovery.

The research on landscape restoration in Ethiopia addressed three key issues: the effects of restoration measures on vegetation cover, the benefits perceived by local communities, and lessons learned about the willingness of communities to maintain restored landscapes. The study focused on the Dimitu and Kelisa watersheds in the Central Rift Valley, and the Gola Gagura watershed in Dire Dawa. Using Geographic Information Systems (GIS) and remote sensing, they identified land use changes through area closures and soil and water conservation measures. In addition, they conducted interviews with 88 rural households, revealing that restoration actions such as zoning and tree planting resulted in significant changes in land cover in 3-5 years. There was a noticeable reduction in barren land, an increase in forest land and woody grassland, and an improvement in ecosystem services. More than 90% of respondents confirmed improvements and a reduction in erosion.

The main objective of their study was to introduce and evaluate an innovative improved spatiotemporal fusion method using learning algorithms to overcome the limitations of traditional temporal fusion techniques. The application of this approach in the reconstruction of long-term Fractional Vegetation Cover (FVC) datasets in the Danjiang River basin, the results of which indicated significant improvements in NDVI reconstruction accuracy by incorporating deep learning, using the STRUM algorithm. With the FSDAF technique identified as the most effective, demonstrating an R2 value of 0.953 and an RMSE of 0.012. In addition, they found ecological dynamics in the watershed, with seasonal “north-high-south-low” patterns and a general improvement in vegetation cover in certain counties, evidencing environmental degradation in the wider watershed. Key factors such as altitude, soil composition, precipitation and temperature influenced these dynamics, having a positive impact on vegetation in the watershed where infrastructure projects are located according to conservation policies (4)

The objective of this study was to explore the relationship between vegetation restoration and ecosystem services in the Jinghe watershed, specifically focusing on the evolution of fractional vegetation cover. They analyzed the influence of restoration practices implemented through the Grain to Green Project on ecosystem services in the watershed, using tools such as the SWAT model, CASA approach and InVEST valuation. They applied statistical tests such as Mann-Kendall, Pearson's R correlation coefficient and gray relational analysis (GRA) to analyze spatio-temporal heterogeneity in vegetation cover and its response to ecosystem services. The results revealed a significant increase in forest and grassland area in the Jinghe watershed since the implementation of the Grain to Green Project. At the watershed level, they identified synergistic relationships between vegetation restoration and conservation of soil, water, net primary production, and habitat quality. At the sub-basin level, some relationships evolve towards trade-offs, on the other hand, it is highlighted that vegetation restoration has positive effects on soil conservation, water, net primary production and habitat quality in the Jinghe watershed (5)

The main objective of their study was to analyze the trends and changes in the Fractional Vegetation Cover (FVC) in the Hulun Lake region from 1986 to 2017, with the purpose of understanding the influence of climatic variations and human activities on the vegetation landscape. Data collected during that period were used, applying the Mann-Kendall trend test and regression analysis to evaluate variations in FVC and their relationship with factors such as climatic parameters and human activities. The results showed that 65.01% of the FLC experienced decreases, 24.55% of which were significant, while only 8.61% showed significant increases. The critical year 1999 presented notable changes in annual precipitation and humidity index; water emerged as a crucial factor affecting FLC in the region (6)

Their research on the strategic and pivotal position of the Yellow River in China's development and economic construction highlights that understanding the dynamics of long-term land cover change and predicting future trends in the Yellow River basin can provide an empirical basis for improving ecological protection and soil and water conservation initiatives. This study employs statistical methods such as the dimidded pixel model, linear regression, Moran's index, and coefficient of variation to conduct a spatiotemporal analysis of land cover in the Yellow River watershed. The Hurst exponent is used for a more detailed analysis of the trend of vegetation cover change in the study area. The results of Liu et al. show that from 2003 to 2020, fractional vegetation cover (FVC) in the Yellow River basin increased at an average rate of 0.19% per year. Furthermore, only 2.22% of the Yellow River basin area shows a relative increase in FVC from 2003 to 2020; most of the increased area is in the northwestern Loess Plateau. The Global Moran index values from 2003 to 2020 are all greater than 0.8, indicating that vegetation cover shows strong agglomeration. According to the local Moran index, the vegetation cover of the Yellow River basin shows a strong spatial difference. According to the coefficient of variation, 73% of the vegetation cover in the Yellow River basin has remained very stable over the past 18 years. In addition, the overall Hurst exponent for the FVC in the Yellow River basin is less than 0.5, indicating a pattern of anti-persistent vegetation change (7)

In traditional multispectral image segmentation or classification procedures, each pixel is assigned the value of an informational or qualitative class that strictly corresponds to the thematic units to be mapped(3,(8). The spectral response is the sum of the spectral responses of the pure elements represented in it, each one weighted according to the proportion of surface it occupies(9)

## 2. MATERIAL AND METHODS

The spatial and temporal scope of the study was the selected basin of the Amazonian area of the Peruvian territory with information on degradation, analyzed for the period from 1985 to 2021 (36 years). The universe is all the Amazon basins of Peru. The sample size is made up of the ecosystem of the Ponasa basin (San Martin) in the Amazon area. The sample size is the type watershed of all the watersheds in the Amazonian zone. For the validation of the results, the sample size was calculated using Cochran's formula (1977).

$$n = \frac{Z^2 * N * p * q}{e^2 * (N-1) + (Z^2 * p * q)}$$

Z = Confidence level (corresponding to the Table of Z values)

p = Percentage of the population that has the desired attribute

q = percentage of the population that does not have the desired attribute = 1 - p Note: When there is no indication of the population that does or does not have the attribute, 50% for p and 50% for q are assumed.

N = Size of the universe

e = Maximum accepted estimation error
n = Sample size

The minimum unit of analysis corresponds to areas of 0.09 ha, which corresponds to the 30 x 30 m pixels of the multispectral images of the LANDSAT satellite for the entire watershed area.Spatial data will be obtained from the NASA2 web server, which has the free download of the LANDSAT satellite image scene catalog from mission 5, 7, 8 and 9. Identified degradation data will be compiled from previous studies conducted in the Ponasa watershed.

The procedure consisted in the preparation and conditioning of degradation information in watersheds, in addition to the determination of the fractional coverages. Fractional cover information was generated by means of spectral mixture analysis, a procedure that was carried out with the help of Carnegie Landsat System Analysis - Lite (Class Lite) or Google Earth Engine software. The parameters of change of the fractional coverage or application of the NDFI were determined. A comparison of the identified degraded areas with the results of the fractional coverages was made. The comparison made by spatial superimposition of both layers of information and the help of randomly distributed sampling points, using QGis or ArcGIS software. Comparison was made with the analysis of degraded areas in recovery.

## 3. RESULTS AND DISCUSSION

### 3.1. Calculation and determination of sampling points:

The determination of sampling points is an important component of the research process and seeks to evaluate the accuracy with which the data have been obtained to explain the degree of coincidence and uncertainty of the analysis(10). In this sense, from the determination of sampling sites, the information on the maps should be compared with information obtained in the field whose sources can be directly observed or with reference information (secondary information). The use of satellite images with higher spatial resolution (up to a resolution of less than 1 m per pixel) is a component that contributes to the process and is taken into account.

This process involves three basic components:

1) The sampling design used to select the reference sample.

2) The response design used to obtain the reference information (degraded areas or non-degraded areas) for each sampling unit.

3) The estimation and analysis procedures.

The formula proposed by Cochran (1977) (11)was used to determine the number of sampling points:

$$n = \frac{Z^2 * N * p * q}{e^2 * (N - 1) + (Z^2 * p * q)}$$

Where:

Z =Confidence level (corresponding to the Table of Z values.

**Table 1.**

*Confidence level*

| Valores de confianza Tabla Z | |
|---|---|
| **95%** | **1,96** |
| 90% | 1,65 |
| 91% | 1,7 |
| 92% | 1,76 |
| 93% | 1,81 |
| 94% | 1,89 |

**Table 2.**

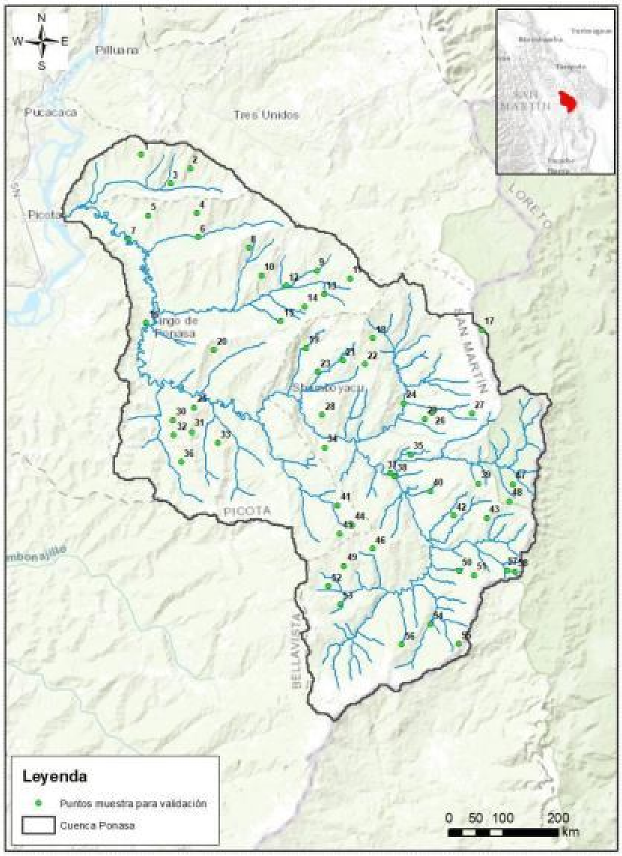
*Data to determine the sample size*

| | |
|---|---|
| **Z** | **1,65** |
| P | 70 % |
| q | 30 % |
| N | 847 926 |
| e | 10 % |

After applying Cochran's formula, n = 57.17 (58 sampling points) was obtained.

**Figure 1**

*Distribution of sampling points*



Source: ANA, Hydrographic Units of Peru.

The number and location of sampling points for GV, NPV, SOIL, is shown in Annex 1.

**3.2. Spectral mixture analysis: fractional coverages GV, SOIL, NPV - Ponasa river basin.**

Using the indicators determined to identify the areas of fractional coverage in the Ponasa river basin, the results of the spectral mixture processing or analysis are presented.

The fractional coverage of green vegetation (GV) shows the greater or lesser photosynthetic activity present in the ecosystems of the Ponasa river basin and for visualization purposes, 04 grouping ranges have been established whose amplitude has been defined according to the natural break points of the ArcGIS program. According to Figure N° 2 and Table N° 3 it can be observed that the highest photosynthetic activity is present in 21.8 % of the basin surface, represented in the map with blue color [VF value 4 - range = 56-99]. High GV values are indicative of climax vegetation cover or mature forests, this level is present in the largest area in the middle watershed zone, followed by the upper watershed and corresponds to 16745.4 ha. It is also important to consider the green range [VF value 3 - range = 44-56] as the second most important in terms of photosynthetic activity and represents 39.2% of the basin's surface, being present in its upper and middle part, corresponding to 29990.5 ha, in this case it belongs to ecosystems with secondary and purple vegetation cover.

Rank 2 [VF2 value - rank = 27- 44], in yellow, should be analyzed, which does not have high photosynthetic activity values but is representative because it is part of 28% of the surface of the basin with 21476 ha. Rank 1 is not described because it is not very representative.

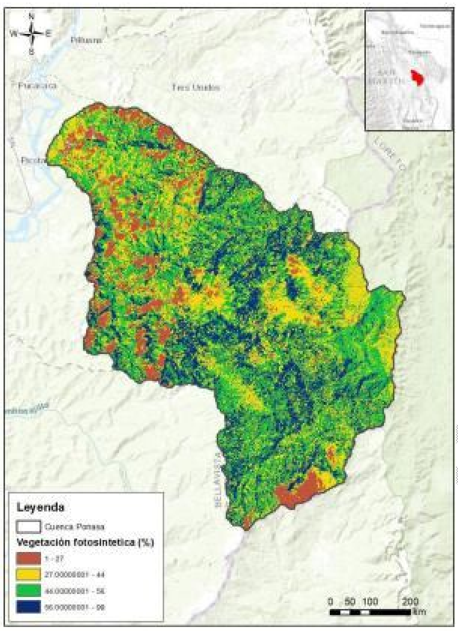
**Table 3**

*Range of photosynthetic vegetation fractional cover - Ponasa Watershed*

| Value GV | Rango % | ha | % cuenca |
|---|---|---|---|
| 1 | 1-27 | 8521.92 | 11.14 |
| 2 | 27-44 | 21476.43 | 28.06 |
| 3 | 44-56 | 29990.52 | 39.19 |
| 4 | 56-99 | 16745.4 | 21.88 |

**Figure 2**

*Fractional photosynthetic vegetation cover - Ponasa Basin*




Fuente: Collectionimages LANDSAT de Google Earth Engine

The Fractional Soil Cover (FSC) is the fraction of the spectral mixture corresponding to bare soil and is represented by the color ranges shown in Table N°4 and Figure N°3.

Comparatively, the soil fraction is lower than the green vegetation fractions and this may correspond to the condition of the ecosystems in the basin, with a significant presence of primary and secondary vegetation, crop fields and pastures, which always present intermediate and high values of photosynthetic activity and medium to low soil values. The first color corresponds to the highest CFS level, which in the map is dark brown [CFS Value 4 - range = 34-100], which is not representative, occupying only a fraction in the lower watershed and corresponds to 1.62 ha. The next level of brown color [CFS Value 3 - range = 11-34], second in importance in CFS, is present in the lower watershed, with 818.73 ha and corresponds to 1.07 % of the watershed. The third in importance in CFS, is expressed in light brown [ CFS value 2 - range = 5-11] and is present in the middle and lower basin, with 2655.54 ha and corresponds to 3.47% of the basin. Finally, we describe the lowest CFS value [ CFS Value 4 - range = 1-5] in orange and present in a dispersed form throughout the basin, with 6373.44 ha and representing 8.33% of the total space of the basin.

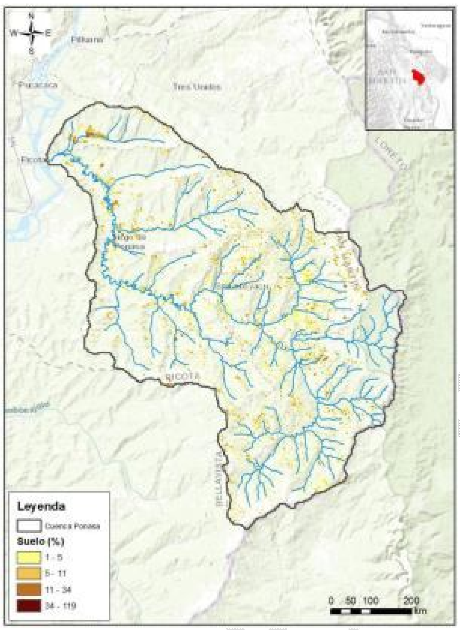
**Table 4**

*Fractional Land Cover Range Ponasa Basin*

| Value CFS | Rango % | ha | %cuenca |
|---|---|---|---|
| 1 | 1-5 | 6373.44 | 8.33 |
| 2 | 5-11 | 2655.54 | 3.47 |
| 3 | 11-34 | 818.73 | 1.07 |
| 4 | 34-100 | 1.62 | 0.00 |

**Figura 3**

*Cobertura fraccional de suelo – Cuenca del Ponasa*




*Source: ANA, Hydrographic Units of Peru.*

The fractional coverage of non-photosynthetic vegetation (NPV) corresponds to the fraction of the spectral mixture of dead or senescent biomass that is the result of disturbances due to vegetation clearing, removal of cover by migratory agriculture, among others, which generate vegetation without photosynthetic activity and generate greenhouse gas emissions due to biomass decomposition. In order to objectively know the distribution of the NPV, they have been grouped into 04 ranges whose amplitude has been defined according to the natural break points. According to Figure N° 4 and Table N° 5, it can be observed that the highest non-photosynthetic activity is present in 1% of the basin surface, represented in the map with the red color [NPV value 4 - range = 20-57].

High NPV values are indicative of a non-photosynthetic vegetation cover that does not provide ecosystem function, a level that occurs in small fractions in the middle and lower watershed in the extreme west and corresponds to 418.5 ha. The second range represented by the pink color [NPV value 3 - range = 9-20] is found in the high-level environment and is also not highly representative, corresponding to 6.12% of the basin area, with 4687.02 ha. NPV values 1 and 2 [ NPV value 1 - range = 1-4] [ NPV value 2 - range = 4-9] respectively are the ones that present low non-photosynthetic activity and are covering 92 % of the basin area represented in 70738.7 ha. In sum, the NPV is not representative in this watershed.

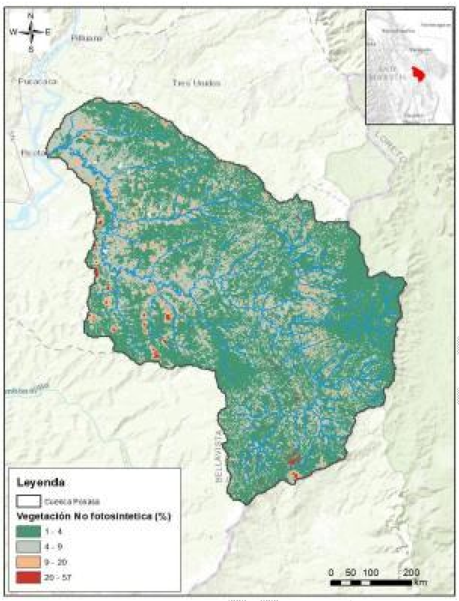
**Table 5**

*Rango de cobertura fraccional de vegetación no fotosintética (NPV) - Cuenca del Ponasa*

| Value NPV | Rango % | HA | % cuenca |
|---|---|---|---|
| 1 | 1-4 | 49650.75 | 64.88 |
| 2 | 4-9 | 21087.99 | 27.56 |
| 3 | 9-20 | 4687.02 | 6.12 |
| 4 | 20-57 | 418.5 | 0.55 |

**Figure 4**

*Fractional cover of non-photosynthetic vegetation (NPV)-Ponasa Basin*




Source: ANA, Hydrographic Units of Peru.

### 3.3. Normalized Fractional difference index - NDFI and comparison with identified degraded areas

As previously mentioned, the spectral mixture analysis (SMA) model decomposes the reflectance values of pixels in remotely sensed data into fractions of purer materials, known as endmembers. Since the spectral mixture analysis for the study area provides various percentage compositions of fractions of photosynthetic vegetation, non-photosynthetic vegetation, soil and shade, the Normalized Fractional Difference Index (NDFI) calculation has been applied.

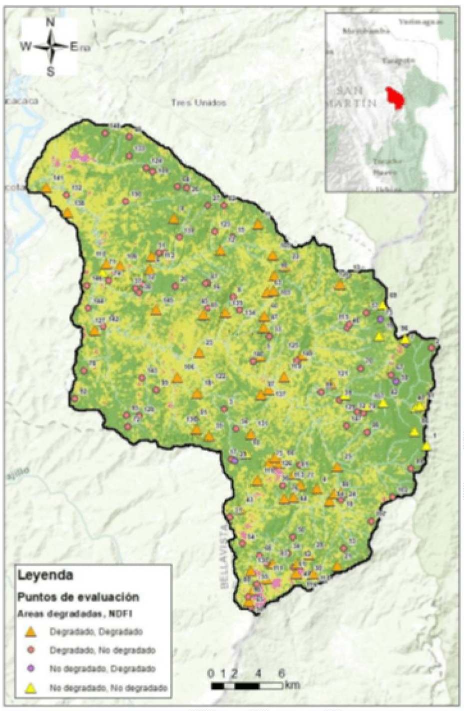
The NDFI was calculated as a tool that provides or detects changes in the forest-vegetation canopy and synthesizes in a single band, spectral information that has been identified as relevant for the identification of forest degradation based on the calculation of the fractional images obtained by the spectral mixture model. The NDFI values range from -1 to 1 and rescale to a range of 0 to 200.
Accordingly, it follows that:

– NDFI values between 0-100, correspond to ecosystems that have been completely deforested.
– NDFI values between 100-189 are associated with damage to the forest canopy.
NDFI values between 190-200 are associated with intact forest cover.

Likewise, for comparison purposes and to observe the relationship between the NDFI values and the degraded areas identified in the Ponasa watershed, the sample point schedule was designed to increase the number of evaluation points, as shown in Figure 5

**Figure 5**

*Sampling points for comparison of identified degraded areas and obtained NDFI values*



Source: ANA, Hydrographic Units of Peru.

150 points have been identified for which the NDFI value has been calculated and compared with the degradation attribute. The detailed result of the points and their corresponding degradation attribute and NDFI are presented in Annex 2.In addition, Table 6 presents the summary of the coincidence or non-coincidence according to the degradation categories found with respect to the NDFI value of the Ponasa watershed.

**Table 6**

*Degradation classes and coincidence with respect to the NDFI value - PONASA Basin*

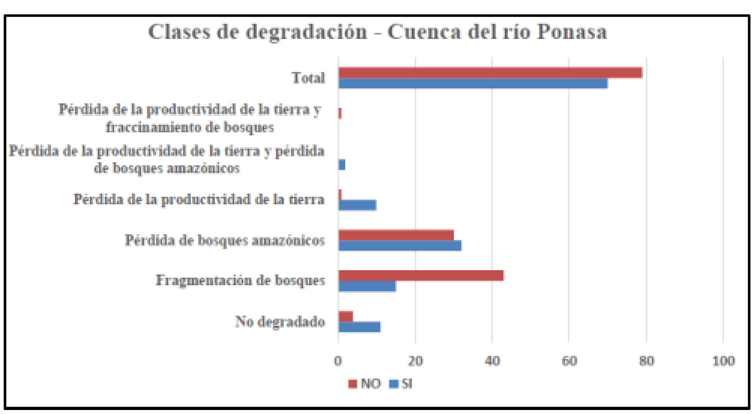
| Degradation classes | YES | NO |
|---|---|---|
| Not degraded | 11 | 4 |
| Forest fragmentation | 15 | 43 |
| Loss of amazonian forests | 32 | 30 |
| Loss of land productivity | 10 | 1 |
| Loss of land productivity and loss of Amazonian forests | 3 | 0 |
| Loss of land productivity and forest fractionation | 0 | 1 |
| Total | 71 | 79 |

The Ponasa river basin is a hydrographic system with strong pressure on the ecosystems of hill and montane forests. according to **(12)** the forest cover in 2000 was 46679.9 ha and went to 35298.8 ha in 2018, suffering a loss of 11381.1 ha, which has meant an increase in the danger of mass removal processes (landslides and landslides) and an increase in the danger of floods.In this sense, the degradation identified in the basin is related to specific degradation values indicated by the NDFI values, to prove that in effect the degradation of these ecosystems is linked to loss of photosynthetic activity, increase in bare soil values and non-photosynthetic activity derived from the process of disturbance of the vegetation cover**(13)**

According to the results in table 6, the frequency with which the range of NDFI values explains the degradation of these ecosystems by loss of vegetation cover, loss in land productivity and combination of both is high, meaning that most of the positive matches are found in values between 0-100 and 100-189, which implies completely deforested ecosystems or disturbances in the forest canopy**(14)**. figure 6 shows the relationship between the two variables.

**Figure 6**

*Number of coincidences between the NDFI and the degradation classes identified in the Ponasa watershed.*



According to the results in Table 6, the frequency with which the range of NDFI values explains the degradation of these ecosystems by loss of vegetation cover, loss in land productivity and combination of both is high, meaning that most of the positive matches are found in values between 0-100 and 100-189, which implies completely deforested ecosystems or disturbances in the forest canopy. Figure 6 shows the relationship between the two variables.

However, the same is not true for degradation classified by tree cover fragmentation**(15)**, in which case the NDFI does not explain this degradation. it should be noted that fragmentation is determined by an analysis of spatial patterns in an area of influence or edge effect of the non-forest zone up to a distance of approximately 210 meters. according to this analysis, open spaces can be identified in the forest canopy, so the values of the percentages in the fractional covers of soil and non-photosynthetic vegetation should be substantially high.

## 4. CONCLUSION

1. The NDFI explains in the case of the present study, the degradation processes produced by the loss of vegetation cover and the loss of net primary productivity of the ecosystem, but it does not relate in the same way in the case of fragmentation.

2. Photosynthetic vegetation, non-photosynthetic vegetation and soil vegetation have been considered and evaluated for the analysis of fractional cover in the Ponasa watershed.

3. The results of the fractional cover analysis have been compared with the degradation recovery research carried out in the Ponasa watershed.

4. The use of fractional cover was validated in part of the ecosystems present in the Ponasa watershed.



## REFERENCES

1. Magán J, Vogl A, Guevara M, Torres M, Fernández L, Pillaca M, et al. Methodology for identifying priority areas for interventions of the remuneration mechanism for water ecosystem services in Amazonian cities, Peru. Ecolapl [Internet]. 2023 Dec 29 [cited 2024 Aug 6];22(2):141–54. Available from: https://revistas.lamolina.edu.pe/index.php/eau/article/view/2090

2. Herández-Moreno MM, Téllez Valdés O, Martínez Meyer E, Islas-Saldaña LA, Salazar-Rojas VM, Macías-Cuéllar H. Distribution of vegetation cover and land use in the municipality of Zapotitlán, Puebla, Mexico. RevMexBiodiv [Internet]. 2021 Aug 18 [cited 2024 Aug 7];92(0):923649. Available from: http://revista.ib.unam.mx/index.php/bio/article/view/3649

3. Valero-Medina JA, Dallos-Bustos CD, Lizarazo I. A new approach for multispectral image classification based on Cartesian complexes. DYNA [Internet]. 2018 Jan 1 [cited 2024 Aug

8];85(204):28–37. Available from: https://revistas.unal.edu.co/index.php/dyna/article/view/66161

4. Wang S, Cui D, Wang L, Peng J. Applying deep-learning enhanced fusion methods for improved NDVI reconstruction and long-term vegetation cover study: A case of the Danjiang River Basin. Ecological Indicators [Internet]. 2023 Nov 1 [cited 2024 Jul 17];155:111088. Available from: https://www.sciencedirect.com/science/article/pii/S1470160X2301230X

5. Tang T, Zhao M, Wang D, Chen X, Chen W, Xie C, et al. Does Environmental Interpretation Impact Public Ecological Flow Experience and Responsible Behavior? A Case Study of Potatso National Park, China. International Journal of Environmental Research and Public Health [Internet]. 2022 Jan [cited 2023 Oct 12];19(15):9630. Available from: https://www.mdpi.com/1660-4601/19/15/9630

6. Mao P, Zhang J, Li M, Liu Y, Wang X, Yan R, et al. Spatial and temporal variations in fractional vegetation cover and its driving factors in the Hulun Lake region. Ecological Indicators [Internet]. 2022 Feb 1 [cited 2024 Jul 17];135:108490. Available from: https://www.sciencedirect.com/science/article/pii/S1470160X21011559

7. Liu C, Zhang X, Wang T, Chen G, Zhu K, Wang Q, et al. Detection of vegetation coverage changes in the Yellow River Basin from 2003 to 2020. Ecological Indicators [Internet]. 2022 May [cited 2024 Jul 22];138:108818. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1470160X22002898

8. Poveda-Sotelo Y, Bermúdez-Cella MA, Gil-Leguizamón P. Evaluation of supervised classification methods for the estimation of spatio-temporal changes in coverage in the Merchán and Telecom moors, Eastern Cordillera of Colombia. Bol Geol [Internet]. 2022 Jul 7 [cited 2024 Aug 8];44(2):51–72. Available from: https://revistas.uis.edu.co/index.php/revistaboletindegeologia/article/view/12745

9. Denis Ávila D, Curbelo EA, Madrigal-Roca LJ, Pérez-Lanyau RD. Spatio-temporal variation of the spectral response in mangroves of Havana, Cuba, through remote sensors. RBT [Internet]. 2020 Feb 3 [cited 2024 Aug 8];68(1). Available from: https://revistas.ucr.ac.cr/index.php/rbt/article/view/39134

10. Manterola C, Grande L, Otzen T, García N, Salazar P, Quiroz G. Reliability, precision or reproducibility of measurements. Assessment methods, usefulness and applications in clinical practice. Rev chilinfectol [Internet]. 2018 [cited 2024 Aug 9];35(6):680–8. Available from: http://www.scielo.cl/scielo.php?script=sci_arttext&pid=S0716-10182018000600680&lng=en&nrm=iso&tlng=en

11. David Odhiambo O, Ouma Onyango C. Estimation of Total Population in the Presence of Missing Values Using a Modified Murthy's Estimator and the Weight Adjustment Technique. AJAMS [Internet]. 2014 May 19 [cited 2024 Aug 9];2(3):163–7. Available from: http://pubs.sciepub.com/ajams/2/3/12/index.html

12. Mosquera-Vásquez M, Tobón-Marin C. Effects of the restoration of tropical montane forests on the ecohydrological functioning of hydrographic basins. Forest (Valdivia) [Internet]. 2023 [cited 2024 Aug 7];44(3):639–53. Available from: http://www.scielo.cl/scielo.php?script=sci_arttext&pid=S0717-92002023000300639&lng=en&nrm=iso&tlng=en

13. Pérez-Vega A, Regil García HH, Mas Caussel JF. Environmental degradation due to land use and cover change processes from a spatial perspective in the state of Guanajuato, Mexico. Geographic Research [Internet]. 2020 Aug 14 [cited 2024 Aug 7];(103). Available from: http://www.investigacionesgegraficas.unam.mx/index.php/rig/article/view/60150

14. Villa PM, Martins SV, De Oliveira Neto SN, Rodrigues AC. Anthropogenic and biophysical predictors of deforestation in the Amazon: towards the integration of REDD+ activities. Forest (Valdivia) [Internet]. 2017 [cited 2024 Aug 9];38(3):433–46. Available from: http://www.scielo.cl/scielo.php?script=sci_arttext&pid=S0717-92002017000300001&lng=en&nrm=iso&tlng=en

15. Otavo S, Echeverría C. Progressive fragmentation and loss of natural forest habitat in one of the global hotspotsof biodiversity. Mexican Biodiversity Magazine [Internet]. 2017 Dec [cited 2024 Aug 9];88(4):924–35. Available from: http://revista.ib.unam.mx/index.php/bio/article/view/2047



## APPENDIX

### TABLE 1

*Number and location of the sampling points for GV, NPV y SOIL*

| Point | GV | NPV | SOIL | EAST | NORTH |
|---|---|---|---|---|---|
| 1 | 34 | 2 | 0 | 359,985.00 | 9,243,885.00 |

| | | | | | |
|---|---|---|---|---|---|
| 2 | 7 | 3 | 0 | 363,495.00 | 9,242,895.00 |
| 3 | 41 | 3 | 0 | 362,085.00 | 9,241,815.00 |
| 4 | 49 | 3 | 0 | 363,975.00 | 9,239,685.00 |
| 5 | 30 | 3 | 0 | 360,495.00 | 9,239,505.00 |
| 6 | 52 | 3 | 0 | 364,065.00 | 9,237,975.00 |
| 7 | 34 | 3 | 0 | 359,085.00 | 9,237,825.00 |
| 8 | 21 | 3 | 5 | 367,695.00 | 9,237,195.00 |
| 9 | 59 | 5 | 0 | 372,555.00 | 9,235,575.00 |
| 10 | 41 | 3 | 0 | 368,625.00 | 9,235,215.00 |
| 11 | 55 | 2 | 0 | 374,925.00 | 9,235,005.00 |
| 12 | 41 | 8 | 0 | 370,395.00 | 9,234,465.00 |
| 13 | 43 | 2 | 0 | 373,065.00 | 9,233,865.00 |
| 14 | 62 | 5 | 0 | 371,685.00 | 9,232,995.00 |
| 15 | 66 | 2 | 0 | 370,005.00 | 9,231,945.00 |
| 16 | 44 | 4 | 0 | 360,345.00 | 9,231,855.00 |
| 17 | 42 | 4 | 0 | 384,405.00 | 9,231,315.00 |
| 18 | 80 | 4 | 0 | 376,575.00 | 9,230,745.00 |
| 19 | 61 | 2 | 0 | 371,805.00 | 9,229,995.00 |
| 20 | 22 | 12 | 0 | 365,205.00 | 9,229,875.00 |
| 21 | 51 | 7 | 0 | 374,445.00 | 9,229,125.00 |
| 22 | 56 | 1 | 0 | 376,005.00 | 9,228,855.00 |
| 23 | 59 | 5 | 0 | 372,615.00 | 9,228,315.00 |
| 24 | 32 | 7 | 2 | 378,765.00 | 9,226,065.00 |
| 25 | 51 | 4 | 0 | 363,795.00 | 9,225,765.00 |
| 26 | 28 | 7 | 5 | 380,835.00 | 9,225,405.00 |
| 27 | 52 | 1 | 0 | 383,685.00 | 9,225,315.00 |
| 28 | 59 | 4 | 0 | 372,945.00 | 9,225,225.00 |
| 29 | 22 | 18 | 20 | 380,295.00 | 9,224,955.00 |
| 30 | 27 | 3 | 0 | 362,265.00 | 9,224,835.00 |
| 31 | 79 | 1 | 0 | 363,615.00 | 9,224,025.00 |
| 32 | 38 | 3 | 0 | 362,325.00 | 9,223,815.00 |
| 33 | 42 | 2 | 0 | 365,475.00 | 9,223,245.00 |
| 34 | 61 | 2 | 0 | 373,125.00 | 9,222,915.00 |
| 35 | 31 | 6 | 2 | 379,275.00 | 9,222,405.00 |
| 36 | 56 | 4 | 0 | 362,865.00 | 9,221,895.00 |
| 37 | 65 | 2 | 0 | 377,805.00 | 9,221,085.00 |
| 38 | 44 | 4 | 0 | 378,135.00 | 9,220,845.00 |
| 39 | 50 | 2 | 0 | 384,135.00 | 9,220,335.00 |
| 40 | 22 | 9 | 7 | 380,685.00 | 9,219,795.00 |
| 41 | 56 | 5 | 2 | 374,055.00 | 9,218,775.00 |
| 42 | 55 | 3 | 0 | 382,365.00 | 9,218,055.00 |
| 43 | 49 | 1 | 0 | 384,735.00 | 9,217,875.00 |
| 44 | 63 | 1 | 0 | 375,075.00 | 9,217,365.00 |
| 45 | 29 | 2 | 0 | 374,205.00 | 9,216,765.00 |
| 46 | 56 | 4 | 0 | 376,545.00 | 9,215,655.00 |
| 47 | 46 | 2 | 0 | 386,625.00 | 9,220,305.00 |
| 48 | 39 | 3 | 0 | 386,355.00 | 9,219,075.00 |
| 49 | 50 | 5 | 0 | 374,505.00 | 9,214,425.00 |
| 50 | 47 | 4 | 0 | 382,785.00 | 9,214,065.00 |
| 51 | 50 | 2 | 0 | 383,835.00 | 9,213,765.00 |
| 52 | 54 | 5 | 4 | 373,395.00 | 9,212,985.00 |
| 53 | 55 | 5 | 2 | 374,235.00 | 9,211,695.00 |
| 54 | 36 | 10 | 5 | 380,715.00 | 9,210,255.00 |

| | | | | | |
|---|---|---|---|---|---|
| 55 | 66 | 3 | 0 | 382,725.00 | 9,208,845.00 |
| 56 | 42 | 1 | 0 | 378,645.00 | 9,208,785.00 |
| 57 | 44 | 2 | 0 | 386,235.00 | 9,214,125.00 |
| 58 | 54 | 1 | 0 | 386,775.00 | 9,214,035.00 |

TABLE 2

*Calculation of the NDFI value and comparison with the degradation attribute in the Ponasa watershed*

| **Punto Mapa** | **Degradado Estudio** | **P_PPN** | **P_Bosque** | **Fragm** | **CLASE Degradado Estudio** | **Valor NDFI** | **NDFI Clase** | **Coincidencia** |
|---|---|---|---|---|---|---|---|---|
| **1** | No degradado | 0 | 0 | 0 | No degradado | 194 | No degradado | Si |
| **2** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 193 | No degradado | No |
| **3** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 191 | No degradado | No |
| **4** | Degradado | 0 | 1 | 0 | Perdida de bosque amazónico | 186 | Degradado | Si |
| **5** | Degradado | 1 | 0 | 0 | Pérdida de la productividad de la tierra | 125 | Degradado | Si |
| **6** | Degradado | 1 | 0 | 0 | Pérdida de la productividad de la tierra | 177 | Degradado | Si |
| **7** | No degradado | 0 | 0 | 0 | No degradado | 149 | Degradado | No |
| **8** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 191 | No degradado | No |
| **9** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 189 | Degradado | Si |
| **10** | No degradado | 0 | 0 | 0 | No degradado | 193 | No degradado | Si |
| **11** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 188 | Degradado | Si |
| **12** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 189 | Degradado | Si |
| **13** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 197 | No degradado | No |
| **14** | Degradado | 0 | 1 | 0 | Perdida de bosque amazónico | 189 | Degradado | Si |
| **15** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 193 | No degradado | No |
| **16** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 191 | No degradado | No |
| **17** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 191 | No degradado | No |
| **18** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 193 | No degradado | No |
| **19** | No degradado | 0 | 0 | 0 | No degradado | 193 | No degradado | Si |
| **20** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 191 | No degradado | No |
| **21** | Degradado | 0 | 1 | 0 | Perdida de bosque amazónico | 179 | Degradado | Si |
| **22** | Degradado | 0 | 1 | 0 | Perdida de bosque | 151 | Degradado | Si |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | amazónico | | | |
| **23** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 189 | Degradado | Si |
| **24** | Degradado | 0 | 1 | 0 | Perdida de bosque amazónico | 156 | Degradado | Si |
| **25** | Degradado | 1 | 0 | 0 | Pérdida de la productividad de la tierra | 187 | Degradado | Si |
| **26** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 193 | No degradado | No |
| **27** | Degradado | 0 | 0 | 1 | Fragmentación de bosque | 191 | No degradado | No |
| **28** | Degradado | 0 | 1 | 0 | Perdida de bosque amazónico | 137 | Degradado | Si |
| **29** | No degradado | 0 | 0 | 0 | No degradado | 184 | Degradado | No |
| **30** | Degradado | 0 | 1 | 0 | Perdida de bosque amazónico | 193 | No degradado | No |