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Contribution of Fractional Cover Analysis for Monitoring Degraded Ecosystems at the Watershed Level

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Authors' contributions

This work was carried out in collaboration among all authors. Authors LW and TP designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Author VM managed the analyses of the study. Authors AR, SE and JM managed the literature searches. All authors read and approved the final manuscript.

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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

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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. Ongoing monitoring of the NDFI is key to understanding ecosystem degradation and recovery and to making informed decisions.

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 images applying 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]. This study of severely degraded alpine meadows, known as heitutan, in the Yongqu River watershed sought to characterize their distribution patterns and understand the influence of topographic and geospatial factors on their occurrence. Using tools such as ArcGIS and remote sensing data, topographic analyses were conducted to derive variables and delineate watershed units. The results revealed that 51.39% of the Yongqu watershed is covered by alpine meadows, with heitutan grasslands being the most common feature in the first-tier tributary unit. Redundancy analysis and structural equation modeling indicated that slope exerts the greatest influence on the formation and distribution of degraded grasslands, followed by slope aspect and distance to roads. On the other hand, distance to river channels, settlements and annual temperature showed negligible influence. These findings provide a comprehensive understanding of the factors contributing to the degradation of alpine meadows in the Yongqu River basin, offering valuable information for the management and conservation of these ecosystems [10].

This research on landscape restoration in Ethiopia addressed three key issues: exploring the effects of restoration measures on vegetation cover, identifying benefits perceived by local communities, and synthesizing lessons learned on the willingness of communities to maintain restored landscapes. The focus was on the Dimitu and Kelisa watersheds, representative of the Central Rift Valley, and the Gola Gagura watershed around Dire Dawa. Using Geographic Information Systems (GIS) and remote sensing, temporal changes in land use were detected through area closures and soil and water conservation measures. Interviews with eighty-eight rural households complemented the assessment. The results showed that restoration actions, such as area closure and tree planting, generated significant changes in land cover in 3-5 years. There was a considerable reduction in barren land, increase in forest land and woody grassland, and an overall improvement in ecosystem services. More than 90% of respondents confirmed improvements and reductions in erosion. In conclusion, the study highlights the positive impact of restoration actions in Ethiopia, with a high willingness of communities to contribute. Challenges such as livestock encroachment and funding shortages were identified, suggesting the need for integrated interventions, local partnerships, equitable benefit sharing, and innovative approaches to address trade-offs and conflicts of interest [11].

The study aimed to evaluate riparian reforestation as a climate adaptation strategy in the Meramec river basin. A soil and water assessment model was used to simulate flow and sediment transport in the watershed, identifying critical source areas (CSA) at the sub-basin level. The effectiveness of riparian reforestation was evaluated by simulating the application of a riparian buffer Best Management Practice (BMP) in each CSA. Although the BMP reduced sediment production by 12.1% for the contemporary period, projections indicate significant increases in sediment production for future climate scenarios. A 277.5% and 221.8% increase in sediment production is anticipated for mid-century with and without the BMP, respectively, and an average increase of 690.7% and 528.3% by the end of the century. The results suggest that, despite the potential reduction in sediment production with the BMP, it may be insufficient to offset impacts from significant climate changes. It highlights the need for additional strategies to address the impacts of watershed degradation in the context of climate change [12].

This study set out to assess and quantify patterns in ecosystem condition in the semiarid Great Basin region. The long-term 90th percentile of Landsat NDVI and biophysical variables were used to generate a System State (SP) map. Ecosystem condition assessment was performed by comparing the actual fractional cover with the SP. It was observed that degraded conditions are more frequent than those above SP expectations, and it was identified that shrub cover deviation is more positive at higher altitudes, while herbaceous cover deviation follows an opposite pattern. In addition, regions with notable annual herbaceous invasions were found to have lower than expected bare ground and shrub cover. The study highlights the importance of SP as a reference for assessing ecosystem condition, revealing patterns that indicate the influence of altitude on vegetation resistance and resilience. In addition, the inverse relationship between annual herbaceous invasion and bare ground and shrub cover provides valuable information for understanding the dynamics of vegetation cover change in response to disturbance agents in the semiarid Great Basin region [13].

In its research on fractional vegetation cover (FCV) is an important indicator of the state of the Earth's land surface. The dynamics of bare soil (BS), non-photosynthetic vegetation (NPV) and photosynthetic vegetation (PV) fractions show patterns of growth, senescence, dormancy and regeneration. The dynamics also reveal trends in land cover and land use management around the world. Satellite data analysis has indicated increasing greenness of the land surface; however, the dynamics of NPV and BS fractions are equally important indicators of many elements of ecosystem function and sustainability. In this study, they conducted a comprehensive assessment of trends in NPV for the global land surface based on trend analysis over the period 2001-2018 using the Global Vegetation Fractional Cover Product. Trends were analyzed using Mann-Kendell regressions over 18 years for each month of the year, generating monthly maps of significant trend areas to provide seasonal assessments. They also compiled areas and percentage areas of positive and negative trends for UN subregions, countries and ecoregions. They produced significant negative trends in BS over 20 million km2 of the Earth's surface, although the areas of negative trends in BS were greatest in China and India, the top 24 countries by area were widely distributed around the world. However, BS increased significantly by more than 11 million km2 [14].

An analysis of the dynamics of land use and vegetation change in the municipality of San Pablo Cuatro Venados, Zaachila, Oaxaca, Mexico, was carried out with the purpose of developing a good management of its ecosystems; for which Landsat 5 TM satellite images were used for 1987 and 2008, and Landsat 8 OLI for 2020; with a spatial resolution of 30 meters. The results showed that from 1987 to 2020 the area under study has gained more surface area, presenting a positive rate of 11.4%, which shows an increase of 221.6 ha and the arboreal vegetation increased its surface area by 698.2 ha, with respect to the 1987 surface area; it is also indicated that the shrub vegetation lost 654 ha, replaced by pasture cover, human settlements, agriculture and arboreal vegetation. In sum, the rate of change of tree cover in the study area showed a rational use of forest resources, with the greatest deforestation occurring in the areas near the population centers [15].

The study on the spatio-temporal evolutionary characteristics of vegetation and the effect of precipitation changes is essential for understanding the regional ecological environment. Trend analysis, partial correlation, significance testing and residual trend analysis were used to investigate the evolution of fractional vegetation cover (FVC) in the Jinghe River Basin (JRB) between 1998 and 2019. The results showed a significant improvement in vegetation cover in the JRB during this period, with an increase in 90.64% of the areas and an extremely significant annual change in FVC ($p \leq 0.01$). However, precipitation showed a trend of insignificant increase, with a more uniform annual distribution and a shift in the center of gravity of precipitation. Although changes in precipitation favored vegetation recovery, their impact was limited, with non-precipitation factors dominating changes in FVC. This study provides a more complete understanding of the effects of changes in precipitation patterns on vegetation cover, contributing to regional ecological protection [16].

The study addresses the increasing degradation of grasslands under the influence of climate change and human activities, highlighting the importance of detecting changes in vegetation cover to better understand human-ecosystem interactions. Using Google Earth Engine (GEE) and 36 years of Landsat satellite imagery (1985-2020) in the Xilin River basin, China, grassland conditions were classified, validating the results with field observation data, obtaining an accuracy of 83.3%. The Dynamic Reference Cropped Cover Method (DRCM) was applied to eliminate inter-annual rainfall variability and focus on the impact of human activities. The results revealed five categories of vegetation cover change: significant increase (9.3%), potential increase (14.2%), stability (48.6%), potential decrease (9.8%), and significant decrease (18.1%). Desert grasslands were the most affected, with a combined potential and significant decrease of 35.2%. This study provides a basis for identifying grassland degradation and developing scientific management policies [17,18].

2. MATERIALS 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) [19].

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

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 [18]. 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) [19] 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.

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 Fig. 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 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

Note: Prepared by the authors.

Table 2. Data to determine the sample size

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

Note: Prepared by the authors.
After applying Cochran's formula, n = 57.17 (58 sampling points) was obtained.

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 Fig. 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.

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 Fig. 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.

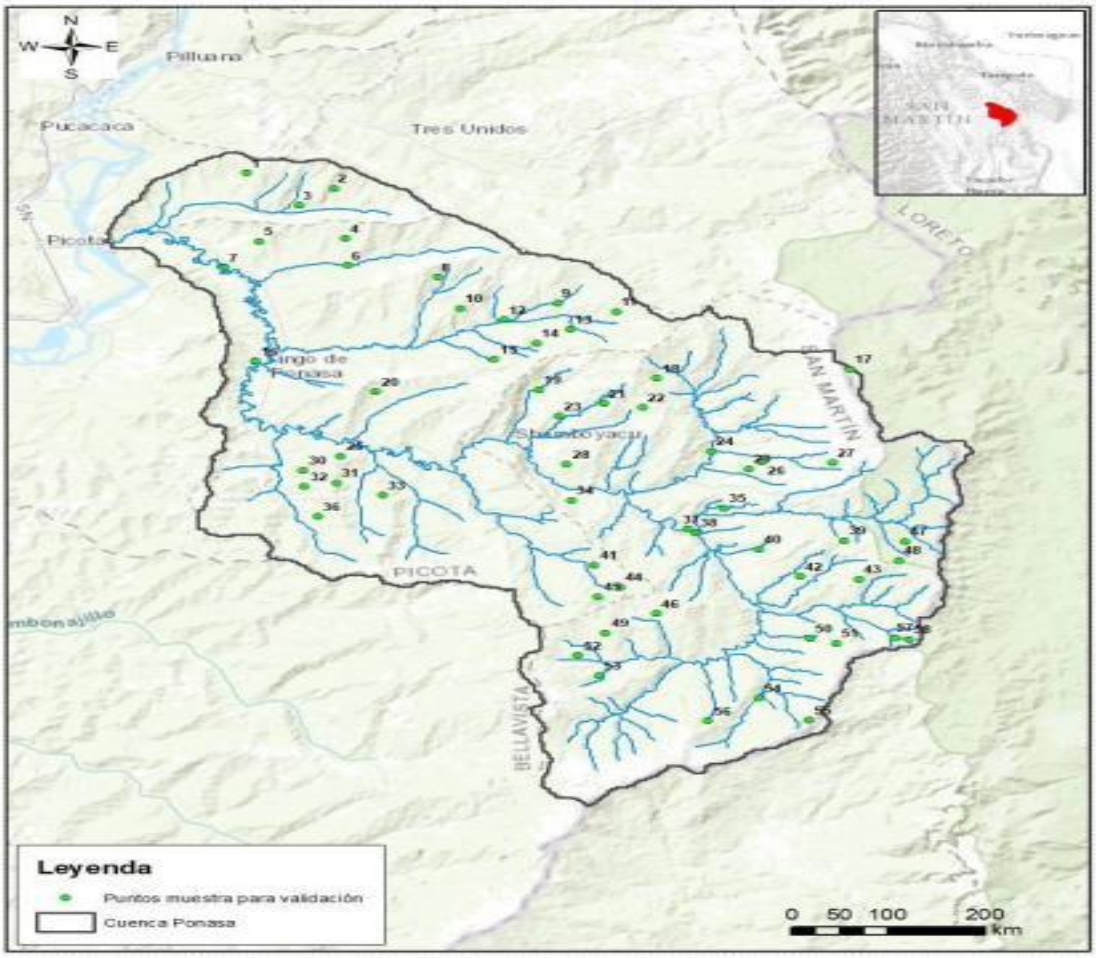

Fig. 1. Distribution of sampling points
Source: ANA, Hydrographic Units of Peru.

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

Note: Prepared by the authors.

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

Note: Prepared by the authors.

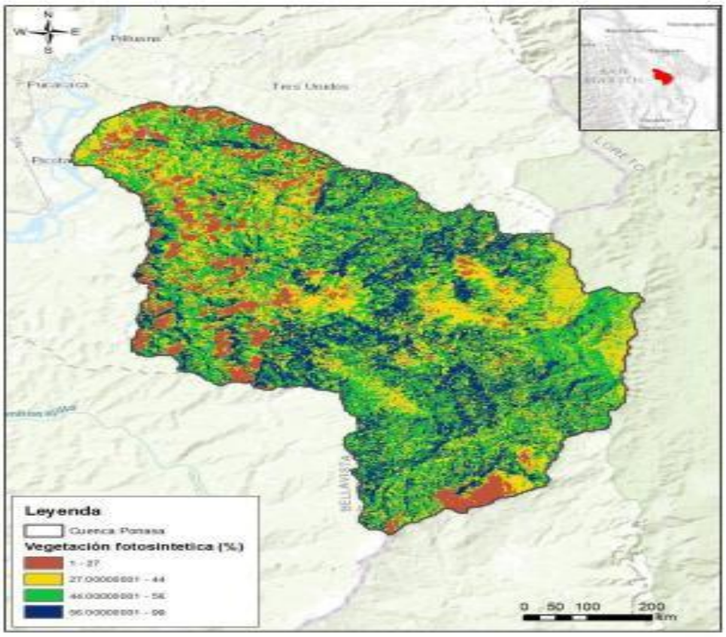

Fig. 2. Fractional photosynthetic vegetation cover - Ponasa Basin
Fuente: Collection images LANDSAT de Google Earth Engine

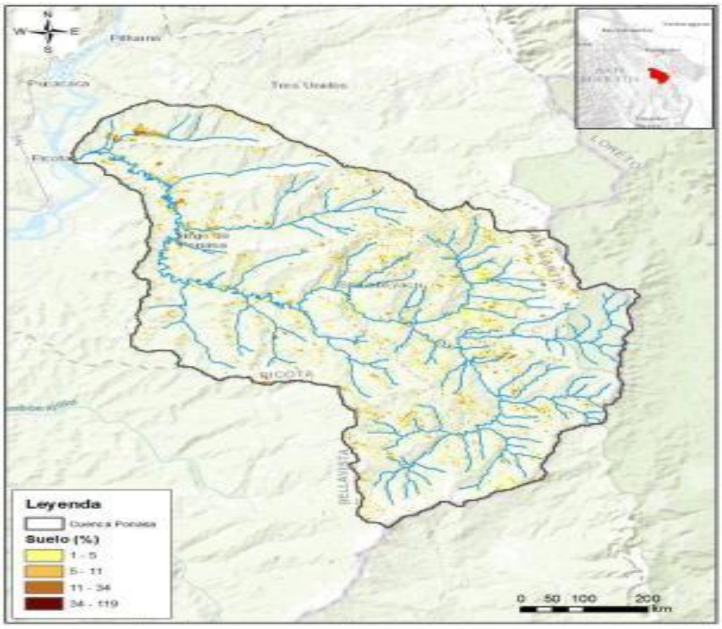

Fig. 3. Fractional land cover - Ponasa Basin
Source: ANA, Hydrographic Units of Peru.

Table 5. Non-photosynthetic vegetation fractional cover range (NPV) - Ponasa Watershed

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

Note: Prepared by the authors.

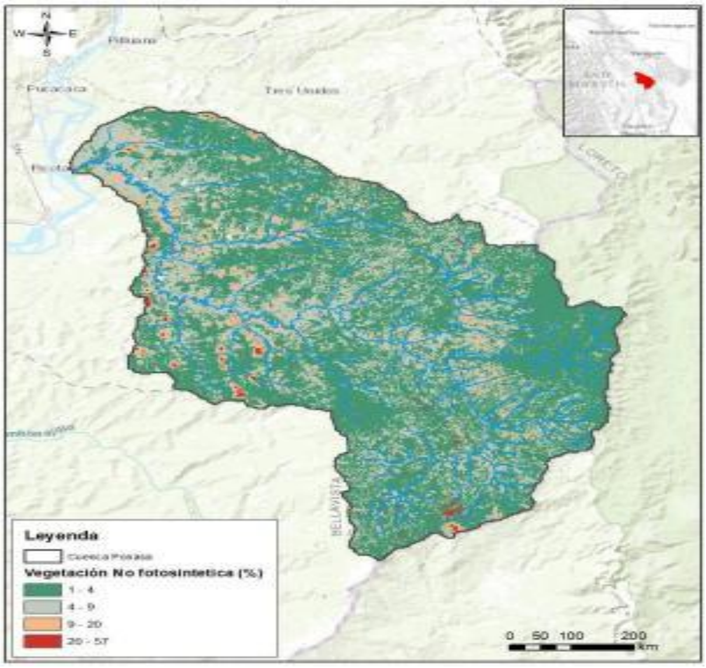

Fig. 4. Fractional cover of non-photosynthetic vegetation (NPV)-Ponasa Basin
Source: ANA, Hydrographic Units of Peru.

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 Fig. 5.

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.

The Ponasa river basin is a hydrographic system with strong pressure on the ecosystems of hill and montane forests. according to [20] 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 and so soil erosion caused by water and wind is one of the main processes of land degradation [21]. 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 [22].

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 [23]. Fig. 6 shows the relationship between the two variables. Soil erosion is a central concern for the environment and natural resources, representing a serious threat to agricultural productivity and being one of the main reasons for soil degradation [24]. Therefore, it is important to identify the area requiring ecological restoration strategies [25], considering that watersheds provide valuable ecosystem services to local communities, such as climate regulation and the provision of high quality water in sufficient quantity to support the development of economic activities [26].

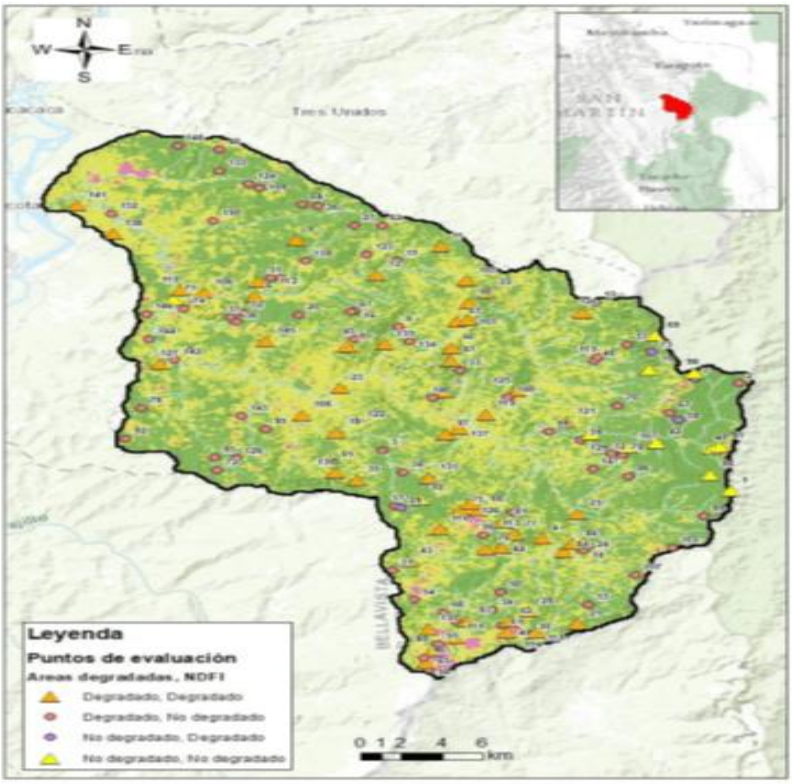

Fig. 5. Sampling points for comparison of identified degraded areas and obtained NDFI values
Source: ANA, Hydrographic Units of Peru.

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

Note: Prepared by the authors.

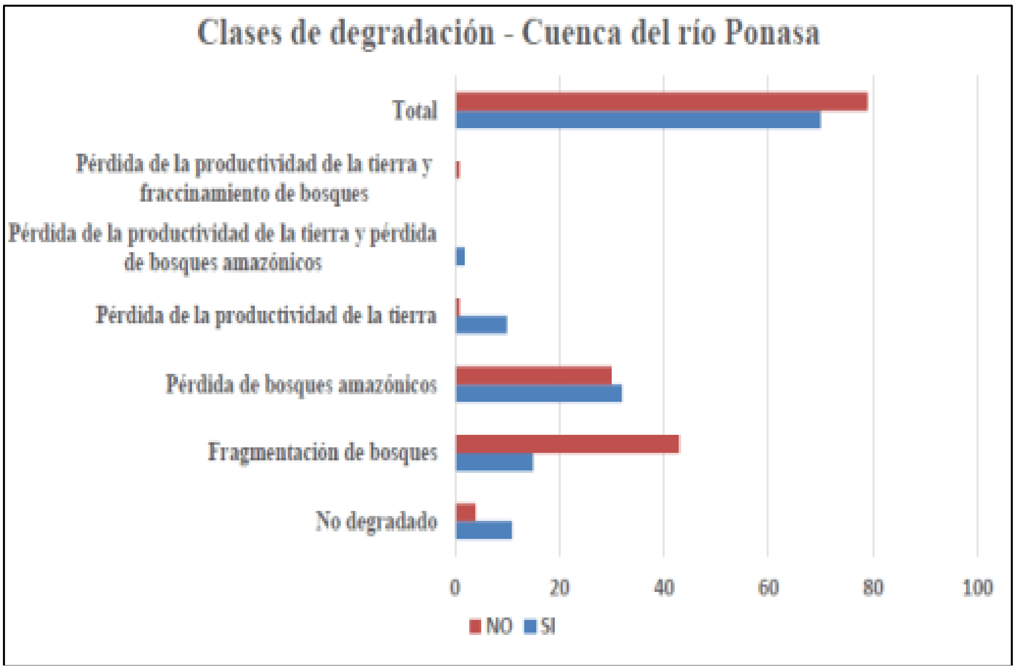

Fig. 6. Number of coincidences between the NDFI and the degradation classes identified in the Ponasa watershed

Note: Prepared by the authors.

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, They are therefore exposed to numerous drivers of change that result in a significant loss of biotic integrity and soil degradation [27]. It is well known that vegetation plays a crucial role in the conservation of soil fertility, as it helps to reduce the loss of fertile soil caused by erosion [28]. Fig. 6 shows the relationship between the two variables.

However, the same is not true for degradation classified by tree cover fragmentation [29], 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, is why the estimation of fractional vegetation cover (FVC) through the use of remotely sensed imagery has become feasible [30].

4. CONCLUSION

The Normalized Difference Fraction Index (NDFI) allowed explaining the degradation processes associated with the loss of vegetation cover and the decrease in the net primary productivity of the ecosystem in the present study, although it did not show the same relationship in terms of fragmentation. Photosynthetic vegetation, non-photosynthetic vegetation and ground vegetation were evaluated and considered to analyze fractional cover in the Ponasa watershed. The results of this analysis were compared with research on the recovery of degradation in the same area, which allowed validating the use of fractional cover in part of the ecosystems present in the Ponasa watershed.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

Table A1. 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 A2. 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	191	No degradado	No

					bosque			
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 amazónico	151	Degradado	Si
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

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